Brunel University

BIOMIMETICS DESIGN TOOL USED TO DEVELOP NEW COMPONENTS FOR LOWER-ENERGY BUILDINGS

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Declaration of Authorship

I, Salmaan Craig, declare that this thesis titled *Biomimetics Design Tool Used to Develop New Components for Lower-Energy Buildings* and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
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- With the exception of such quotations, this thesis is entirely my own work.
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ABSTRACT

BIOMIMETICS DESIGN TOOL USED TO DEVELOP NEW COMPONENTS FOR LOWER-ENERGY BUILDINGS

by Salmaan Craig

The contributions to knowledge documented in this doctoral thesis are two-fold. The first contribution is in the application of a new biomimetic design tool called BioTRIZ. Its creators claim it can be used to facilitate the transfer of biological principles to solve engineering problems. The core case-study of this thesis documents how this tool was used to frame and systematically explore low-energy solutions to a key technical problem in the underdeveloped field of radiative cooling. Radiative cooling is a passive mechanism through which heat from a building can be rejected to the sky – an abundant but underused natural heat sink. Published in the Journal of Bionic Engineering, the study was the first independent application of BioTRIZ in the academic literature. The second contribution to knowledge is in the design, development and testing of the most promising biomimetic concept to come out of the BioTRIZ radiative cooling study. 'Heat-selective' insulation gives a roof mass a cool view of the sky because integrated pathways focus and channel longwave thermal radiation through it. It is biomimetic because it achieves infrared transparency by adding structural hierarchy to the component, rather than manipulating the properties of the material itself. Test panels on a rooftop in central London cooled to between 6 and 13 degrees below ambient temperature on May and April nights. Radiative cooling powers of between 25 and 70 W/m^2 were measured when plates were at ambient temperature. Daytime radiative cooling below ambient temperature occurred when clouds blocked direct sunlight. Radiative cooling power was increased by 37% using reflective 'funnels'. Two additional BioTRIZ analyses are presented as minor case studies. They each attend to a key technical problem in the field of passive thermal energy storage in buildings. They serve to illustrate the type of results that can be expected from using BioTRIZ during low-energy building design.

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No island here. Many people have helped me develop my understanding in subjects that were alien to me when my project supervisors David Harrison and Andrew Cripps first decided to take a punt on me four years ago (I know no other more patient duo). Ian Pegg, Pablo Izquierdo and James Dickinson have always been willing to entertain my wilder ideas. Gideon Susman came in at the right time and conversations with him have invariably led to new insight.

Dad kept me on the early path to this point when at times I thought that I wanted to get off. (He also made sure that this thesis was free of any Bush-isms). Mum was always proud. And I'm glad Francesca's around.

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Executive Summary

1. Background

The energy consumed through using buildings and producing building materials forms a significant portion of overall energy consumption in affluent societies today. These costs are met mostly through the combustion of fossil-fuels. The exploitation of this unique solar inheritance is a thoroughly modern activity that is interfering in crucial biospheric cycles. Energy flows through buildings need to be better structured and managed, and their occupants need to change existing patterns of behaviour. There are several reasons why this prospect is challenging. The way buildings come into being is a complex and adversarial affair driven by economic considerations and the avoidance of risk, which favours incremental improvements of established designs. Current environmental standards and environmental design tools do little to advance the *status quo*. And there is generally a large discrepancy between the performance of buildings as designed and buildings as built, with designers knowing very little about how their designs actually perform.

Biomimetics – the practice of getting engineering inspiration from nature – may offer a new paradigm through which to redesign the built environment. The biomimetics field is beginning to flourish as an academic discipline in its own right. There is a growing library of remarkable biological phenomena, and biomimetic studies are being geared to suggest new ways of doing useful things while treading more lightly on the planet. But translating biological principles into concrete energy and material savings in the built environment is no trivial task. A group of biologists claim to have created a framework that assists in this delicate process of transfer. BioTRIZ is a look-up table which, if you can define your engineering problem in its terms, is supposed to offer you a handful of biological principles that have resolved the equivalent problem in the natural world.

This research project is about using this new biomimetics tool to frame and resolve some key engineering problems in low-energy building design; technical bottlenecks that are stopping buildings making better use of renewable thermal resources. The focus is on developing the most promising concepts into prototypes for new environmental technology that may, in the future, help reduce energy consumption in buildings. Buro Happold, an international building engineering consultancy, is sponsoring this project as part of the Engineering Doctorate program in order to explore whether product development can become a new area of business for the company. The founder, Ted Happold, worked during the 1970's with German architect Frei Otto, who took direct inspiration from biology in his designs for lightweight membrane structures. In collaboration with Brunel University, this research has been conducted within the Sustainability and Alternative Technologies (SAT) group in the London branch of Buro Happold.

2. Research objective

The core objective was outlined at the beginning of this project by the sponsor company. It was to conceive, develop and test an innovative 'green' building product to proof-of-principle stage. The emphasis was on reducing the energy consumed in buildings.

Two decisions were made to make the scope of the task manageable. The first defined the scale of the innovation aimed at. Only opportunities on the 'building component' level would be addressed. This meant the novel arrangement of existing materials into new building blocks. The second decision determined the type of thing that the innovation should do. The functional focus would be in the passive control of thermal flows through the building envelope.

BioTRIZ was discovered a year into the project. It was proposed by the research engineer as a promising means through which to execute the core objective. It has helped realise the project goal and has given the research a distinct intellectual foundation. Documenting its application has led to an additional contribution to knowledge.

3. Summary of method and approach

The core research objective was met in three distinct stages, each associated with a different method. The stages were: opportunity harvesting, concept development, and prototype testing. First, a review of a wide range of building design and technology literature was conducted in order to harvest pertinent opportunities for new technology development. Several were banked, but one in particular was chosen to take forward to the second stage. The most promising opportunity was in the field of radiative cooling, which involves rejecting heat passively into the sky – a very large 'object' with a low effective temperature. For the second stage, the biomimetics design tool BioTRIZ was used to analyse and resolve a key technological problem that was hindering radiative cooling being implemented in buildings. The aim was to develop a roof component that helps keep buildings in hot countries cool without additional energy input. The analysis resulted in a new biomimetic concept that could be brought to the third and final research stage – the testing of a proof-of-principle prototype. The method of testing was one demonstrated previously by practitioners in the radiative cooling field.

4. Summary of studies and results

The first step toward realising the research objective was the harvesting of opportunities, by literature review, for developing new low-energy building technology. The function of the literature review had a different emphasis to that which is usual for doctoral research in the fields of science and technology, which tend to be compartmentalised enough for a specialised area to be framed *a priori*. The unusual function of the literature review led it to be divided between the first four chapters of the thesis rather than being restricted to the first, although its total length is standard. The first two chapters are contextual. Chapter 1 introduces buildings and their relation to the environment in energetic terms. Chapter 2 introduces BioTRIZ and explains how it shows promise as a tool through which to redesign elements of the built environment.

The latter two chapters of the literature review are strategic, the aim being to identify suitable opportunities and select the most promising for development in the next research stage. Chapter 3 (*The evolution of building envelope technology)* finds that the success of heating, ventilation and air-conditioning systems has enabled a standard blueprint for commercial buildings to be exported around the world, irrespective of climatic context. This 'international vernacular' ignores some remarkable climate adaptation techniques for buildings developed over thousands of years. It also ignores several promising new technological developments which suggest a future in which buildings would have greater thermal responsiveness and selectivity. Some of the thermal conflicts that are exacerbated by this 'international vernacular' may be resolved with building products normally associated with the fit-out of buildings, or multi-functional components that together make-up the envelope of a building.

Chapter 4 concludes the literature review and distils the key opportunities surveyed in chapter 3. There are two that stand out. The first is the clearly underdeveloped area of radiative cooling. The sky is an abundant heat sink, but its cooling potential has been ignored in modern building design, despite civilisations past showing how effective radiative cooling can be. This was selected for exploitation and development in the next research stage. The second area of note is thermal storage by building components or products, a prospect enabled in particular by developments in the field of phase-change materials. Both areas involve making better use of locally available thermal resources, which may reduce energy demand in buildings.

The second step towards realising the research objective was carried out by analysing a radiative cooling problem using BioTRIZ. This process is documented in this thesis in chapter 5 (*BioTRIZ analysis – how to use the sky as a natural heat sink)* and in the Journal of Bionic Engineering (Craig *et al.* 2008*)*. A conventional roof was analysed to demonstrate why it misses out on free cooling in a hot climate with cool skies. For a roof to cool radiatively below ambient temperature, its mass should be radiantly coupled to the sky, but thermally decoupled from ambient and solar gains. The conflict occurs in the insulation. According to the BioTRIZ look-up table, it is an 'energy vs. energy' conflict. The biomimetic principles thus offered were contemplated within a tightly framed context to inspire concepts for new roof systems. Doing so led to the realisation that conventional insulation could be restructured around pathways that focus and channel longwave radiation. This type of 'infrared-transparent' or 'heat-selective' insulation does not yet exist, and was chosen as the concept to be developed in the next research stage. The biomimetic principle it embodies is that infrared transparency is achieved by adding structure to the insulation rather than by manipulating the bulk properties to create a new material.

The third step towards realising the research objective was the development and testing of the new concept for heat-selective insulation. Chapter 6 (*Heat-selective insulation for radiative cooling of buildings)* describes how prototypes were built and tested using a method demonstrated by practitioners in the radiative cooling field. The tests were carried out during April and May nights on an office roof in central London. Test panel temperatures fell to 6 and 13 degrees below ambient temperature. Radiative cooling powers between 25 and 70 W/m^2 were recorded when cooling plates were at ambient temperature. At 20 degrees above ambient, total cooling powers of between 90 and 200 W/m^2 were observed. Daytime radiative cooling below ambient temperature was evident when clouds blocked direct sunlight. Radiative cooling power was increased by 37% using reflective 'funnels'. The results indicate that a robust, heat-selective roof panel is technically feasible, designed for large enclosures in hot climates, such as transport hubs and exhibition halls. Better focussing and direction of longwave thermal radiation would be required to get useful radiative cooling for multi-storey buildings in built-up areas, because of the small ratio of sky view to floor space.

Two additional minor BioTRIZ case-studies are presented in chapter 7 ('Two more BioTRIZ case-studies'). The energy and material saving attributes of the concepts generated from either study remain to be tested. But they each serve to illustrate how the BioTRIZ method can help translate biomimetic principles into low-energy building design. The first minor case-study describes the concept design of a sacrificial formwork product for concrete structures, made from biodegradable extruded starch foam. The idea is to use it to 'unlock' the thermal mass in buildings, by creating concrete elements with empty networks inside them, so that cool night air can be passed through to discharge the mass of accumulated heat more effectively. BioTRIZ principles inspired the multifunctional hierarchical spiral-form of the void-former concept. The second minor case-study describes the design of a range of office products made of phase-change materials which store latent heat. Hitherto this type of material has been integrated with limited success into building fabrics where a thermal compromise occurs. BioTRIZ principles suggested segmenting the required volume and putting each part under the control of occupants.

5. Conclusion

The core objective of this project was to conceive, develop and test an innovative 'green' building product to proof-of-principle stage. The emphasis was on reducing the energy consumption of buildings. This objective has been achieved in the development and testing of 'heat-selective' insulation for radiative cooling of buildings. This is a new technology that makes use of an abundant natural heat sink that is distinctly underutilised today. With further development, it may help reduce energy demand for certain types of buildings in climates where cooling is necessary.

The development and testing of heat-selective insulation is presented as the core contribution to knowledge in this thesis. This is because it explicitly meets the objectives set out at the beginning of the research project by the sponsor company. But another contribution to knowledge has been made that is of interest to an audience beyond building services engineers and radiative cooling practitioners. It is in the documentation of *how* the idea came about. The field of biomimetics is attracting more interest as more people realise that our current modes of consumption are unsustainable. Ways of doing useful things for less energy and material are needed, and it is not unreasonable to surmise that 3 billion years of evolution might be able to provide us with some of the answers. The BioTRIZ radiative cooling analysis published in the Journal of Bionic Engineering is the first independent application of the tool in the academic literature. The study demonstrates how BioTRIZ can be used to impose a framework on a technical problem from which solutions that reduce energy and material throughput can be conceived and evaluated. It also emphasises that the low-energy strategies that BioTRIZ offers already form part of our technological repertoire; the trick is to recognise the manner in which they can be employed. Together with the two minor BioTRIZ case studies, this thesis helps suggest the type of answers that biomimetics may have for the difficult problems faced in restructuring and managing energy flows through buildings.

Introduction

Outlook

This thesis documents how a biomimetics design tool called BioTRIZ was used to conceive and develop a new low-energy building technology to proof-of-principle prototype stage. The process is documented in two parts. The first part, which makes up the first four chapters of this thesis, is a literature review. The second part, which makes up the last four chapters of this thesis, documents the core environmental technology development case-study. Two supplementary case-studies are also included. Apart from chapters 4 and 8, each chapter begins with an abstract that summarises the content and findings of that chapter. After this introduction, the reader may wish to get a sense of the whole thesis by reading the abstracts in series.

Part I, the literature review, consists of two contextual and two strategic chapters. Chapter 1, *the energy costs of buildings in fossil-fuelled civilisation,* surveys the impact of buildings on the environment using metrics for power density (watts per square meter) and energy intensity (joules per gram). Chapter 2, *BioTRIZ – a new tool for doing biomimetics,* posits that one new biomimetics design tool may be useful in helping to redesign elements of the built environment to reduce energy and material consumption. The focus of the literature review changes with chapters 3 and 4. Chapter 3, *the evolution of building envelope technology,* harvests opportunities for applying BioTRIZ to develop new low-energy building technology by collating different thermal strategies historically employed in buildings over many years in different climates. Chapter 4 distils the results of this survey into two key technological opportunities, each of which involves the passive exploitation of a natural heat sink to reduce energy demand in climates where cooling is necessary. One in particular stands out in the underdeveloped field of radiative cooling to the sky – itself a very large 'object' with a low effective temperature.

Part II consists mostly of the core case study of this thesis, which is spread over two chapters. Chapter 5, *BioTRIZ analysis – how to use the sky as a natural heat sink,* demonstrates how BioTRIZ was used to analyse and resolve a key radiative cooling problem, resulting in a biomimetic concept for a new low-energy building technology. Chapter 6, *heat-selective insulation for radiative cooling of buildings,* documents the tests carried out on prototypes based on the new biomimetic concept. Chapter 7 documents two additional case-studies in which BioTRIZ was used to develop concepts for low-energy building components. The thesis concludes with chapter 8.

Motivation

The prime motivation behind this research project was to develop an innovative 'green' building product. The development goal was formed partly by the motivations of the sponsor company, the building engineering consultancy Buro Happold, which wanted to explore the possibility of product development as new area of business. This EngD project provided one platform through which to learn more about how that might work. The research was conducted within the Sustainability and Alternative Technology group in Buro Happold and the School of Engineering and Design in Brunel University.

Statement of thesis

The main case-study provides evidence in support of two theses. The first thesis proposed is technological:

A mass can be cooled below ambient temperature by nesting pathways in surrounding insulation that channel longwave radiation toward a cool sky.

This describes the function and means of operation of heat-selective insulation, the new environmental technology developed during this research project. It embodies what is innovative about the concept. Empirical evidence, from prototype testing documented in chapter 6, demonstrates that passive radiative cooling can be achieved by the proposed means.

The second thesis proposes that:

BioTRIZ can be used to impose a framework on a technical problem from which solutions that reduce energy and material throughput can be conceived and evaluated.

Chapter 5 supports this claim by demonstrating how the tool was used to systematically frame and resolve a radiative cooling problem, resulting in a concept for a new environmental technology, heat-selective insulation. Two minor BioTRIZ case-studies in chapter 7 give additional evidence. However, it is recognised that the case-studies do not prove or disprove the efficacy of BioTRIZ as an instrument for achieving environmental technology development goals. Only with comparative data, perhaps from the study of numerous designers applying the tool in controlled conditions, could such a hypothesis be confidently corroborated. It is unlikely that any general conclusions about the effectiveness of the tool can be made from a report by a single person. It would be too difficult to separate the tool from the abilities of the person using it.

Statement of contributions

The contributions to knowledge borne from this research project are two-fold. The first contribution is in the application of the new biomimetic design tool BioTRIZ to a technological problem in the field of radiative cooling for buildings. Published in the Journal of Bionic Engineering, the study presented in chapter 5 was the first independent application of BioTRIZ in the academic literature.

The second contribution to knowledge is in the design, development and testing of the most promising biomimetic concept to come out of the BioTRIZ radiative cooling study. 'Heat-selective' insulation gives a roof mass a cool view of the sky because integrated pathways focus and channel longwave thermal radiation through it. It is biomimetic because it achieves infrared transparency by adding structure to the component, rather than manipulating the properties of the material itself. Prototype tests, documented in chapter 6, show that the principle of operation is sound.

PART I

Literature Review

Chapter 1

THE ENERGY COSTS OF BUILDINGS IN FOSSIL-FUELLED CIVILISATION

Abstract

The energy consumed through using buildings and producing building materials forms a large portion of overall energy consumption in affluent societies today. These costs are met mostly through the combustion of fossil-fuels. The exploitation of this unique solar inheritance, which took aeons to produce and cannot be replenished over the conceivable time span of human civilisation, is a thoroughly modern activity that is interfering in crucial biospheric cycles. Energy flows through buildings need to be better structured and managed, and their occupants need to change existing patterns of behaviour. There are several reasons why this prospect is challenging. The way buildings come into being is a complex and adversarial affair driven by economic considerations and the avoidance of risk, which favours incremental improvements of established designs. Current environmental standards and environmental design tools do little to advance the status-quo. And there is generally a large discrepancy between the performance of buildings as designed and buildings as built, with designers knowing very little about how their designs actually perform.

Introduction

This chapter sets the context for the research. It explains why it is important to reduce the energy costs of buildings, the available strategies for doing so, and how this prospect is made challenging by the way construction happens. The energy costs of buildings are surveyed in terms of power density (watts per square meter) and energy intensity (joules per gram).

1.1 Energy consumption in fossil-fuelled civilisation

Modern civilisation has set itself apart from all pre-industrial societies by adding two kinds of energy source (Smil 2007 p. 203). The first is fossilised stores of solar energy extracted in the form of coals and hydrocarbons (crude oils and natural gases). Fossil fuels were formed through slow heat and pressure transformations of accumulated biomass typically lasting $10^7 – 10^9$ years. The second is electricity generated mostly by burning these fuels. (Electricity is also generated using water and nuclear fission and, to a much lesser extent, wind and the Earth's heat (EIA 2005a)). In contrast, pre-industrial societies mostly derived their energy from sources that were almost immediate transformations of solar radiation (flowing water and wind) or that took relatively short periods of time to become available in a convenient form (Smil 2007 p.203). Times ranged from a few months of photosynthetic conversion to produce food and feed crops to a few decades to accumulate phytomass in mature trees to be harvested for fuel wood or charcoal.

The development of modern civilisation has depended on the conversion of fossil-fuels into a variety of final energies, including thermal, kinetic, chemical and electric. These conversions can now occur with unprecedented efficiency and flexibility. But perhaps the most prominent characteristic of fossil-fuelled civilisation is the exponential rise in per capita energy consumption, a story told in national statistics for Total Primary Energy Supplied (TPES), which encompasses fuel extraction and primary electricity generation.

In richer pre-industrial societies, typical annual wood and charcoal consumption ranged between 20 GJ and 40 GJ per capita (Smil 2007 p. 257). The only biomass based economy to surpass this was the sparsely populated and forest-rich North America, which reached 100 GJ per capita in 1860. During the nineteenth century countries with rich resources of coal increased their rates of gross fossil energy consumption rapidly, for instance, in Britain, from 20 GJ in 1800 to 116J in 1900. Now the highest levels of per capita use occur in the US and Canada (>300 GJ) and across the EU (120-180GJ) (EIA 2005a).

A greater proportion of the total energy consumed has been made productive because conversion efficiencies have improved. At most only around a tenth of total consumption in biomass based civilisations was converted effectively because of the low first-law efficiency of fireplaces, stoves and furnaces, whereas the efficiency often assumed by commentators today is usually 40%, this figure being representative of an overall mean for all types of energy conversions (Smil 2007 p. 257). Hence a person in a rich pre-industrial society might have had 2-4 GJ of energy put to effective use over a year, while for a modern European the figure is closer to 50-70 GJ, and for a modern North American, over 120 GJ. Even though per capita values for energy consumption garnered from national TPES statistics (TPES/population) are abstract, it is safe to say that greater efficiencies have not brought about a reduction in overall consumption.

One other prominent attribute of modern energy consumption is that its global distribution is highly skewed. The rates for populous developing countries remain far behind those of affluent countries. In 2003, China averaged less than 40 GJ per capita, India less than 15 GJ, and Nigeria less than 10 GJ (EIA 2005a). But the enormous disparity is brought better into focus by contrasting the shares of populations with those of TPES. In the same year the United States alone, with 5% of world population, used about 22% of total energy, and the G8 countries, with 12% of the world's population, consumed about 46 % of the world's energy (Smil 2007 p. 258). In contrast, the poorest one-quarter of humanity (sub-Saharan Africa, Nepal, Bangladesh, most of rural India) consumed less than 3% of the world's TPES.

The gap is even greater with respect to the most flexible form of energy — electricity. At the turn of the twentieth century, average per capita electricity consumption in affluent countries was about 10MWh, with Norway approaching an extraordinary 30 MWh, the United States in excess of 13 MWh, and most of Western Europe at about half of the U.S. mean value (Smil 2007 p. 259). The world's poor countries averaged just 1 MWh with some two billion people (nearly one-third of humanity) having no access to electricity.

A final trend worthy of note is evident from the comparison of consumption by sector. The rising affluence of modern societies is reflected in the declining shares of industrial consumption and slowly increasing shares of residential, commercial and transportation demand (Smil 2007 p.260; Pérez-Lombard *et al.* 2008). At the end of the twentieth century, industrial energy was below 50% of the total in all rich Western countries – about 45% in Japan compared to 65% in the early 1960s; 35% compared to nearly 50% in the US in 1950. In contrast, Chinese industries consumed 70% of the country's TPES in the year 2000.

Two conclusions can be drawn from this survey of the main characteristics of modern energy consumption. If developing countries are to continue to develop, global consumption is likely to increase. So, therefore, is the overall contribution from commercial and residential buildings.

The unifying metrics of power density (watts per square meter, W/m^2) and energy intensity (joules per gram, J/g) will be used in the next three sections to demonstrate in more detail the energy costs associated with using buildings and the energy embodied in buildings and their materials.

1.2 Power density of buildings

Collectively, buildings are either the largest or second largest consumers of energy (behind industrial energy conversions) in all rich societies (Pérez-Lombard *et al.* 2008). This is partly because the growing population is spending more time in buildings. But it is also because the services delivered in these buildings are becoming more sophisticated and people's expectations are rising. Buildings in the United States took about 40% of all fuels and 75% of their electricity in the year 2000 (Smil 2007 p. 260). Consumption attributable to buildings was 37% of final EU energy in 2004, bigger than industry (28%) and transport (32%) (Pérez-Lombard *et al.* 2008).

Space heating is the dominant demand in every rich nation. Depending on the climate it is between 50% and 80% of all residential consumption. The U.S. rate is just over 50% and the UK rate over 60% (Smil 2007 p. 260; Defra 2006). Next come appliances (~25% in US households) and water heating (~20% in US households). Residential air-conditioning use has been rising. In the US it plays a key role in boosting peak electricity demand, when in the summer it accounts for one-quarter of all household electricity.

For private houses standardised comparisons of heating energy required are usually done per unit area per heating degree-day (in C to the base of 18˚C). Japan averages annually 1,800 heating degree-days, the US about 2,500, and Canada 4,600 (Zhang 2004). The average in kJ/m^2 per degree-day for US housing stock in 1990 was about 150; new buildings 100-120; super-insulated houses, 30-50; and the most efficient designs, 15-20 (EIA 2001). In terms of actual consumption, national means of total residential energy consumption at the end of the twentieth century prorated to less than 10 W/m^2 of floor area in China, about 14 W/m^2 in Japan, 15-20 W/m^2 for all types of US housing (mean of ~17 W/m^2 for single-family detached houses), and 25 W/m^2 in Canada (Smil 2007 p. 262)

Differences in power densities (W/m^2) occur not just because of differences in climate. The consumption by a super-insulated home in a cold climate might be comparable to the consumption by a conventionally insulated home in a temperate climate. Different lifestyles and affluence levels also set different consumption baselines. For instance, people in different countries may tolerate lower indoor temperatures and be more selective about which rooms they heat.

Commercial buildings have a higher specific energy use than households. Most multi-storey glass structures put up in North America between the early 1950s and the early 1970s averaged 110-140 W/m^2 of floor area. A typical 20-storey glass building of those years required 2-2.5 kW/m^2 of its footprint, and New York's 110-story World Trade Center twin towers used about 12 kW/m^2 of their footprints, or a total of 80 MW per building (Smil 2007 p.262).

These enormous power densities were not considered expensive until the first oil crisis in 1973. By the mid-1980s the primary energy required by new buildings was below 50 W/m^2, and many all-electric buildings have been designed for 10 W/m^2 or below, less than 30W of primary energy per square meter of occupied area (or, for a 50-storey structure, no more than 1.5 kW/m^2 of the foundations). An extensive survey of US commercial buildings shows a nationwide mean of about 33 W/m^2 for all structures, with the rates ranging from less than 15 W/m^2 for storage to more than 90 W/m^2 for food service and health care buildings (EIA 2005a). On average, one-third of this flux went for heating, one-fifth for lighting, and only about 6% for office equipment.

1.3 Energy intensity of building materials

Timber, stone, and bricks, either sun-dried or kiln-burned, were the dominant building materials of the pre-industrial world suitable to construct the four components – walls, columns, beams and arches – needed to erect structures (Smil 2007 p.191). These materials were extracted, transported, shaped and put in place using only simple tools and animal or human labour. The least energy intensive materials were sun-dried bricks, usually made of a compacted mixture of clay and chopped straw. Fired bricks were first used in Mesopotamia, later becoming popular in both the Roman Empire and Han China (Smil 2007 p.192). Firing in open pits was a common and extremely wasteful practice; only experiments with enclosed kilns brought even baking and reduced fuel consumption.

The dimensions of pre-industrial structures were surpassed by the advent of inexpensive structural steel and modern concrete during the late nineteenth century

(Addis 2007 p. 365). In terms of overall mass, reinforced concrete is the dominant building material of modern construction. It is used everywhere in buildings, bridges, roads and dams. Concrete is a mixture of cement, aggregate and water, pioneered by the Romans. It is made by hydration, a reaction between cement and water that produces tight bonds and a material that is very strong in compression but weak in tension and hence has to be reinforced for most construction uses.

Modern Portland cement did not arrive until 1824, when Joseph Aspin fired limestone and clay at very high temperatures to vitrify alumina and silica to produce a glassy clinker (Addis 2007 p. 344). These high temperatures (~1500°C in today's furnaces) make clinker production the most energy intensive part of the cement production process, which also involves the crushing, drying and grinding of the raw materials needed to make clinker, and the final grinding to yield the finished material. Depending on the process and the principal fuel used (coal or natural gas), most of the published values for clinker are 3.2—7 GJ/t, compared to a net theoretical minimum of 1.75 GJ/t (Sheinbaum and Ozawa 1997). After mixing with water and aggregate (sand or gravel that is cheap at about 100 MJ/t), concrete embodies 1-2 GJ/t and reinforced concrete that includes 100 kg/m3 of steel bars embodies 2-3 GJ/t (Smil 2007 p. 281)

This energy intensity is similar to the three traditional construction materials. Fired clay bricks need 4-8 GJ/t, and the energy 'cost' of stone quarrying is commonly less than 1 GJ/t, although transportation costs, particularly for large pieces, can multiply that value several fold (Smil 2007 p. 282). The energy cost of wood varies greatly, from as low as 0.57 GJ/t and as high as 41.2 GJ/t. This reflects a difference in the sources (climax vs. immature, native vs. plantation, hardwood vs. softwood), harvesting techniques, and the extent of processing and drying. But the most representative energy costs for wood probably fall between 2 GJ/t and 7 GJ/t (Glover, White and Langrish 2002; CWC 2004; Buchanon and Honey 1994). Modern techniques of chipping, gluing and compressing raise the energy cost of particle board to 8 GJ/t and of plywood to at least 10 GJ/t.

The energy expended in manufacture may be high but these processes are used because cash costs of fossil-fuels are still relatively cheap and capital intensive production methods are very cost efficient. This is particularly true of steel, which is processed by the smelting of pig iron, and provides a large part of the physical infrastructure of modern civilisation. Innovations such as continuous casting brought the energy costs of steel down from 25 GJ/t by 1975 to below 20 GJ/t in the late 1990s. About 65% of that total is consumed in the blast furnace during the smelting of pig iron. To produce iron from hematite, modern blast furnaces consume between 12.5 GJ/t and 15 GJ/t. This is roughly twice the theoretical limit (6.6 GJ/t) and a vast improvement compared to 1900 when it cost 50 GJ/t (Smil 2007 p.284).

Aluminium is the second most important structural metal of modern civilisation. Its production is highly energy intensive, a whole order of magnitude above that of steel from blast furnace iron. Starting with the carbide anode electrolysis method, adding the inevitable electricity losses in generation and transmission, the energy costs of other fuels, bauxite mining, production of alumina and carbon electrodes, and the casting of the smelted metal, the total rate is about 200 GJ/t (Smil 2007 p.284). Among structural metals, only titanium requires more energy (up to 900 GJ/kg) to be produced from its ores.

1.4 Energy intensity of buildings

Although valuable and wide ranging studies have been made (Brown et al 1996), it is considerably more difficult to quantify the energy embodied in buildings and manufactured products than it is to quantify the energy used in producing basic materials. Analyses must consider not only the components used in the final assembly but also the cost of long-distance transportation, which is common in the global economy. These realities, as well as different assumptions regarding the recycling and waste rates, analytical boundaries, and typical conversion efficiencies, result in often substantial differences in published energy costs. The energy cost of houses and other buildings elude easy generalizations because of very different shares of principal construction materials and the quality of interiors.

The mass of modern structures is dominated by one of three main structural materials – wood, steel or concrete – but houses include a large assortment of other components whose embodied energies range from less than 10 GJ/t (tiles) to more than 200 GJ/t (machined aluminium alloys). As a result, the energy cost of residential space in rich countries varies from 3 GJ/m^2 to 9 GJ/m^2, with floors and roofs usually the largest items (Buchanon and Honey 1994; CWC 2004). These values translate to a wide range of grand totals for single-family houses, from as little as 200-300 GJ for small wooden houses and 500-700 GJ for small steel based houses and more than 2 TJ for large houses using a mixture of materials. An average three-bedroom, wood-framed bungalow embodies an average of 500 GJ.

Several studies have compared the embodied energy costs of identically sized family houses using the three principal structural materials. Predictably, concrete houses have the largest mass, and depending on the design, either they or steel houses require the most energy (Glover, White and Langrish 2002). A study of 220-m^2 family houses in the Toronto area found final embodied energies of 1.12 TJ for wood-based, 1.42 TJ for steel-based, and 1.76 TJ for concrete based designs (CWC 2004), implying energy intensities of approximately 5, 6.5 and 8 GJ/m^2, respectively. Similarly, a process analysis of a multi-storey Swedish building showed the concrete-frame structure embodying 60% more energy that an identically sized wood-framed one (Börjesson and Gustavsson 2000)

Nationwide US data show the expected progression from other structures. Warehouses are relatively cheap (5-7 GJ/m^2), high rise apartments take 8-9 GJ/m^2, stores restaurants, hotels, motels, and industrial buildings need 10-13 GJ/m^2, and hospitals and office buildings need 18-20 GJ/m^2, mainly because of more metals in structures, elevators, and finishing (EIA 1998). A detailed analysis of two Hong Kong high-rise designs showed energy costs of 6.5-7 GJ/m^2, with steel accounting for about 70% of the total (Chen, Burnett and Chau 2001). As a result, a five-storey building with 75 apartments embodies as little as 25 TJ, a luxury 30-storery building with 1000 m^2/floor needs 300 TJ.

As expected, life cycle assessments show that the colder the climate, the lower the share of embodied energy in whole-life energy costs. A large 200-m^2 Canadian house that uses about 25 W/m^2 for heating and lighting and embodies about 1.5 TJ, the ratio of construction to operation energy will be only 0.16 over a 50-year period. For detached and semidetached houses in temperature climates, the ratios are 0.3-0.4 and rise to more than 0.75 for super-insulated structures (Mithraratne and Vale 2004; CWC 2004).

With the power-density and energy-intensity of buildings examined, the following two sections consider some of the environmental consequences of fossil-fuelled civilisation.

1.5 Anthropomorphic interferences in biospheric cycles

Three centuries of fossil-fuelled industrialisation, urbanisation and intense farming has changed both the extent and the rates of environmental intervention by humans. Of particular concern is the modern interference in the carbon, nitrogen and sulphur cycles, each of which plays a unique roles in sustaining life on earth. During the pre-industrial era human interference in the three cycles was limited to the burning of biomass and conversion of natural ecosystems to cultivated lands, and some concentrated dumping and recycling of organic wastes (Smil 2007 p. 327). But intense and wide-scale burning of fossil-fuels reintroduced long-dormant stores of carbon and sulphur into the atmosphere and generated increasing amounts of nitrogen oxides. In addition, agricultural intensification relied on the expanding use of inorganic nitrogen fertilisers. As a result, anthropogenic fluxes of the three elements now form large shares of their total biospheric flows.

Of most concern is the consequent rise in atmospheric concentrations of CO_2, the most prevalent greenhouse gas. A reliable record of atmospheric CO_2 is available for the past 420,000 years, thanks to the analyses of air bubbles from ice cores retrieved in Antarctica and Greenland. Pre-industrial CO_2 levels were never below 180 parts per million (ppm) and never above 300 ppm (Alley *et al.* 2007). Between the beginnings of the first civilisations 5000-6000 years ago and the onset of the fossil-fuelled era, these levels fluctuated narrowly between 250 ppm and 290 ppm. Continuous measurements began in 1958, far from anthropogenic sources and forested areas, at Mauna Loa and the South Pole. When these measurements began, CO2 levels averaged 320 ppm; by 2000 it had surpassed 370 ppm – an annual increase of about 1.2 ppm (1 Gt C = 0.47 ppm).

The post-1850 rise of fossil fuel combustion brought global carbon emissions (1t C= 3.66 t CO2) from less than 0.5 Gt in 1900 to over 6.5 Gt by the year 2000 (Alley *et al.* 2007). The cumulative total of carbon emissions from fossil fuel combustion was about 280 Gt between 1850 and 2000. This is by far the most worrisome aspect of modern activity, because it is unbalancing a crucial long-term feedback relationship that helps keep the temperature of the biosphere in check. If surface temperatures decrease, atmospheric CO_2 gradually accumulates, helping to keep biosphere temperature steady.

The combined thermal burden of other anthropogenic greenhouse gases, such as CH_4 and N_2O, are now roughly equal to that of CO_2 (Alley *et al.* 2007). This has happened because, although they are more sparsely distributed in the atmosphere, they absorb outgoing infrared radiation at higher rates. Compared to 1880, the combined forcing of all greenhouse gases reached nearly 3W/m^2 by 2000 and 3.05 W/m^2 by 2003. Black carbon added nearly 0.5 W/m^2, but the net effect of aerosols was to cool the Earth at 1.39 W/m^2. Adding the effects of land use and snow albedo (the proportion of reflected solar radiation) produced overall forcing of 1.8 (+/- 0.85) W/m^2 relative to 1880.

The doubling of pre-industrial atmospheric CO_2 concentrations would most likely raise average tropospheric temperatures by 2C-4.5˚C and cause relatively rapid global climate change, including unevenly distributed higher seasonal temperatures (faster warming in polar regions), an accelerated water cycle, changed precipitation patterns, and rising ocean level (Alley *et al.* 2007). Worryingly, energy consumption continues to grow substantially. Future limits on human energy use may arise not from a shortage of resources, but from the necessity to keep the critical biospheric cycles in balance. The potentially destabilizing environmental, health, and socio-economic consequences of these changes have become a major topic of interdisciplinary research and public policy (Epstein and Mills 2005).

1.6 Urban environments and heat islands

In 1800 only 3% of the global population of 1.2 billion was urban; by 2005 it was just above 50% of 6.5 billion (UNO 2006; Demographia 2005). This profound transformation – from an overwhelmingly rural, decentralised, parochial, low-energy society to a predominantly urban, centralised, globalised, high-energy culture – may have run its course in rich nations but is still accelerating in modernizing countries

Cities are highly complex interactive socio-physical systems, shaped by many players with competing expectations and priorities as well as by physical and technical infrastructure (RCEP 2007 p. 8). From these complex interactions emerge environmental issues unique to urban environments. One such systemic problem is the clearly discernable urban heat island effect. Urban heat islands (UHI) are caused by persistent heat rejection by buildings and other urban sources in concert with the higher thermal capacity and lower albedo of built surfaces, a smaller sky view that hinders radiative cooling, and less green spaces (meaning less evaporative cooling) (Taha 2004). UHIs are on average about 2˚C warmer, and their cores may temporarily have temperatures up to 8˚C higher than the surrounding countryside (Taha 2004). The effect is most readily identifiable at night because urban convective flows diminish in the absence of solar heating of paved and built up areas (Camilloni and Barros 1997).

UHIs have negligible large-scale climatic effects (Peterson 2003), but there are undeniable local impacts, and they can lead to greater energy consumption. Well documented effects include increased cloudiness (up to 8% more), precipitation (up to 14% more), and thunderstorms (up to 15% more) near and particularly downwind of UHI-affected areas as well as decreased relative humidity (2%-8% lower), wind speed (20%-30% lower annual mean), and direct solar radiation on horizontal surfaces (15%-20% lower due to structural shading) (Taha 2004). In aggravating summer heat waves and reducing night-cooling, the frequency of premature deaths (due to heat loss and dehydration) is increased and living, working and moving are made less tolerable for everybody without air conditioning.

The most readily quantifiable effect of urban heat islands is the increased use of electricity for additional air conditioning (and decreased winter heating). On warm afternoons in Los Angeles, electricity demand rises nearly 3% for every 1˚C rise in the daily maximum, and the probability of smog increases much more steeply, by 5% for every 0.25˚C rise (Heat Island Group 2000a). UHIs increase the number of cooling-degree days by 15%-35% in large US cities and by as much as 90% in Los Angeles (Taha 2004). A welcome effect in Los Angeles has been the extension of the growing season as far as 10km beyond the city's edges (Zhang et al. 2004)

Tree planting is the most efficient way of reducing UHI intensity. Urban parks are 0.5C-2.5C cooler than their surroundings. Lighter coloured pavements and cool roofs are also effective since they reflect a greater proportion of solar radiation (they have higher albedo). Traditional roofing surfaces have albedos ranging from 5% (asphalt roofs of commercial buildings, dark house shingles) to 20% (green shingles), and only slightly more reflective roof shingles with albedos of 35%-40% can reduce the temperature differences between roof and surrounding air by about 10˚C (Heat Island Group 2000b). Konopacki *et al.* (1997) calculated that the universal adoption of light coloured roofing materials would reduce US air conditioning demand by about 10 TWh.

Having reviewed some important environmental impacts associated with energy consumption in buildings, the next section looks at the broad strategies available for energy conservation in buildings.

1.7 Energy conservation in buildings

The first law of thermodynamics dictates that energy is always conserved. Thermodynamically, therefore, the term *energy conservation* is misleading. But it is nevertheless a term widely used in calling for the more sensible and *effective* use of energy. The term will continue to be used here.

Broadly, there are three ways that energy can be conserved in buildings. The first is doing without, an option rarely considered in affluent societies habituated to the idea of growth and comfort. But buildings in certain climates need certain services less than others. For instance, the need for air-conditioning can be negated in temperate climates with good passive design and tolerant occupants. And US research suggests that occupants of naturally ventilated buildings are comfortable over a much wider range of temperatures compared to occupants of air-conditioned buildings, primarily because the higher degree of personal control shifts expectations and preferences (Brager & de Dear 2000).

The second energy conservation strategy is to reduce the use of energy-intensive products through better design. This includes the design of appliances and components used in buildings and how they work in concert with the building system as a whole. For better or worse, the way a building is designed will influence how occupants use the appliances it contains. Examples of the worse kind seem rife. Commonly, the benefits of fitting new compact fluorescent bulbs may be reduced or cancelled by leaving them on too long, a behaviour trait that can be encouraged by the way the building is designed. For example it is not uncommon to find the floor in a deep-plan office artificially lit throughout, despite ample daylight, even near the perimeter windows. This could be avoided simply by designing in more local light switches.

Maximising conversion efficiencies is the third energy conservation strategy. Only in a minority of cases have further improvements of conversion efficiencies run into physical limits. Many boilers are in first law terms more than 90% efficient. But beyond such instances there is a huge number of wasteful conversions in buildings. Halving the total required energy in houses through super-insulation is not exceptional. And modest improvements, multiplied by the millions units operating in modern mass consumption societies, would translate to huge savings. Further savings can come from structural changes. In comparison with a three-bedroom, single-storey house, an equal-sized two-storey building has an energy efficiency gain of 15%, a two-storey duplex

30%, a two-storey triplex 35%, and a low-rise apartment building 40% (Burchell and Listokin 1982).

Since the first energy crisis in 1973, much attention has been given to improving the efficiency of devices, products and technology. Some claim that the future elimination of large existing conversion inefficiencies and the shift toward increasingly service-based and less material intensive economies can lead to stunning reductions of energy use at the national level (Lovins 1976, 1988; Hawken, Lovins and Lovins 1999). One of the principle objectives of the proponents of this soft energy path is a restructuring of how energy is delivered. In general, rich societies need 20%-40% of their useful energy as low-temperature heat (well below 100˚C), and supplying this demand by burning fossil fuels at temperatures exceeding 1000˚C leads to very low second-law (exergetic) efficiencies. This second-law efficiency would soar with wider application of solar conversions (see Smil 2007 p.380)

The most often cited example of this mismatch is the use of fossil-fuelled generated electricity for resistance heating (using inexpensive hydroelectricity, as do Norway and Quebec, is a different matter). Combined heat and power (CHP), or co-generation, addresses a part of the qualitative mismatch between sources and final uses that is regrettably common in high-energy-use society. CHP is the use of a single primary heat source to produce simultaneous electricity and heat, saving 10%-30% of fuel in comparison with a separate generation of the two final energies (Smil 2007 p. 268). Like multi-storey housing, it is an energy conservation strategy particularly suited to urban environments.

But it is important to realise that the economical use of fuels seldom seems to result in diminished consumption. Indeed, the diffusion of a radically more efficient technology often leads to greater absolute consumption. By the year 2000 the efficiency of British lighting was 1000 times that in 1800, but per capita use was 6,500 times greater and total lighting consumption was 25,000 times higher (Fouquet and Pearson 2006). And while the typical power density of new houses is now considerably lower than right after the Second World War, in some countries houses have grown larger. The average size of new US houses increased by more than 50% during the last quarter of the twentieth century, to just over $200m^2$ (USBC 2006). Air-conditioning provision is also rising and, if current trends continue, it is estimated that 40% of commercial floor space in the UK will be air-conditioned, compared with 10% in 1994 (RCEP 2007 p.

98). To focus on the increased efficiency of air-conditioners here would be missing the point. Regardless of efficiency, increased uptake will negate energy savings, particularly if users maintain indoor temperatures they would normally consider too cold in winter. This is a point too subtle for many involved in the building design process.

The national histories of energy consumption surveyed earlier in this chapter show that efficiency gains have not brought any long-run decline in overall energy use. If anything, they show that relative savings have been accompanied by rising absolute consumption. While efficiency is an important aspect of the energy conservation challenge in buildings, fixation upon it can disconnect the problem from the solution. Efficiency emphasises output, which may be optimised but not necessarily minimised.

Having reviewed the opportunities for and limits of basic strategies for energy conservation in buildings, the following and last section asks why their wide scale successful implementation is difficult.

1.8 The industry favours incremental improvement

The design and production of physical artefacts and information systems today – from airplanes and buildings to software and business processes – can be very complex collaborative affairs, with thousands of participants working on different elements. The vastness and complexity of these projects mean that it soon becomes impossible for one single person to keep abreast of all developments. In these circumstances it is natural for large scale collaborative design networks to take on a distributed form, where there is no centralised controller, and global behaviour emerges as a result of concurrent local actions (Klien *et al* 2003).

The dynamics of distributed networks are a central focus of complex systems research (Klien *et al* 2003; Braha and Bar-Yam 2004). One attribute of such networks is the interdependence of groups, agents or elements. A design decision by one group has ramifications for many groups. This makes it difficult to converge on a single design that satisfies all the interests of the different groups involved. As a result, large collaborative design projects are often characterised by expensive and time-consuming processes and a tendency to favour less risky incremental improvements of established designs. Whole life-cycle issues such as environment impact tend to take a collective back-seat.

Qualitative evidence of distributed network behaviour abounds in the construction industry, with both Vischler (1989) and Egan (1998) expressing exasperation at its adversarial nature, citing the sheer numbers of players involved in explaining the lack of accountability and large number of disputes. They describe a building design process which is wholly unsystematic, one that rolls on quickly to meet programme deadlines, with design team participants dealing with imperfect information and competing goals and values. The fragmentation of the industry has developed over many years, with a number of specialists and consultants – some of which have interests only in very narrow areas of performance – now filling the increased gap between lead designer (if there is such a thing anymore) and building user (Cooper 1975). Other than profit, it is rare for a common drive to emerge between agents. Egan's (1998) primary concern was with the general lack of innovation in the industry, but his conclusions are applicable to green innovation and reducing energy consumption and environmental impact in general.

It does not help that there is large discrepancy between the performance of buildings as designed and buildings as built. In commercial and institutional buildings especially, designers don't seem able to predict energy consumption. Predicted thermal transmittance through building fabrics are more often than not shown to be optimistic when compared to measurements after construction (Olivier 2001). Studies of the performance of 16 'low-energy' buildings showed design estimates to be frequently lower than actual consumption, with large differences in consumption between buildings performing similar functions (Bordass *et al.* 2001a).

Designers know very little about how their designs actually perform, because they receive no feedback once construction is complete and occupancy begins. The result is that obvious design errors continue to be made. Olivier (2001) found mismatches between use of spaces and control systems in large deep plan offices. Systems ran at full output even when there were few occupants, and large systems were left to support small loads (e.g. main chillers cooling a server room), and poor control interfaces meant occupants couldn't tune their comfort. The lack of design feedback on performance must surely be unique among the producing industries (Cooper 2001). Several commentators have called for urgent changes to be made (Pegg 2007; Bordass *et al.* 2001b)

Fortunately energy conservation isn't left entirely to building designers. The EU Energy Performance of Buildings Directive (EPBD) – if implemented as intended – will be an important driver to improve the environmental performance of buildings. It requires new and existing homes, public sector buildings and commercial properties to display an energy rating when the building changes hands. The EPBD requires Member States to review their building regulations every five years.

The last update in the UK was in April 2006. Part L of the building regulations deals with energy efficiency. Historically, it has regulated on the maximum rate of heat loss through the fabric of a building, enforcing incremental improvements. With a renewed focus on reducing CO_2 emissions, designers can now trade reductions in fabric losses for other energy efficiency measures, such as better boilers or smaller windows (ODPM 2006). Unfortunately, the effect of these measures only has to be 'proved' at the design stage by computer models left unverified after building is complete and occupancy begins. And several important issues that affect energy consumption remain unregulated, such as the balance between natural daylight and artificial lighting.

Other standards include the EcoHomes ratings developed by the Building Research Establishment (BRE) and those standards set by Passive House and the Beddington Zero-Energy Development project (BedZED). But there is little incentive for housing developers to go beyond the Building Regulations, and the Industry as a whole, with a tried, tested and profitable product, resists proposals for the tightening of standards. More than incremental progress in house building may come about with the creation of the Code for Sustainable Homes, which sets out different levels of ambition, including energy efficiency, carbon dioxide emissions, water consumption and waste. While the Code for Sustainable Homes is voluntary, it is envisaged that over time the Building Regulations will be tightened to reflect it (RCEP 2007 p. 100).

Beyond standards, it remains difficult for architects or engineers to explore the environmental benefits of innovative building configurations. To support environmental decision-making there is Life Cycle Assessment (of which the energy analyses surveyed in section 1.4 form an important part), which can be used to compare alternatives in terms of environmental service per unit of service delivered (Hofstetter 1998; Lainchbury *et al.* 2002). It is a scaleable tool the depth and breadth of which can be varied. A full peer reviewed study can take years while a quick screening could take a few days. At the quicker end of the scale is a large selection of eco-design tools developed to support product designers in considering the environmental ramifications of their decisions (Graedel 1996; Jönsson 2000; Jones *et al.* 2001). These are meant especially for the early stages of design where eco-interventions are most likely to succeed, before burdensome decisions have crystallised leaving room only for eco-tweaking. However, fundamentally, for all LCAs, the choice of system boundaries determines the outcome, and the certainty of results can obviously be compromised if little time and resources are invested. This is a particular sticking point for building designers, particularly if the results of an analysis may not be applicable on the next project.

Conclusion

Collectively, buildings are either the largest or second largest consumers of energy in all rich societies, playing a significant role in human interference in the carbon cycle. Technological improvements need to be complemented and reinforced by greater awareness of energy use and behavioural change. But conserving energy in buildings is proving difficult for a number of reasons. The building design process is complex and adversarial, favouring incremental changes to established designs. There is a large discrepancy in performance between buildings as designed and building as built, and – uniquely among producing industries – there is no consistent feedback to designers on performance.

Chapter 2

BioTRIZ – A NEW TOOL FOR DOING BIOMIMETICS

"Categories straddle the boundary between the mind and the world: they are socially developed mental representations, but they must fit the properties of real objects in the real environment if they are to be useful"

Ulric Neisser, 1987, *Concepts and Conceptual Development*, Cambridge University Press, Introduction.

Abstract

TRIZ is a Russian problem-solving methodology for engineers. Among several methods and tools within it are a set of forty problem-solving 'gambits' for resolving engineering trade-offs, derived from the study of millions of significant patents. These principles can be arranged into six general classes of inventive interventions, namely, changes in energy, information, substance, structure, space and time. Using this framework, biologists have demonstrated that, in analogous situations, the inventive 'strategies' that natural systems use differ from those usually applied by humans. On the whole, over different scales of size, biology manipulates structure and information, while humans tend to manipulate substance and energy. The biologists say that this finding could be used to give biomimetics – the practice of getting engineering inspiration from nature – a theoretical backbone. In addition to their study, they have created a new tool to supplement the TRIZ problem-solving repertoire. BioTriz is a 6x6 look-up table that, if you are able to define your technical problem in its terms, will present you with the TRIZ principles that, somewhere in the natural world, have solved that same problem. The BioTRIZ tool may help resolve thermal conflicts in building design and so reduce energy consumption in buildings.

Introduction

This chapter first examines the engineering methodology TRIZ, paying particular attention to what makes it unique in comparison to other design methodologies on offer: a theoretical structure meant to facilitate the transfer of engineering know-how across technological disciplines. The second part of the chapter reviews how a group of biologists used an adapted version of this theoretical structure to capture how biological systems solve 'technical' problems in the natural world and produce a new biomimetics design tool called *BioTRIZ*. The chapter concludes by suggesting how *BioTRIZ* may illuminate the process of low-energy building design, and assist in developing new low-energy building technology.

2.1 TRIZ and the transfer of engineering know-how

The engineering design methodology *TRIZ* (Теория решения изобретательских задач; *Teoriya Resheniya Izobretatelskikh Zadatch; Theory of Inventive Problem Solving)* was developed by the Soviet engineer and patent clerk Genrich Altshuller (1926-1998) and others from the middle of the twentieth century onwards (Altshuller 1984, 1999; Terninko *et al* 1998; Salamatov 1999; Moerhle 2005). The system of tools, methods and knowledge-bases for solving engineering problems continues to develop today. Most TRIZ is in the public domain through online journals without formal processes of peer-review and the proceedings of annual conferences [1]. But some of the knowledge-bases, which categorize technological possibilities by the function they serve, are held by commercial consulting organizations [2]. Some of these organizations offer TRIZ software, but on the whole the methods are exercises in thought, demanding no more than pencil and paper. There are various interpretations of TRIZ, both of its findings and applications. But at the core lies a unique outlook on how invention occurs, how technology evolves, and how insights from these areas can be used to improve the process of engineering innovation systematically.

Altshuller believed that the process of invention was dialectic. The word 'dialectic' is connected with the Greek word 'dialegein', meaning to discourse, which refers to the conversational method of argument. The German philosopher Hegel (1770-1831)

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[1] See, for example, the TRIZ journal (www.triz-journal.com), the European TRIZ Association (http://etria.net/portal/), and the Altshuller foundation (http://www.altshuller.ru/).

[2] See, for example, Ideation (http://www.ideationtriz.com/), Creax (www.creax.com) and Systematic Innovation (http://www.systematic-innovation.com).

argued that the process of thought follows a logical pattern, and he called this pattern dialectic. Broadly, Hegel argued that thought proceeds by contradiction and reconciliation of contradiction, the overall pattern being one of thesis, antithesis and synthesis (Speake 1983, p. 94). Marx and Engels borrowed Hegel's view that change has to be explained in terms of contradiction. This outlook on the world ultimately developed into the dialectical materialism of classical Marxist theory, which Altshuller would obviously have been heavily exposed to.

It is thus no surprise that Altshuller should explain the development of technology in terms of contradiction. For him, the driving force at the heart of technological change was the dialectical structure of engineering problems. They occur when two features of a technological system come in conflict with one another – thesis versus antithesis – and 'invention' is the removal of these contradictions. The improvement of a system's strength, say, is often associated with the cost of an increase in weight. Significantly, for Altshuller, there were a finite set of these conflicts, contradictions, or trade-offs that were general to all technological systems, no matter the particular engineering discipline, technology, system or device. He and his colleagues defined 39 features, or parameters, which are commonly pitted against one another in various technological fields. As well as 'strength' and 'weight', this set includes other dimensional and physical attributes, such as volume, speed, quantity, device complexity and composition (see table 1). It also includes features that refer to energy throughput and information, such as temperature, power, energy loss, information loss and ease of operation. This makes a total of 39 x 39 possible engineering problems, or 'technical contradictions'.

Strikingly, Althshuller claimed there were only 40 strategies worth knowing for removing these technical contradictions. He emphasized that a trade-off was resolved not by optimizing between two conflicting features, but by changing or adapting the system in some way so that both features could improve. For instance, a device may be made stronger *and* lighter by applying the principle 'composite materials'. Altshuller and his colleagues examined in the order of 3 million significant patents in order to amass and refine other such principles. Other than 'composite materials', the list of 40 inventive principles includes porous materials, thermal expansion, periodic action, asymmetry, flexible shells, mechanical substitution, phase transition, homogeneity, segmentation, extraction, and feedback (see table 2). The parameters and inventive principles were brought together in the most renowned tool in the TRIZ repertoire,

Altshuller's 39 Parameters

*[**Moving objects** are objects that can easily change position in space, either on their own, or as a result of external forces. **Stationary objects** are objects which do not change their position in space, either on their own or as a result of external forces.]*

1. Weight of moving object
The mass of the object in a gravitational field. The force that the body exerts on its support or suspension or on the surface that it rests

2. Weight of stationary object

3. Length of moving object
Any linear dimension, not necessarily the longest

4. Length of stationary object

5. Area of moving object
Or part of a surface occupied by an object

6. Area of stationary object

7. Volume of moving object

8. Volume stationary object

9. Speed
Velocity of an object; rate of a process or action

10. Force or intensity
Includes any interaction that is intended to change an object's condition

11. Stress or pressure
Includes tension

12. Shape
The external contours or appearance of a system

13. Stability of object's composition
The wholeness or integrity of the system; the relationship of the system's constituent elements. Wear, chemical decomposition, and disassembly are all decreases in stability. Increasing entropy is decreasing stability

14. Strength
Resistance to change in response to force; resistance to failure or fracture

15. Duration of action by stationary object
The time for which the object can perform the action; service life; durability

16. Duration of action by moving object

17. Temperature
The thermal condition of the object or system. Loosely includes other thermal parameters, such as heat capacity, that affect the rate or change of temperature

18. Illumination intensity
Light flux per unit area, brightness, light quality, etc.

19. Use of energy by moving object
The measure of the object's capacity for doing work; energy required to do a job - includes use of energy provided by the super-system (e.g. heat or electrical)

20. Use of energy by stationary object

21. Power
The rate of energy use or work

22. Loss of energy
Energy that does not contribute to the job being done (see 19 - reducing the loss of energy sometimes requires different techniques from improving the use of energy, which is why this is a separate category)

23. Loss of substance
Partial of complete, permanent or temporary loss of some of a system's materials, substances, parts or subsystems

24. Loss of information
Partial of complete, permanent or temporary, loss of data or access to data in or by a system. Includes sensory data such as aroma, texture etc.

25. Loss of time
Improving the loss of time means reducing the time taken for the activity

26. Quantity of substance
The number or amount of a system's materials, substances, parts or subsystems which might be changed fully or partially, permanently or temporarily

27. Reliability
A system's ability to perform its intended functions in predictable ways and conditions

28. Measurement accuracy
The closeness of the measured value to the actual value of a property of a system. Reducing the error in a measurement increases the accuracy of the measurement

29. Manufacturing precision
The extent to which the actual characteristics of the system or object match the specified or required characteristics

30. Object-affected harmful factors
When external harm affects the object. Susceptibility of a system to external harmful effects

31. Object-generated harmful factors
A harmful effect is one that reduces the efficiency or quality of the functioning of the object or system. These harmful effects are generated by the object or system as part of its operation

32. Ease of manufacture
The degree of facility, comfort or effortlessness in manufacturing or fabricating the object or system.

33. Ease of operation
Simplicity: A process is difficult if it needs many operations, many people, special tools, has low yield, or is difficult to do properly

34. Ease of repair
Quality characteristics, such as convenience, comfort, simplicity, and time to repair faults, failures, or defects in a system.

35. Adaptability or versatility
The extent to which a system or object responds positively to external changes. Also, a system that can be used in multiple ways for a variety of circumstances.

36. Device complexity
The number and diversity of elements and element interrelationships within a system. The user may be an element of the system that increases complexity. The difficulty of mastering the system is a measure of complexity

37. Difficulty of detecting or measuring
Measuring or monitoring systems that are complex, costly, require much time and labour to set up and use, or that have complex relationships between components, or components that interfere with each other, all demonstrate "difficulty of detecting or measuring". Increasing cost of measuring to a satisfactory error is also a sign of increased difficulty of measuring

38. Extent of automation
The extent to which a system or object performs its functions without human interface. The lowest level of automation is the use of a manually operated tool. For intermediate levels, humans program the tool, observe its operation, and interrupt or re-program as needed. For the highest level, the machine senses the operation needed, programs itself, and monitors its own operations

39. Productivity
The number of functions or operations performed by a system per unit time. The time for a unit function or operation. The output per unit time, or cost per unit output.

Table 1. *Altshuller's 39 engineering parameters. After Vincent et al (2006).*

Altshuller's 40 Inventive Principles

1. Segmentation; fragmentation
Divide an object into independent parts; make it sectional or able to be dismantled; increase the degree of fragmentation or segmentation

2. Extraction
Extract the disturbing part or property from an object; extract only the necessary part (or property) of an object.

3. Local quality
Change an object's structure, action, environment or external influence/impact from uniform to non-uniform; make each part of an object function in conditions most suitable for its operation; make each part of an object function fulfil a different and/ or complementary useful function.

4. Asymmetry
Change the shape or properties of an object from symmetrical to asymmetrical; change its shape to suit external asymmetries (e.g. ergonomic features); or if it is asymmetrical, increase its asymmetry

5. Merging; consolidation
Bring identical or similar objects, or operations in space, closer together (or merge them); make them contiguous or parallel

6. Universality
Make an object perform multiple functions; eliminate the need for other parts; eliminate idle or intermittent motion

7. Nested Doll
Place one object inside another; place multiple objects inside others; make one part pass (dynamically) through the cavity of the other.

8. Anti-weight
To compensate for the weight of an object, merge it with other objects that provide lift, or make it interact with the environment (use aerodynamic, hydrodynamic, buoyancy and other forces)

9. Preliminary anti-action; pre-stressing
When it is necessary to perform an action with both harmful and useful effects, this should be replaced with anti-actions to control harmful effects; pre-stress in opposition to known undesirable working stresses

10. Preliminary action
Perform the required change of an object in advance (totally or at least partially); arrange objects in such a way that they will come into action from the most convenient place and without losing time for their delivery

11. Beforehand cushioning
Prepare emergency means to compensate for low reliability of an object

12. Equipotence
If an object has to be raised or lowered, redesign the object's environment to eliminate the need, or have the action be performed by the environment

13. The other way around
Invert the action used to solve the problem (e.g. instead of refrigerating an object; heat it); make moveable parts (or external environment) fixed, and fixed parts moveable; invert the object (or processes).

14. Spheroidality; curvature
Move from straight parts of an object to the curved ones, from flat surfaces to spherical ones and from parts shaped as a cube (parallelepiped) to ball-shaped structures; use rollers, balls, spirals; go from linear to rotary motion (or vice versa); use centrifugal force.

15. Dynamics
Change the object (or outside environment) for optimal performance at every stage of operation, make them adaptable; divide an object into parts capable of movement relative to each other; change from immobile to mobile; increase the degree of free motion

16. Partial or excessive action; abundance
If you can't achieve 100 percent of a desired effect, then go for more or less

17. Transition to another dimension
Move into an additional dimension, from 1D to 2D, from 2D to 3D; go from single storey or layer to multilayered; incline an object, lay it on its side; use the other side of the object; use light falling onto the neighbouring square or onto the other side of the given square

18. Mechanical vibration
Cause an object to oscillate or vibrate; increase its frequency; use its resonant frequency; use piezoelectric vibrators instead of mechanical ones; combine ultrasonic and electromagnetic field oscillators.

19. Periodic action
Instead of continuous action, use periodic or pulsating actions; if an action is already periodic, change the magnitude or frequency of the period; use periods between actions to perform a different action

20. Continuity of useful action
Carry on work without a break; all parts of an object operate constantly at full capacity; eliminate idle and intermediate actions.

21. Rushing through
Conduct a process or stages of it (e.g. destructive, harmful, hazardous operations) at high speed

22. Blessing in disguise; harm into benefit
Use harmful factors (from environment as well) to achieve a positive effect; eliminate the primary harmful action by adding it to another harmful action to resolve the problem; amplify a harmful action to such a degree that it is no longer helpful

23. Feedback
Introduce feedback to improve the process of action; if feedback is already used, change its magnitude, sign (+ve or -ve) or influence in accordance with operating conditions.

24. Intermediary; mediator
Use an intermediary carrier article or intermediary process; merge one object temporarily with another

25. Self-service
An object must self-service, modify, control or repair itself; use waste resources (energy or substance)

26. Copying; substitution
Replace unavailable, complex, expensive, awkward or fragile object with simplified and inexpensive copies; replace an object, or process with optical copies or images. Employ in the course of this the change of the scale (increase of decrease copies); if visible optical copies are used, move to infrared or ultraviolet copies.

27. Cheap short-lived objects
Replace an expensive object with a multiple of inexpensive objects, comprising certain qualities, such as service life.

28. Mechanical substitution
Replace a mechanical system with a sensory one; replace mechanical with optical, acoustic or olfactory; employ electrical, magnetic and electromagnetic fields for interaction with the object; move from static to moving, from stable in time to changing, from non-structured to structured fields; employ fields in combination with ferromagnetic particles

29. Pneumatics and hydraulics
Use gas and/or liquid parts of an object instead of solid parts (e.g. inflatable filled with liquid, air cushion, hydraulic, hydro-reactive.)

30. Flexible shells and thin films
Use flexible shells and thin films instead of 3D structures; isolate the object from its environment using flexible membranes.

31. Porous materials
Make an object porous or add porous elements (inlays, covers, etc); if an object is already porous, use the pores to introduce a useful substance or function (impregnate the pores with some other substance)

32. Colour change
Change the colour or transparency of an object or its external environment; to improve visibility of things that are difficult to see, add colour or luminescent elements; change the emissive properties of an object subject to radiant heat

33. Homogeneity
Objects interacting with the main object should be of the same material (or material with identical properties)

34. Discarding and recovering
After completing their function (or becoming useless,) reject objects, discard them (by dissolving, evaporating, etc) or modify during the process; restore consumable / consumed parts of an object during operation

35. Parameter change
Change: the physical state (e.g. to gas, liquid or solid), concentration, density, degree of flexibility, temperature, volume, pressure or any other parameter

36. Phase transition
Use phenomena of phase transition (e.g. volume change, the liberation or absorption of heat, Curie point, etc.)

37. Thermal expansion
Use thermal expansion or contraction of material; use multiple materials with different coefficients of thermal expansion

38. Strong oxidants; accelerated oxidation
Replace air with oxygen-enriched air or pure oxygen; expose air or oxygen to ionising radiation; use ionised oxygen; replace ozonised (or ionised) oxygen with ozone; replace ozone with monatomic oxygen

39. Inert medium; vacuum
Replace a normal environment with an inert one; add neutral parts, or inert additives to an object; carry out the process in a vacuum

40. Composite materials
Change from uniform/homogenous to composite (multiple) materials

***Table 2.** Altshuller's 40 Inventive Principles. After Vincent et al. (2006).*

the *contradiction matrix* (see Domb 1997), a look-up table made up of the 39 x 39 possible problems. Most of the boxes are populated with a handful of inventive principles that have been successful in resolving that problem.

Another unique tool is a series of *Evolutionary Trends,* used to suggest where the design of a technological system might better be directed. There are different versions of this series available, often depicted as morphological sets (see figure 1). Some commentators go as far as describing them as objective laws, and some commercial organizations continue to 'discover' new ones with varying degrees of triviality. But the core set is engaging, particularly when compared to the evolution of biological systems (Pahl and Vincent 2002; Vincent and Mann 2002). Supposedly, technical systems tend to evolve towards increased functional complexity and versatility, often with associated structural simplicity. In both technology and biology, control systems tend towards decentralized feedback, and skeletal systems – with gravity as a limiting factor – tend towards compliance and flexibility.

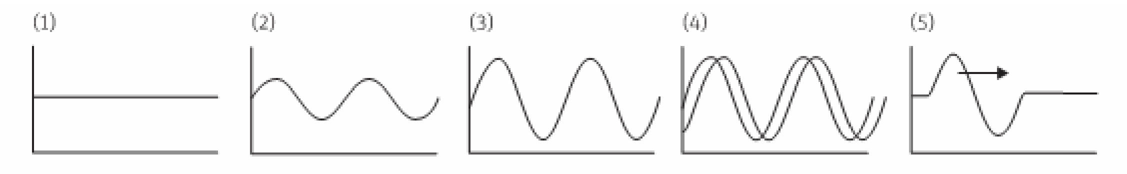


Figure 1a. *A TRIZ evolutionary series on the coordination of rhythm, after Vincent and Mann (2002). The effectiveness of the action increases from left to right. (1) Continuous action; (2) pulsating or periodic action; (3) resonating action (larger output for the same input); (4) several actions at once; (5) traveling wave.*

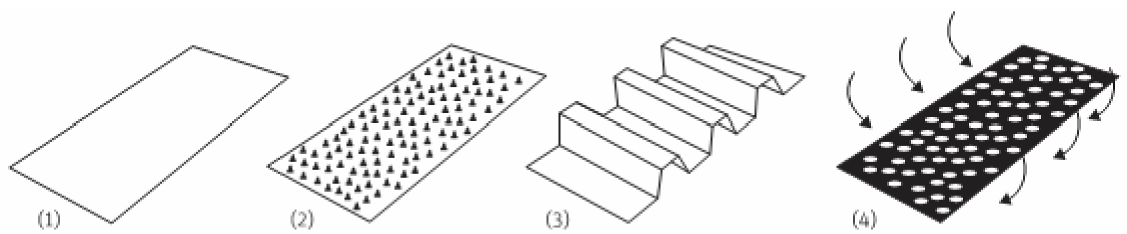


Figure 1b. *A TRIZ evolutionary series on surface segmentation, after Vincent and Mann (2002). (1) Flat surface; (2) surface with protrusions; (3) rough surface; (4) surface with active pores.*

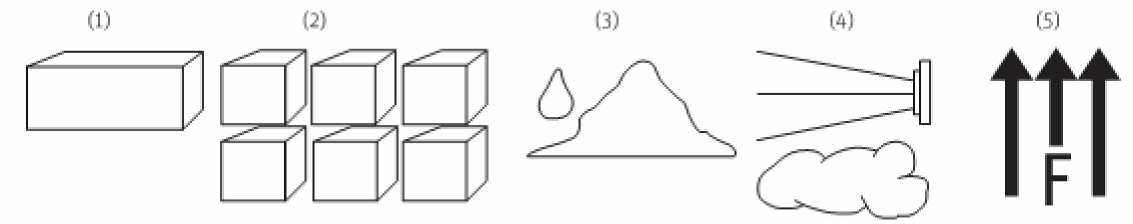


Figure 1c. *A TRIZ evolutionary series on segmentation of substances or objects, after Vincent and Mann (2002). (1) Monolith; (2) monolith has been segmented coarsely; (3) fine segmentation to liquid or powder with increase in surface area; (4) gas or plasma; (5) force field.*

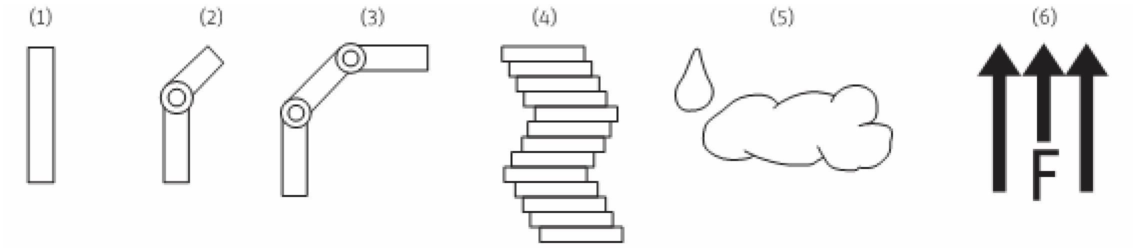


Figure 1d. *A TRIZ evolutionary series on dynamization, after Vincent and Mann (2002). (1) Immobile system; (2) a joint in the system; (3) several joints in the system; (4) proliferation of joints leads to a soft elastic system; (5) further proliferation of joints leads to a liquid or gas; (6) a force field.*

Another TRIZ tool is the 'system operator', a nine-box framework used to analyze a problem as part of its environment so that any opportunities for solving it simply in some place or time other than where it occurs are not missed. This tool is part of a range of methods meant to help sharpen problem definition. There is also a combination of functional analysis and the inventive principles called *Substance-Field* (or Su-Field or S-Field) analysis. There have been several revisions of a TRIZ 'algorithm' called ARIZ which brings all the tools and techniques together in a procedural format (Salamatov 1999).

The inventive principles and other outcomes of the TRIZ project resemble elements of the individual strategies used by expert designers in various disciplines. In particular, studies have highlighted that expert designers are good at grouping together problems that are amenable to solution by the same principle (Cross 2004). Furthermore, they often describe these principles as being part of a set of 'nuggets' of design know-how, or problem-solving 'gambits', which are amassed, condensed and categorised over their careers (Lawson 2004). Lawson notes this is similar to the finding that chess masters rarely analyse a board situation, rather they *recognise* it, and the schema for the situation also includes one or more known gambits for solving it. It was Schön (1988) who highlighted the ability of experts to impose a coherent structure to sticky design-situations, one that guides successfully subsequent moves. He gave the name 'problem-framing' to the process of formulating a design problem; the aim is to do it in a way that stimulates and pre-structures the emergence of good design solutions (Cross 2004). Dialectical 'contradiction-thinking' can be seen as an explicit method for problem-framing, just as the inventive principles can be understood as a sophisticated set of 'gambits'.

Lawson (2004) has asserted that expert designers rely on experiential knowledge more than they do theoretical knowledge (in the field of cognitive science, experiential knowledge is referred to as 'episodic' knowledge, and theoretical knowledge is referred to as 'semantic' knowledge). He argues that the conceptual frameworks through which experts recognise and make sense of design situations are necessarily episodic. This is simply because the theoretical structures that are capable of storing knowledge that lead us from each problem to the right solution do not exist. The design research community in the West is currently grappling with the issue of whether forms of design know-how are too situated in their specialist domains to be applicable across disciplines (Friedman 2003; Cross 2003, 2007). TRIZ, which may facilitate the transfer of engineering know-how across a wide range of technological, engineering and design disciplines, deserves more attention from scholars in this field.

2.2 BioTRIZ and the transfer of biological know-how

A critical history of the many analogies that have been made between biology and architecture is documented by Steadman (1979). Examples of direct functional transfer are few and restricted to the realm of structural design. D'Arcy Wentworth Thompson (1860-1948) was the first to look carefully at how animals and plants work as load-carrying structures, anticipating the modern science of biomechanics, and his book *On Growth and Form* (Thompson 1992) is still influential in architectural circles today, although it is rare to see it used as more than just a library of images to inspire sculptural design. It is well known that Antoni Gaudí (1852-1926) built models to study how natural structures were conditioned along the purest lines of compression and bending, and that Frei Otto (1925-) took direct inspiration from spider webs to produce efficient lightweight tensile structures (Addis 2007, p.556). But efficient structural design cannot directly reduce the power density of buildings (see chapter 1). Biology is rife with ingenious thermal strategies that have yet to be seriously considered by architects and engineers (Vogel 2005a, 2005b; Heinrich 1999, Schmidt-Neilson 1997). The translation of such strategies to the built environment is in part the object of this research. But the process is far from trivial.

Mimicking the way nature does engineering remains an empirical affair. Before an interesting natural phenomenon or mechanism can be transferred to the realm of technology, the general principles behind its functioning must be understood so that a useful analogy can be defined. This approach has brought some notable success stories (Vincent *et al.* 2006), but the results are usually unpredictable and limited to 'technology-push' scenarios. The notion of self-cleaning buildings did not come about until the self-cleaning properties of the lotus leaf were understood well enough to produce 'Lotusan', which, as a paint, bears no ostensible resemblance to a lotus leaf whatsoever.

There is certainly much to learn from nature. Fratzl (2007) explains how biological (natural) materials consist of relatively few constituent elements used to synthesize a variety of polymers and minerals. He contrasts this with artificial (man-made) materials, which are based on a much larger range of constituent elements that have enabled the invention of many materials with special properties not used by nature. These materials include copper, bronze and iron in pre-industrial times, to steel and concrete during the industrial revolution, and silicon in the information age. All these materials require high temperatures for fabrication. Biological organisms do not have access to such high temperatures. But nature has nevertheless developed a range of materials with remarkable properties. The key is the complex, hierarchical structuring of natural materials, an approximate outcome of a process of self-assembly guided by instructions stored in the genes and constrained by a range of external factors, such as temperature, mechanical loading and the supply of water, light and nutrition. Fratzl (2007) gives the example of the branch of a tree, which will grow differently in the direction of the wind than it will in the opposite direction, without any change in genetic code.

This subtle 'bottom-up' growth is in stark contrast to blunt 'top-down' fabrication in engineering. Engineers will design a part then select a suitable material that will perform for as long as the part is in service. But because natural materials grow they can adapt to the changing conditions that engineers must pre-empt. They grow into hierarchical materials, in which the microstructure at each position of the part is adapted to the local needs (Jeronimidis 2000). Hierarchical structuring allows the construction of complex organs based on much smaller and often very similar building blocks. Examples include bone, trees, seashells, spider-silk, optical microstructures, super-hydrophobic (self-cleaning) surfaces and the attachment systems of geckos (Fratzl 2007). Nature has evolved flexible and robust materials which can make engineering materials seem over-designed and over-specialised in comparison.

Despite the many biomimetic success-stories, and the important lessons to be learnt, the discipline of biomimetics has so far developed without a theoretical underpinning. This has not gone unnoticed. The central issue is how to translate the functions, mechanisms and principles from the science of biology so that they can be used in the various technological, engineering and design disciplines. TRIZ, with its system for defining technical problems and its set of problem-solving 'gambits', was noted as a promising place with which to start (Vincent and Mann 2002).

The first step toward incorporating biological knowledge into TRIZ was a framework used for a statistical analysis of the TRIZ contradiction matrix. Bogatyreva *et al* (2004) wanted to examine whether the distribution of the inventive principles within the table was random or whether it followed certain patterns. In order to carry out their analysis, they arranged the 40 inventive principles and 39 parameters into six meta-categories, or 'fields of operation' (see table 3). These were 'substance', 'structure', 'energy', 'information', 'space' and 'time'. The assumption was that a system is made of matter or materials (substance) arranged in a particular order (structure). Whatever its purpose, the actions it carries out require energy, and this energy needs to be regulated (information). And a system resides in some environment, which can be described as a three-dimensional space in which events occur on different time scales. In other words, *things do things somewhere.*

Using the logical framework, the study did uncover some patterns, implying that certain technological problems have tended to be solved with certain sets of principles[3]. But it was the framework and not the results of the study that was to have most influence. Vincent *et al.* (2006) made a 6x6 matrix populated with the results of the analysis of 3000 biological conflicts and their solutions. They named this matrix

Table 3. *Classification of TRIZ inventive principles and parameters (Vin. et al. '06)*

Things

Substance
(Add, remove, change properties of a material)

Parameters
Weight of moving & stationary object (1, 2)
Loss of substance (23)
Quantity of substance (26)

Inventive Principles
Copying (26)
Colour change (32)
Homogeneity (33)
Parameter change (35)
Phase transition (36)

Structure
(Add, remove, regroup structural parts)

Parameters
Stability of an object's composition (13)
Manufacturing precision (29)
Ease of manufacture (32)
Device complexity (36)

Inventive Principles
Segmentation (1)
Extraction (2)
Local quality (3)
Merging (5)
Universality (6)
Nested doll (7)
Partial or excessive action (16)
Intermediary (24)
Discarding and recovering (34)
Composite materials (40)

Do Things

Energy
(Change energy source or field)

Parameters
Total force (10)
Stress or pressure (11)
Strength (14)
Temperature (17)
Illumination intensity (18)
Use of energy by moving & stationary object (19, 20)
Power (21)
Loss of energy (22)

Inventive Principles
Anti-weight (8)
Preliminary anti-action (9)
Equipotence (12)
Mechanical vibration (18)
Mechanical substitution (28)
Pneumatics & hydraulics (29)
Thermal expansion (37)
Strong oxidants (38)
Inert atmosphere (39)

Information
(Change interactions or regulation of a system or its elements)

Parameters
Loss of information (24)
Reliability (27)
Measurement accuracy (28)
Object-affected & object-generated harmful factors (30, 31)
Ease of operation & repair (33, 34)
Adaptability or versatility (35)
Difficulty of detecting & measuring (37)
Extent of automation (38)

Inventive Principles
The other way around (13)
Blessing in disguise (22)
Feedback (23)
Self-service (25)

Somewhere

Space
(Change position or shape of system or parts)

Parameters
Length of moving & stationary object (3, 4)
Area of moving & stationary object (5, 6)
Volume of moving & stationary object (7, 8)
Shape (12)

Inventive Principles
Assymetry (4)
Spheroidality (14)
Flexible shells & thin films (30)
Porous materials (31)
Another dimension (17)

Time
(Change speed of process or order of actions)

Parameters
Speed (9)
Duration of action of moving & stationary object (15, 16)
Loss of time (25)
Productivity (39)

Inventive Principles
Preliminary action (10)
Beforehand cushioning (11)
Dynamics (15)
Periodic action (19)
Continuity of useful action (20)
Rushing through (21)
Cheap short-lived objects (27)

Table 4a. *Condensed TRIZ matrix (Vin. et al '06)*

fields	substance	structure	space	time	energy	information
substance	6 10 26 27 31 40	27	14 15 29 40	3 27 38	10 12 18 19 31	3 15 22 27 29
structure	15	18 26	1 13	27 28	19 36	1 23 24
space	8 14 15 29 39 40	1 30	4 5 7–9 14 17	4 14	6 8 15 36 37	1 15–17 30
time	3 38	4 28	5 14 30 34	10 20 38	19 35 36 38	22 24 28 34
energy	8 9 18 19 31 36–38	32	12 15 19 30 36–38	6 19 35–37	14 19 21 25 36–38	2 19 22
information	3 11 22 25 28 35	30	1 4 16 17 39	9 22 25 28 34	2 6 19 22 32	2 11 12 21–23 27 33 34

Table 4b. *BioTRIZ matrix (Vin. et al '06)*

fields	substance	structure	space	time	energy	information
substance	13 15 17 20 31 40	1–3 15 24 26	1 5 13 15 31	15 19 27 29 30	3 6 9 25 31 35	3 25 26
structure	1 10 15 19	1 15 19 24 34	10	1 2 4	1 2 4	1 3 4 15 19 24 25 35
space	3 14 15 25	2–5 10 15 19	4 5 36 14 17	1 19 29	1 3 4 15 19	3 15 21 24
time	1 3 15 20 25 38	1–4 6 15 17 19	1–4 7 38	2 3 11 20 26	3 9 15 20 22 25	1–3 10 19 23
energy	1 3 13 14 17 25 31	1 3 5 6 25 35 36 40	1 3 4 15 25	3 10 23 25 35	3 5 9 22 25 32 37	1 3 4 15 16 25
information	1 6 22	1 3 6 18 22 24 32 34 40	3 20 22 25 33	2 3 9 17 22	1 3 6 22 32	3 10 16 23 25

BioTRIZ, and compared it to a newly distilled 6x6 version of the original TRIZ matrix (see table 4). The two matrices were only 12% similar. With only the inventive principles used to resolve spatial conflicts showing any similarity (73%), the implication was that biology and technology use very different strategies to solve the same problems.

The two graphs in figure 2 capture their results. Most technology, and most building technology, occurs on size levels of up to 1m. At this scale and below, the most important problem solving variables for technology are energy and material (figure 2a). For biology, they are information, structure and space (figure 2b). It is important to remember that these data represent the number of times a certain type of inventive principle has been applied, and not, for instance, the quantity of energy or information that has been used. Indeed, solving a problem by manipulating energy can, in this context, mean reducing energy throughput. If a particular problem is solved by replacing an existing mechanical system with a pneumatic system (inventive principle 29, *pneumatics and hydraulics,* see table 2*)*, the new improved version might become more energy efficient. But inventive principle 29 registers as a manipulation of energy. The meaning of the inventive principles must be studied carefully to understand the results depicted by the graphs shown in figure 2.

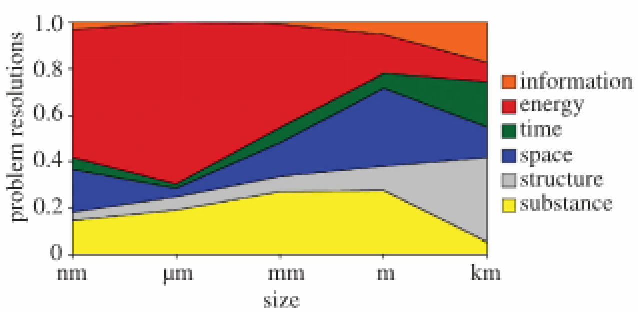


Figure 2a. *The types of problem-solving strategies that human technology employs on different length scales (Vincent* et al. *2002). Technology tends to function by manipulating energy and substance.*

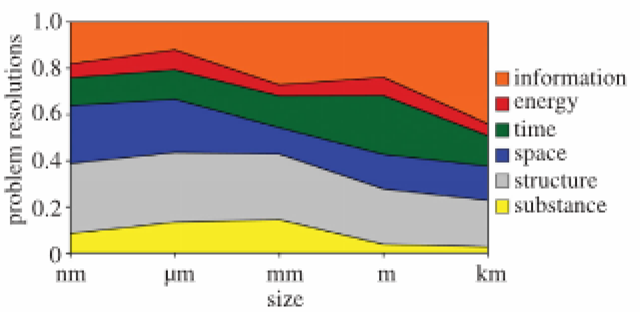


Figure 2b. *Types of effects observed in biology at different length scales (Vincent* et al. *2002). Natural systems tend to function on account of how they are structured and the way information is managed.*

The point is that biological systems tend to use entirely different strategies than those that tend to be employed in technology. Biology achieves functional variety by manipulating the shape, structure and combinations of materials. Engineering appears to take a blunter, more global approach. When faced with a problem, we tend to change the amount or type of material, or change the energy requirement. One biomimetics lesson that the study of Vincent *et al.* (2006) emphasises is that instead of developing new materials each time we need a new function, we should be adapting and combining the materials we already have. Ashby documents how to design hybrids of two or more materials, taking functional advantage of space and shape on different levels of length scale (Ashby 2005, chap. 13; Lakes 1993). Lattices, sandwich structures, foams, particulate and fibrous composites can perform multiple functions, including mechanical, thermal, optical and electrical (Wadley 2006). Perhaps the conflicting thermal energy flows through building envelopes could be better structured and managed using such an approach. This would take emphasis away from the blunter approach of improving the performance of heating and cooling systems, and might help reduce the power density of buildings. In particular, there may be some lessons to learn from biology about how to make better use of local thermal resources so that buildings are less reliant on active heating and cooling in the first place. The BioTRIZ matrix (table 4a) may help guide this process in the conceptual design stage.

Conclusion

Comparisons between biology and engineering suggest that we rely unnecessarily on manipulating energy and matter to solve engineering problems. Partly this has to do with the fundamentally different way in which man-made technology and biological organisms come into being. For instance, man-made materials are fabricated using very high temperatures which biology does not have access to, and based on a very large range of constituent elements which biology evidently has no need for. Natural materials are complex, hierarchical structures, an outcome of a self-assembling process guided by instructions stored in the genes and constrained by a range of environmental constraints in constant flux. In contrast, engineers are forced to embed a response to each likely future outcome within a one-off static blueprint. No wonder engineering solutions can appear blunt in comparison.

TRIZ, a Russian engineering methodology, may facilitate the transfer of problem-solving strategies ('gambits') across engineering disciplines. BioTRIZ is a thinking tool based on TRIZ through which engineering problems can be examined and biomimetic responses conceived. A problem is formulated in terms of two contradictory features selected from a list of 39, such as ‘strength’ vs. ‘weight’. Each of these features belongs to one of six meta-categories which together form the basis of the 6x6 BioTRIZ look-up table. In each of the 36 boxes are a set of numbers, each of which refers to one of 40 principles for solving engineering problems. A group of biologists observed and categorised 3000 problem-solving instances from biology to populate the table. The features and principles are not their own – they belong to TRIZ. BioTRIZ is meant to tell the user which strategies have been employed by biological systems when; the source is lost in the process. The tool may help better frame and solve the complex problems at the root of energy consumption in buildings.

Chapter 3

THE EVOLUTION OF BUILDING ENVELOPE TECHNOLOGY

"Technology...the knack of so arranging the world that we don't have to experience it." Max Frisch, 1957, *Homer Faber*. Aberlard-Schuman, London, p. 165

Abstract

High power density commercial buildings are responsible for a growing proportion of world energy consumption. Commercial buildings are fundamental to today's global economy because they house the people and technologies that carry out the retrieval, handling, storing and generation of information and know-how. Air-conditioning and fluorescent lighting enabled the design of deep plan commercial buildings which were attractive to developers because all space was equally lettable and could be subdivided easily. Some differences in office design around the world emerged because of national differences in urban context, market conditions and labour laws, which in some countries allowed the effective expression of common complaints about noise levels, thermal comfort issues and lack of access to natural lighting and the outside. Nevertheless, an 'international vernacular' that ignores local climatic context has emerged. This type of design exacerbates a range of thermal conflicts, necessitating increases in energy demand.

Commercial building designers and developers draw little from the wide and varied technological repertoire available for climate adaptation that has been developed over thousands of years in different places around the world. For instance, the Persians demonstrated hundreds of years ago that ice for cooling buildings could be manufactured through a passive radiative interaction with the sky. But this abundant natural heat sink is today ignored despite the fact that some of the hottest climates have the coldest skies. Radiative cooling technology, like other strands of development on the periphery, hint at the possibility of more selective and responsive buildings that, in principle, make better use of locally available thermal resources. These include double

skin facades, dynamic insulation, phase-change materials and chromogenic glazing, which have been implemented in some owner-occupied buildings by corporations wanting to advertise their green credentials. Development of such technologies and their successful integration into buildings is a complex challenge, partly because the thermal resources that they utilise can at times be unavailable or counterproductive.

Introduction

The intention of this chapter is to harvest environmental technology opportunities ripe for BioTRIZ analysis. The first section of this chapter surveys some thermal strategies of note from different vernacular architectures. The strategies are related to climate, defining a range of naturally occurring heat sources and heat sinks. The second section traces the development of heating, ventilation and cooling technologies developed during the Industrial Revolution. The third section tracks some social and technological changes in office design during the twentieth century, demonstrating how the commercial 'international vernacular' ossified. The final section reviews some promising but peripheral technological developments. Biological analogies are included throughout this chapter where pertinent. Among several opportunities harvested in this review, radiative cooling technology, which uses the sky as a natural heat sink, seems particularly suitable for BioTRIZ analysis.

3.1 Climate adaptation

The Earth's inhabited regions have extremes of about 50˚C in subtropical deserts and -60˚C in Arctic winters. In stark contrast, the range of body core temperatures that humans must sustain is very narrow. The standard physiological core temperature is 37˚C; above 42˚C is fatal; below 33˚C life-threatening hypothermia ensues (Schmidt-Nielson 1997). The options open to humans for adapting to temperatures below the zone of comfort (which for resting unclothed people is 24-29˚C) are thus limited. Studies of basal metabolic rate and vasoconstriction show native populations to be more physiologically adapted to local climate than relative new-comers (Smil 2007 p.132). But the most successful response is undeniably to create a microclimate, either through clothing or shelter.

3.1.1 Creating a micro-climate

Smil contends that the intelligence to mimic hunted animals was key to adaptation in extreme climates (Smil 2007 p.131). The furry adaptations of Arctic animals are reflected in the multi-layered clothing developed by the Inuit. The ingenious heat retentive design of the *iglu* is well documented (Oliver 1997 Vol.1.VI4B), and some commentators describe it as a sophisticated evolution of an artic animal den. Whatever the source of inspiration, the success of the Inuit's adaptations is reflected in their poor naked body insulation – they have the highest rate of thermal conductance of any population studied (Smil 2007 p. 133).

One desert adaptation employed by humans and animals alike is the use of black surfaces and air gaps to generate convective cooling. At first glance, the black colour of Bedouin robes and tent membranes seems counter-intuitive, as it absorbs the majority of incoming radiation. But this heat is subsequently lost by convective heat transfer, exaggerated by the increased temperature differences, before impinging on the body. The dark plumage of large-winged birds and the black exoskeletons of long-legged beetles have been cited as biological precursors. But such analogies are contentious because the goat-hair used to weave Bedouin textiles is black in the first place (Olivier 2007, Vol 2.IV.1.d).

The pressure to limit fuel consumption has left a clearer imprint on some vernacular architecture. The basic temperate-climate repertoire of solar harnessing principles was developed in ancient Greece when insatiable demand for wood left much of Greece stripped of trees by the fifth century BC (Addis 207 p. 21). Local governments were forced to legislate in the face of growing demand from builders, ship builders, charcoal producers (charcoal was used to smelt mineral ores) and citizens who needed wood for cooking and heating. Guided by the writings of several concerned philosophers and scientists, including Socrates, Plato and Aeschylus, building designers and town planners responded with several creative initiatives.

On buildings, these included shading devices that allowed the low, winter sun to penetrate deep into the building while providing shade from the higher summer sun. Internal layouts were arranged so that the penetrating winter-sun charged heavy internal walls with heat. In the summer, these heavy walls buffered diurnal swings in temperature, keeping the inside cool during the hottest part of the day, with the help of small, shuttered, north-facing windows that brought some ventilation without direct sunlight. Olynthus in northern Greece, where new housing for 2,500 people was ordered in the 5th Century BC, became an exemplar in solar conscious design (Addis 2007 p. 21). Streets ran east to west to ensure south facing houses, and the apartments were of two types according to whether they were on the north or south side of a street. Each was designed with rooms facing south onto a courtyard to ensure maximum benefit from the winter sun.

The Roman architect and engineer Vitruvius extended these solar harnessing principles throughout the Roman Empire in the first century BC, tailoring advice on room layout, house style, and design detail to suit various locations, depending on temperature, rainfall, humidity, prevailing winds, and latitude. Again, the intention was to try to curb fuel consumption. By that time it was common for larger houses and public baths to have central heating where winters were harsh. To bring heat upstairs in some two-storey buildings, hypocaust ducts would open on the roof to create the necessary pressure difference. A large hypocaust might need 120 kilograms of wood per hour (Addis 2007 p.31). From the first century AD, Roman builders began putting glass or thin sheets of mica or silicate in the windows of the more expensive houses. Pliny the Younger (c. 61-113) refers to one of his favourite rooms as a *heliocaminus* – a sun oven (Addis 2007 p. 43). An early form of double glazing was found in Herculaneum, which was buried along with Pompeii when Mount Vesuvius erupted in 79 AD (Addis 2007 p.59).

Perhaps the most sophisticated examples of climate harnessing have sprung from the hot-arid Iranian plateau, where the evolution of Persian building types draws upon influences from the Caspian Sea to the Gulf and from the Hindu Kush to the Mediterranean (Olivier 1997 Vol. 2.IV.8). Architectural examples from as early as 900 AD can be studied as whole-building cooling machines, with geometry, high thermal capacity materials, wind-towers (*Badgir)*, passageways, vegetation and underground streams working in concert to produce convective and evaporative cooling (Bahadori 1976).

This architecturally rich plateau is also home to the world's most spectacular ice-houses (Oliver 1997 Vol. 1.VI.e). Their mud-brick, egg-shaped domes – now abandoned for health reasons – can rise up to 14m above pits which are as much as 12m deep. Their size was necessitated by the success of an ice-producing capability unique to the area. On cloudless winter nights, long, thin, shallow troughs were filled with water, which rapidly cooled by freely radiating up to the thin, dry, cold atmosphere above (Bahadori

1976; Martin 1989). Such was the rate of heat rejection that ice would form despite ambient temperatures above freezing. Adobe walls stopped the warmer wind from melting the recently formed ice. As dawn broke, these walls shaded the ice so there was ample time to cut it up and move it to the seasonal stores in preparation for summer.

3.1.2 Natural heat sinks for cooling

Central to all these climate adaptation strategies is the exploitation of naturally occurring heat sources and heat sinks. In cooler climates, vernacular architectures show strategies for harnessing solar energy and maintaining warmer temperatures. In hotter climates, they show strategies for protecting against external heat gains, maintaining cooler temperatures, and rejecting heat into locally available heat sinks. Figure 3 compares a temperate climate with a hot-arid climate: London, England with Riyadh, Saudi Arabia. Hourly ambient, wet-bulb and sky temperature data was taken from weather files on the dynamic thermal modelling software TRNSYS (2008), and analysed to gauge the size and availability of three naturally occurring heat sinks:

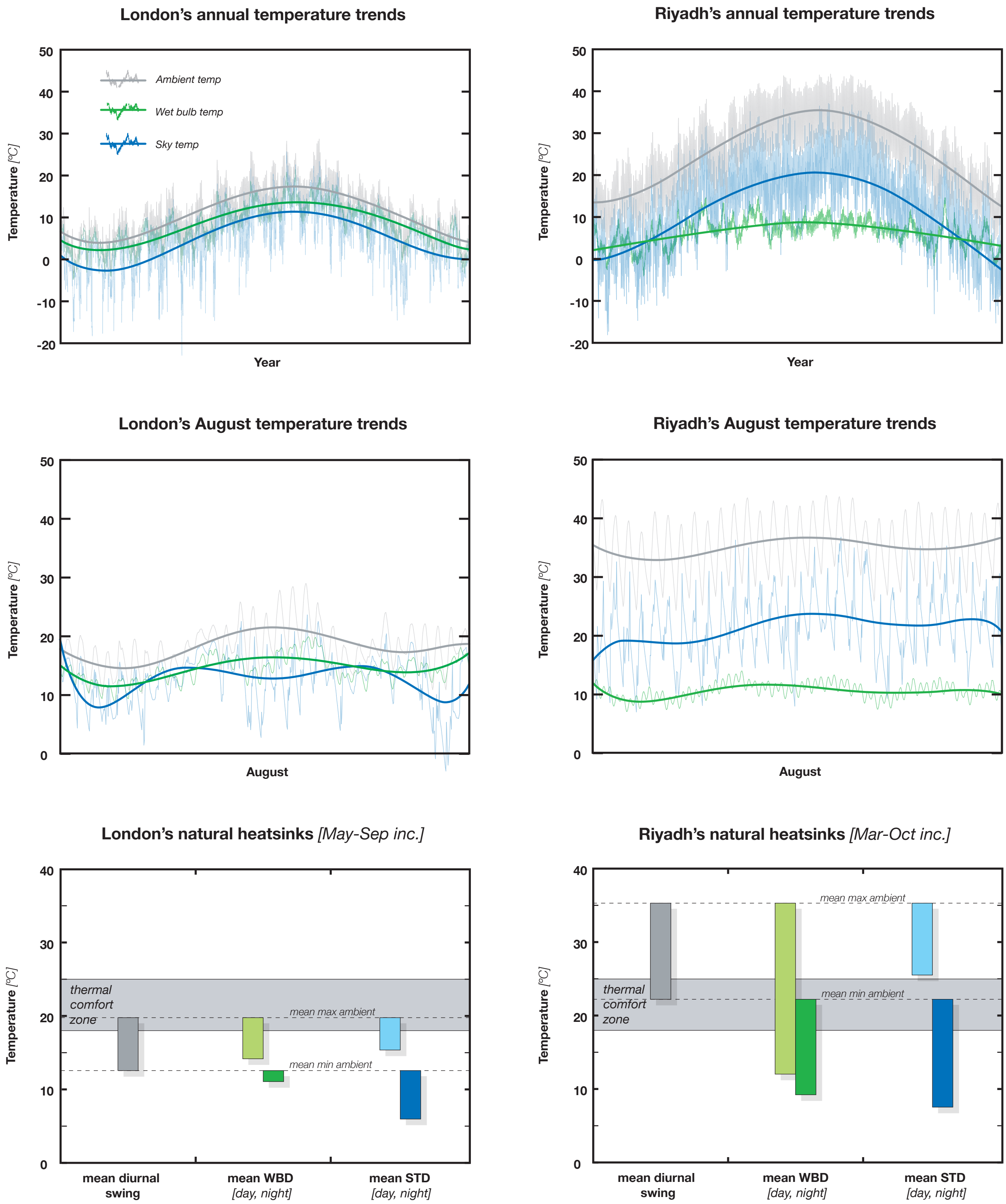
a) Diurnal swing. The ambient temperature difference between day and night indicates the scope for convective cooling at night. Exploitation of high thermal capacity materials – thermal massing – is synonymous with this form of heat rejection. (Thermal coupling to the ground can also help maintain cool temperatures, but average annual air temperatures are a better indication of the ground temperature)

b) Wet Bulb Depression (WBD). The difference between ambient and wet bulb temperature indicates the scope for evaporative cooling. The wet bulb temperature is the temperature the air can be reduced to if fully saturated.

c) Sky Temperature Depression (STD). The difference between ambient and sky temperature indicates the scope for radiative cooling. Dry and clear skies are the coldest as they emit less infrared radiation back down to earth. Sky temperature is a meteorological construct, computed as a function of ambient temperature, air humidity, cloud-cover and local air pressure (Martin & Berdhal 1984).

The bottom two graphs in figure 3 show the average size of these heat sinks during the respective cooling periods for London and Riyadh. Note that the bars are positioned

Figure 3. *Climate analysis: London, England vs. Riyadh, Saudi Arabia (see text). Hourly weather data for ambient (grey), wet bulb (green) and sky temperature are plotted over a year (top two graphs). Zooming in during August indicates that sky temperature can be the least predicatable of the three (middle two graphs). Mean temperature differences during summer indicate scope for different cooling strategies (bottom two).*



There is good scope for thermal mass and night ventilation (grey column), daytime evaporative cooling (light green) and night radiative cooling (dark blue)

Thermal mass and night ventilation (grey column) can be supplemented by evaporative (green) and radiative (blue) cooling both day and night.

relative to the 'thermal comfort zone' – here set between 18C and 25C. In principle buildings in London shouldn't need mechanical cooling at all – the mean maximum ambient temperature between May and September is well within the thermal comfort zone. But the urban heat island effect and high occupant and equipment densities make things more challenging. The graphs shows that nocturnal convective cooling and thermal mass well employed could do much of the cooling work. The graph also shows there is scope for daytime evaporative cooling and for nocturnal radiative cooling. The differences between ambient, wet bulb and sky temperatures in Riyadh are more distinct. Thermal mass and nocturnal convective cooling show promise, but the strategy by itself is unlikely to keep occupants comfortable. The scope for evaporative and radiative cooling is considerable.

3.2 Climate manipulation

Fossil-fuelled civilisation brought technical advances enabling the development of systems for creating 'artificial' interior climates. The development of both ventilation and central heating for buildings was largely a consequence of constructing the first buildings to house large numbers of people from the beginning of the seventeenth century, namely prisons, hospital, and theatres. Large scale systems of temperature and humidity control in response to external conditions were first implemented in dramatic greenhouses of the mid-nineteenth century. Refrigeration and air-conditioning were first accomplished in Europe, but their widespread use – including precise humidity control, first in industrial, then in commercial and domestic buildings – was a wholly American story that unfolded in the early twentieth century.

3.2.1 Heating, ventilation and greenhouses

Thermal comfort provision in medieval Europe was a relatively humble affair. English farmhouses in medieval times, for instance, relied heavily on the radiant heat from a central fireplace, with smoke vented through large unglazed windows (Olivier 1997 Vol.1.VI.4-B). This emphasis on ventilation meant internal air temperature would only be one or two degrees above ambient, negating any effects of insulation.

Windows were not glazed on a wide scale until the seventeenth century. Advances in production made glass cheaper, flatter and more transparent, and it became possible to make bigger panes, held together with fewer and thinner glazing bars and mullions (Addis 2007 p. 214). Glass was introduced into the windows of even the poorest houses, partly to prevent the spread of fire between adjacent buildings in densely packed streets. Large sash windows became popular because they brought in more daylight, afforded better views, and, when open, disturbed the composition of the façade less than casement windows did. This conflicted with other important functions of the building envelope, particularly keeping heat in and noise out.

Robert Hooke (1635-1703) established in the 1670s that the constituent of air essential for respiration was the same as that needed for burning (Addis 2007 p. 278). Despite this, a common belief prevailed that the fog from burning candles and fires indoors was healthier than the urban air. To some extent this may have been true, since rapid urbanisation at the time was not being matched by corresponding improvement in the provision of clean water and sanitary treatment of human waste.

One of the first successful interventions was made by the Reverend Stephen Hales (1677-1761), a scientist and fellow of the Royal Society, who dramatically reduced sickness and mortality rates at Newgate prison in London. He persuaded the authorities to create ventilation holes in the cell walls and install massive hand-powered fans to force stale air out (Addis 2007 p. 280). Cellular designs of later buildings facilitated cross ventilation, as did some examples of heat-driven ventilation. The French engineer Jean-Frédéric, Marquis de Chabannes (1762-1836), designed three exhaust stacks into the newly built Covent Garden Theatre in London, c.1815 (Addis 2007 p. 322). Each stack exhausted air through large roof-mounted cowls that faced the wind on the inlet, much like Persian *Bagdir*. The drive of each upward flow was supplemented by a different source of heat that provided other useful functions in the building. For instance, air at the top of the auditorium was heated by the gas-lit candelabra directly below one exhaust stack, an idea that became widely repeated.

The Scottish chemist and engineer David Boswell Reid (1805-1863) was responsible for the first large-scale use of mechanical ventilation in St. George's Hall in Liverpool (1841-1854) (Addis 2007 p.330). Four fans, each 3 meters in diameter were driven by a single steam engine, providing 7 – 10 cubic feet of air per person per minute, and could be adjusted to suit the number of people using the building, from 100 up to 5000. Air was pumped into a large plenum beneath the main hall and entered the room through thousands of holes in the wall near floor level. The whole system had to be run by numerous operatives who could control air flows in ducts by adjusting a multitude of canvas flaps.

By this time the heating of buildings by passing steam through pipes and radiant panels was widely implemented. The earliest examples were in mills and factories; sometimes steam was brought to upper floors through their hollow, cast iron columns. William Strutt (1756-1830) and one of his engineers, Charles Sylvester (1774-1828), from the 1790s onwards developed a coal stove surrounded by a vaulted air chamber made of brick, which transferred the useful heat but not the smoke (Addis 2007 p.319). The Belper stove as it was called was later refined by embedding iron pipes in the brick work to improve the efficiency of heat transfer. They also developed a heating and ventilation system for a hospital that incorporated an underground labyrinth that, because of the stable ground temperature, pre-warmed air in winter and pre-cooled it in summer.

The heating and ventilation of large public buildings was well established by the 1850s, and the sizes of the plant and equipment needed to provide them were calculated in a rational if not scientific way. Thomas Tredgold (1788-1825) is credited as being the first person to bring together engineering and the needs of human physiology into a theory of human comfort (Addis 2007 p. 328). But the majority of design engineers still assumed that heat losses through walls, floors and roofs were negligible. The French physicist Eugène Péclet (1793-1857) was the first person to calculate heat losses from a building envelope. He also demonstrated that an air gap of greater than 20 mm did little to further reduce thermal transmittance through double glazing, which was by then widely used in the colder regions of continental Europe (Addis 2007 p.405).

The first means of controlling the internal environment of buildings was developed for greenhouses built to create an artificial climate for plants (Addis 2007 p.326). Demand in the eighteenth and early nineteenth centuries came from the increasing commercialisation of agricultural production by the Germans and Dutch who wanted to extend the growing season, and an upper class fascination with exotic plants. Glasshouses became markedly larger between about 1820 and 1850 as they reached the height of fashion, enabled by the increasing sophistication of their heating and ventilation systems.

At first, steam from boilers had simply been used to create the desired humidity. The realisation grew that the façade had to admit light, heat, and water vapour at certain times, and prevent heat and water vapour escaping at other times. Thermostatic devices that monitored internal conditions and sent instruction to steam boilers, various types of ventilators and shading devices began to appear. Doubly-curved shell structures ensured that some part of the glazed envelope was always perpendicular to the sun's rays. Glasshouses such as the Great Conservatory at Chatsworth, near Derby, England (1836-1840) and the Palm House at Kew Gardens, West London (1844-48) exhibit both remarkable iron and glass composite structure and precise control of internal climatic conditions.

3.2.2 Cooling and air-conditioning

The demand for cooling in eighteenth-and nineteenth-century European cities first arose as a means of preserving food (well-off families were installing icehouses on the grounds of their estates), chilling drinks and making ice-cream (Addis 2007 p.218). This demand was first met by natural ice harvested and shipped from Norway before a transatlantic trade grew in the 1840s. Some engineers had already begun to experiment with the ice cooling of buildings. In an ambitious retrofit of the House of Lords in the 1830s, David Boswell Reid specified the summer provision of large blocks of ice to be placed in the main ducts for incoming air to pass over (Addis 2007 p.329). At the peak of ice-harvesting in the 1860s, over 200,000 tons of 'natural' ice was being shipped worldwide from the US. The industry declined in the 1870s when locally produced 'artificial' ice became available from improved refrigeration machines.

At the beginning of the nineteenth century scientists had begun to study the cooling that arose both from the expansion of a gas and the evaporation of a liquid (Fenn 1982 p.92). It was found that large amounts of heat could be taken away from an enclosed space by an evaporating liquid as part of a closed vapour-compression cycle. Early versions of ice-making machines were made by entrepreneurs from several countries, but their success was limited as experiments remained a hit and miss affair. Unbeknown to these entrepreneurs, the French scientist Nicolas Léonard Sadi Carnot (1796-1832) was laying the foundations of modern thermodynamics (Fenn 1982 p.101). He established the concept of the heat engine as a continuously operating cycle in which work is produced by receiving heat at a high temperature and rejecting it a low temperature, and that the amount of work produced was limited by the temperature difference between the heat supplied and that rejected. He also established that such a cyclic process was reversible – work could be used to cause heat to flow from a low temperature to a higher temperature, the basis for both refrigeration and the heat pump.

In the 1850s, the British physicist William Thomson, later Lord Kelvin (1824-1907), and the German physicist Rudolf Clausius (1822-88), working separately, used Carnot's ideas to revise how people understood the performance of steam engines, and established the two basic laws of thermodynamics: that heat and work are equivalent; and that heat cannot, of itself, pass from one body to a hotter body. Thomson realised the practical benefits of a machine that could pump heat from a low temperature to a high temperature and described the theoretical basis of designs for both the heat pump as a means of heating air and its inverse, the refrigerator, as a means of creating cold (Addis 2007 p.334). His work led to the scientific improvement of those few refrigeration machines based on the vapour-compression cycle that had already been built. Around this time, an alternative refrigeration method based on the vapour-absorption cycle was developed and manufactured, which avoided the need for a mechanical compressor, and so required less energy to run.

The first successful commercial refrigeration machines were developed by Carl von Linde (1842-1934) for German and Austrian brewing firms who wanted to extend beer production into the summer (Addis 2007 p.408). Demand for cooling in buildings was growing in the 1880s, but was still being met by the trade in ice harvesting. As Reid had demonstrated decades earlier, blocks of ice could be placed on wooden racks so that incoming air passed over the ice as it was drawn into the ventilation ducts that supplied air to the buildings interior.

The forerunner of modern air-conditioning did not arrive until the construction of the New York Stock Exchange in 1901 (Addis 2007 p.410). It was the first to have some means of controlling humidity, and, significantly, its refrigeration equipment was installed using thermodynamic principles and the Mollier diagram developed in 1892 by the physicist Richard Mollier (1863-1935). The Mollier diagram (also known as the psychrometric chart) shows the relationship between dry bulb temperature, wet-bulb air temperature, and relative humidity, and the heat content, or enthalpy, of the air-water vapour mixture. With it the American consulting engineer Alfred Wolff (1859-1909) could calculate how much energy would be required to deliver air at the desired temperature and humidity at different times of the year at the New York Stock Exchange. Wolff installed a combined heat and power system, with three 150-ton ammonia-absorption chillers powered by the exhaust steam from engines that drove electricity generators. The waste from the condensers (today called grey water) was recycled, stored in tanks on the roof, and used to flush the toilets.

This system, and others installed in public buildings during that decade, had no reliable means of controlling humidity. They could not dehumidify the air, and, since humidity can only be calculated indirectly by measuring both wet and dry bulb temperature, reliable hygrometers had not yet arrived. It was in the industrial sector, where there was more scope for return on investment, that reliable humidity control was first achieved. It had been common from the 1880s to spray water, atomised by compressed air to form a mist, into textile factories, where it was paramount that fibres were kept damp so as not to become brittle. In 1904, as soon as reliable hygrometers became available, they were installed in cotton factories to allow humidifying systems to respond to monitored levels both inside and out.

A successful means of dehumidifying air was developed by the American Willis Carrier (1876-1950) who setup a company in 1907 after receiving several commissions from the textile industry (Addis 2007 p.412). He monitored meticulously the performance of both plant and changes in temperature and humidity levels in the building. Using this empirical data, he was able to improve the performance of his systems. Carrier went on to target many other industries for which humidity was a critical issue, including bread-making, printing, and cigarette manufacture.

The air-conditioning of non-industrial buildings, such as movie theatres and some hotels, did not take off until the early 1920s, when air-conditioning became an essential feature in the leisure industry to attract customers (Addis 2007 p.525). Movie theatres offered a pleasant way of escaping the unbearable heat and humidity in many American cities. Carrier adapted various new technical developments in refrigeration for use in air-conditioning systems. At the same time the steam engine was being replaced by the electric motor as the power source for compressors and fans, resulting in dramatically smaller and more powerful air-conditioning systems.

3.3 An international vernacular

The importance of high-rise commercial buildings to the modern era is reflected in their high power density and growing contribution to the overall energy consumption of affluent and developing nations. Just as factories were a symbol of the industrialisation era at the start of the nineteenth century, high-rise offices are emblematic of the current post-industrial era, where the production of know-how is becoming more important than the production of goods and products. Economic activities and social organisations are now more than ever dependent on the capacity to retrieve, handle, store and generate information and knowledge (Castells 1994). These are precisely the activities that take place in office buildings. But why should these activities require so much energy throughput?

3.3.1 White collar factories and the glass box

The concentration of enterprise and finance increased rapidly in Europe during the first quarter of the twentieth century, in many ways mirroring what had first started in 1870s America (van Meel 2001 p.25). Mergers and new techniques of mass production created large professional corporations that needed administering and coordinating. The American engineer Frederick Taylor was able to break down a business process into a series of repeatable steps analogous to industrial production. The 'proleterisation' of office work was underway. As the nature of office work became more routine, the operational and physical design of offices changed from being small residential buildings filled only with a handful of educated men to 'white-collar factories': large open floor spaces with an orthogonal arrangement of desks facing the same direction so work could flow from one desk to another under supervision of clerical staff. Women were employed in white-collar jobs in large numbers. Frank Lloyd Wright designed the Larkin Building (1904) in Buffalo to house over 1,000 women, who processed huge volumes of paper for a mail order business, in one large air-conditioned space naturally lit through glass blocks in the roof.

Consulting engineers who specialised in the design and specification of ventilation and air-conditioning systems began to emerge in 1920s America, just as consulting engineers specialising in structures did in the 1870s when large iron-framed buildings were being erected in Chicago and New York (Addis 2007 p.524). Specific and impartial advice was needed, as some unscrupulous contractors were installing ventilation systems that provided chilled air with no humidity control, claiming that it was full air-conditioning, and compensating for this lack by increasing air speeds, resulting in complaints from members of cinema audiences who suffered stiff necks. There was much debate about which internal environment to create. In 1922 the American Society of Heating & Ventilation Engineers (ASH&VE) plotted a 'comfort zone' on the psychometric chart that defined comfort in terms of wet- and dry- bulb temperatures, after carrying out research on the ranges of temperature and humidity that different people judged to be 'more' or 'less' comfortable.

In the 1930s, a number of firms began breaking into the domestic market with small stand-alone room air-conditioners that provided an easy way to retrofit air-conditioning in a building without a central system. For commercial landlords the window unit system meant that tenants renting office space could each provide air-conditioning, but at their own expense. Air-conditioning became a standard feature of commercial offices in the United States during the building boom that followed World War II. A similar pattern occurred in each major city: once the proportion of office buildings with air-conditioning reached about 20 percent, the rest had to follow quickly to prevent their tenants moving to better premises. New York and Philadelphia reached this point in 1953, after which virtually all new office buildings were designed and built with air-conditioning (Addis 2007 p.524).

Post-war optimism was reflected in a new type of office building that would become strongly associated with commercial and international architecture for the next 50 years (Van Meel 2007 p. 29). The glass box – a rectangular high-rise office block with continuous glass facades – was enabled by the success of air-conditioning and the arrival of fluorescent lighting. Floor depth was no longer limited by the necessity for daylight and natural ventilation. The revolutionary architects of the Bauhaus movement in Germany first conceived of full-story-height glazed facades, notably Walter Gropius and Adolf Meyer. Modernist visions of functional, tinted, sky-piercing shafts were articulated by Gordan Bunshaft at Lever House (1952) and Mies van der Rohe in the Seagram Building (1958). These curtain-walls had tinted glazing to reduce glare and solar heat penetration. The idea of deep, open, universal floor spaces was attractive to developers because all areas were equally easy to let and subdivide. Suspended ceilings meant air and light could be distributed however the internal partitions were arranged.

Despite the unprecedented opportunity to rebuild European cities in the Modern style presented by wartime devastation, new European offices remained on the whole shorter and of shallower floor plan. Van Meel (2001) puts this down mainly to transatlantic differences in urban setting. The layouts of European cities are much older and more complicated than the US grid. Height regulations to preserve the historical character of European cities were relaxed after the war, but planners were still not fond of tall buildings, some seeing the corporate power they reflected as a threat to the welfare state. And of course the European frame of reference for what constituted 'high' was different to what is was in the US. No high-rises appeared in

Europe prior to the Second World War, while the culture for building high had been cultivated in Chicago and New York since the 1880s.

3.3.2 Office landscapes and cellular networks

In the 1960s Europe replaced America as the frontrunner in office design (Van Meel 2001 p.33). New, mostly European, management theory stressed the importance of 'human relations' and argued conventional office buildings no longer met the needs of modern office work. Exchange of information no longer had to take place in a vertical direction, downward from boss to worker, but along functional lines, ignoring departmental or hierarchical barriers. Like American offices, 'Office Landscapes' had large and open areas with air-conditioning to make their deep spaces habitable. But communication had to be able to flow freely without being hindered by walls or doors. Rest areas were dispersed between groups of desks that were arranged in line with the results of studies of communication patterns between different groups of the organisation. Removable screens and lightweight furniture structured space, and wall-to-wall carpets, ceiling treatments and screens with acoustical surfaces had to control the noise. It was also seen as cost-efficient and progressive. Just as the 1950s faith and optimism in technological progress was reflected in the glass-box, the Office Landscape captured the spirit of the 1960s, with society becoming more open and receptive to progressive ideas.

The popularity of the office landscape faded all over Europe during an economic downturn triggered by the oil crisis in 1973, along with post war optimism (Van Meel 2001 p.37). The sudden hike in cost for space heating and lighting meant the corporate showcases of the 1950s and 1960s became expensive to run. Employees were also increasingly dissatisfied with the environments afforded by glass boxes and office landscapes. European office culture was not accustomed to such openness and direct contact, such noise levels, nor the lack of natural lighting and thermal comfort. As office landscapes fell out of fashion, British office design went one way and Continental another.

In Continental Europe, a preference for cellular offices emerged and standards for space per employee increased (Van Meel 2001 p.37). This was because employees became more and more influential in organisational decision making. Laws were passed in Germany, the Netherlands Sweden and Italy that gave employees' representatives the right to sit on the supervisory board of a company. Offices designed like small villages popped up across Northern Europe, with units for small groups of workers linked by walkways, atria and communal areas. The most radical reaction occurred in Sweden, where it became common to give each employee a private office with individual climate control, daylight and an outside view.

British users had the same complaints as their Continental counterparts but had no formal rights to be involved in decisions concerning their working environment (Van Meel 2001 p.41). Moreover, the new organisational theory had less influence on physical design in Britain than on the Continent because the British market was dominated by developers. British organisations leased offices rather than building their own facilities, as most German, Swedish and Dutch companies did. Instead, open-plan offices were adjusted to incorporate private cellular offices, with the ideals of the office landscape replaced with a renewed focus on efficiency and flexibility. In other words, British open-plans became sophisticated versions of white-collar factories.

The degree of sophistication was marked by several technical innovations (Van Meel 2001 p.42). One was the introduction of systems furniture. Herman Miller's 'Action Office' furniture system reduced the problems with privacy and noise in a flexible way. Another innovation was seen in Norman Foster's Willis Faber and Dumas Building (1975) in Ipswich that anticipated the growing importance of information technology at a time when typewriters and telephones were still the only commonly found communication equipment. Arup Associates tackled energy concerns and put the high thermal capacity of the concrete Central Electricity Generating Board to good use by creating void networks inside walls and floors, so that air could be passed through them at night to cool the concrete structure down in the summer (Addis 2007 p.599). The next day the structure would be ready to absorb heat, reducing the need for mechanical air-conditioning. Fabric energy storage techniques are now well known, but still not used widely considering the number of reinforced concrete structures built (CIBSE 1998).

3.3.3 Electronic to virtual offices

With the energy crisis drawing to a close (albeit temporarily), the 1980s saw a global economic upturn and the arrival of personal computers, which were common on desktops by the mid-80s (Van Meel 2001 p.43). Computerisation was a global development, and cabling and cooling problems had to be solved in every office. For the first time computers were used to create 'intelligent' or 'smart' buildings with HVAC systems, security and maintenance controlled automatically. The development boom in London was its most rapid physical transformation since the Blitz, if not the Great Fire of 1666. British developers studied American practice to meet the demand for 'modern' offices.

A copy of a Manhattan skyscraper appeared in Canary Wharf (1991), at the time the tallest building in Europe. It had a classic American plan, with a central core, large uncomplicated floor slabs, increased floor-to-floor heights and high levels of servicing (Van Meel 2001 p.44). Richard Rogers' design for Lloyds of London (1986) caught the attention of cultural commentators. It was regarded as the first European representation of how information technology could change architecture. All secondary functions – lifts, stairs, toilets – were located outside around the perimeter of the building. Inside, a large atrium brought daylight into the deep plan form. Office areas were equipped with raised floors and suspended ceilings that could accommodate vast quantities of cabling and services.

In contrast, user satisfaction remained the main driving force in Continental office design (Van Meel 2001 p.46). Following the rejection of office landscapes in the 1970s, office design continued towards cellular workplace layouts because privacy, individual climate control, daylight, openable windows and an outside view were thought crucial for the well-being of employees. Raised floors were rare because the narrow floor depths of buildings meant that workplaces were close to windows, so computers could be served by trunking running along the perimeter. Several corporate headquarters were built like small 'cities', with buildings cut into separate 'houses' united by internal 'streets' or 'squares'.

The 1990s saw another downturn in business activity and the demand for new buildings slackened (Van Meel 2001 p.47). Simultaneously, changes in information technology – Mobile phones, laptops, internet browsers and email – inspired radical ideas about what buildings and offices could be, as people imagined what it would be like for employees to be freer of space and time. Despite grand ideas, UK changes in office design were largely cost driven. Open plans remained popular and the developments in IT enabled desk-sharing to begin. But public perception of US-style open plans was changing with studies of Sick Building Syndrome. Air-conditioned offices without an outside view or daylight entrance became associated with absenteeism and dissatisfied employees. Amenities such as break areas were given more attention in order to create more 'human' atmospheres. In Northern Europe costs also became important. In the decade of harsh global competition, expensive tailor-made offices were no longer practical. Cellular layouts failed to match new ways of working where team-work and interaction were central. More open work areas appeared, yet floor plans remained shallower and smaller than in the UK.

3.4 On the technological periphery

Various technologies – from porticoes in Ancient Greece to louvers in the middle-ages – have successfully varied the amount of entering solar radiation depending on the time of day or year. But the density of commercial activity has brought new problems. In modern commercial buildings, seamless glass facades offer occupants along the perimeter of the building access to natural daylight and an outside view. Large areas of glazing allow free solar greenhouse heating in the winter and natural daylight to pour in all year round. But they can cause overheating in the summer and can be poor isolators of thermal energy (this thermal energy can be positive (heat) or negative ('coolth') in relation to the surrounding environment – the point is that for it to remain useful, it needs to remain isolated). Such conflicts have driven the development of various strands of selective and responsive building envelope technology. Unfortunately many of these developments remain on the technological periphery, with tested implementation limited to a few owner-occupied buildings that can claim 'green' credentials.

3.4.1 Spectral selection

Since pioneering work in the 1950s, thin films and coatings have been developed to enable greater manipulation of the solar spectrum, its components (ultraviolet makes up ~9% of the total, visible 40% and near infrared 52% (Smil 2007 p.27)), and longer wave infrared (thermal) radiation, which emanates from all bodies at temperatures found in and around buildings. The most mature of these technologies are found in solar thermal collectors and photovoltaics, which rely on thin-films to maximise solar gain and minimise radiative losses (Hutchins 2003). Arguably more influential on building design are transparent low-emittance (low-e) coatings, applied on many a super-insulated window today. They enhance the greenhouse effect by reflecting longwave thermal radiation back inside; normal glass absorbs then re-emits thermal energy, so a portion is lost outside. For hotter climates there are now window films and coatings that reflect the invisible near infrared portion of solar radiation away, and so reduce the sun's heating effect without reducing daylight transmission.

These technologies allow the designer to be more selective with solar radiation. But they are all static, and so cannot respond in tune with seasonal and diurnal cycles. Chromogenic glazing can be seen as the modern equivalent of louvers. The optical properties of chromogenic materials vary in response to an external stimulus, whether that is light (photochromic), temperature (thermochromic), or an electric field (electrochromic) (Hutchins 2003). The Stadtsparkasse Bank (1999) in Dresden, Germany was the first to install electrochromic glazing. It darkened in response to the most intense periods of sunlight, but also let proportionally less near infrared through in its tinted state.

3.4.2 Convection control

Conduction rates through double-glazed windows have dropped dramatically since the first Roman prototypes and the nineteenth century demonstration by Eugène Péclet that making air gaps greater than 20mm did little to retain heat further (see above 3.2.1). Internal vacuums have been created and sustained in large window panels, although the costs remain prohibitively expensive (Garrison and Collins 1995). More common are double and triple glazed units filled with an inert noble gas such as argon, in combination with low-e coatings to suppress radiative exchange. These dense substitute gases convect less easily than air, thereby exchanging less heat between glass layers. A variety of translucent cellular materials such as silica gels or plastic honeycombs are available on the market (Kaushika and Sumathy 2003). The cells suppress convection while either the network of cells or the surrounding material permits a degree of visible light through. The cells can also act to store heat. Of greater commercial impact are pressurized Ethylene-Tetrafluoroethylene (ETFE) pillows, which give the 'Biome' at the Eden Project in St Austell and the National Aquatics Centre in Beijing their distinctive bubble-aesthetic.

Air spaces between walls have been used in several vernaculars to reroute heat from an intense sun, in an effort to keep internal spaces cool (Olivier 1997). Once the outer wall overheats from absorbing solar energy, air in the space begins to move on account of the exaggerated temperature difference, taking heat up and away from the internal wall. The French engineer Felix Trombe developed a similar system in the 1960s for solar heating. Glazing was placed in front of a massive wall, often painted black. The enhanced greenhouse effect produced hot air to be channelled into the interior. Such harnessing of solar-powered convection is displayed in the double-skin facades of several high-rise commercial buildings around the world, although most is found in owner-occupied buildings in Germany (Poirasiz 2004). During the winter, solar-heated air is cultivated and retained between two glazing skins that form the outer envelope of the building, and sometimes passed around from the south side to the north side with fans to create an encompassing thermal buffer. In the summer, flaps are opened to allow solar-heated air to escape upwards through the interstice, thus drawing air from inside the building to create a natural ventilation flow.

Many new super-insulated Scandinavian homes use mechanical ventilation to provide fresh air and heat exchangers to recover the heat from the stale air before it is exhaled. Returning to a biomimetic analogy, the ability to decouple mass flow from heat flow is especially tuned in animals such as dolphins and aquatic birds, which, through vasoconstriction, are able to pass heat from artery to vein before it can escape through flippers or feet (Schmidt-Nielson 1997). But there is one technique in decoupling mass and heat-flow that has been applied in building technology but has not yet been observed in nature. Vogel explains the phenomenon of counter-convection, which, using a combination of a porous material and a difference of pressure on either side, allows fresh air to enter with very little heat escaping (Vogel 2001b). An interior's pressure is reduced, so that fresh air is drawn through the empty networks of the porous material that makes up the building envelope. Along the way, the incoming air picks up the heat that is flowing through the material in the opposite direction. In principle, the fresh air enters at a temperature very close to that of the interior. A small number of buildings have been installed with prototype versions of this so-called 'dynamic insulation' that also filters the incoming air (Imbabi 2006).

3.4.3 Phase change materials

A number of post energy-crisis technological innovations, necessitated in part by market forces favouring the design of open-plan offices, were highlighted in section 3.3.2. These included the use of systems furniture to combat occupant issues with noise and privacy, and the 'unlocking' of the thermal capacity in concrete structures to temper requirements for air-conditioning. One new technological development suggests that systems furniture, and other products normally associated with the fit-out of buildings, may be able to help solve the energy-consuming thermal problems that ill-designed commercial buildings exacerbate.

Phase-change material (PCM) is a type of material that absorbs and stores large amounts of latent heat on melting, and releases that heat on freezing. Obviously all materials will change phase at some temperature, but of special interest to building services engineers are those with low transition temperatures in and around the area of occupant thermal comfort. Several PCM-based building components and systems have been tested in the academic literature for either heating or cooling, including Trombe walls, wall boards, shutters, and building blocks (Tyagi and Buddhi 2007). For a cooling application that would reduce demand for air-conditioning, PCM would be integrated into a building in some way so that on melting, it could absorb the excess heat that would otherwise raise the temperature of the room above comfort levels.

Despite academic activity, very few commercial PCM products and installations exist. One of the technical issues is that the material must be able to discharge fully into what is a limited range of heat sinks in order to be useful for cooling applications. For instance, one of the few products on the market - PCM wall-boards – have a tough time rejecting accumulated heat because of lack of thermal contact with cool night air. This is partly because of their plaster exterior and partly because of where in the building they are designed to go. This conflict is similar to that resolved by Arup Associates when they designed the concrete structure of the Central Electricity Generating Board to allow cool night air to pass through it (see section 3.3.2).

3.4.4 Radiative cooling

The atmosphere provides ecosystems with radiant heat that would otherwise escape into space. How much incoming longwave (LW) energy we receive depends mostly on whether the sky above is humid or dry, cloudy or clear, or – as is increasingly the case – polluted or clean (Martin 1989). Hot arid regions receive less LW than humid equatorial regions because there is less moisture in the air to absorb light and re-emit LW. The former climate type is characterised by, among other things, a large diurnal swing in temperature, which occurs because the barren ground continually exchanges LW radiation with the cold sky, cooling rapidly when the sun goes down. At least one desert animal seems to have taken advantage of this phenomenon: the desert Jack Rabbit (*Lepus spp)* has been observed resting in open shade with its very large vascularised ears facing the sky (Vogel 2005a). Equally resourceful, the Persians used radiative cooling at night to make ice for their wind-driven air conditioning systems (see section 3.1.1.)

Since the Persians, no other architectural vernacular has taken advantage of cool skies so extensively. In hot climates with the coldest skies, buildings are being designed to rely on air-conditioning. But there have been some advances in radiative cooling technology, coinciding with increasing scientific interest during the twentieth century in the workings of the atmosphere. A number of bespoke roof mounted radiators – usually meant for solar thermal water heating – have been run at night to cool water or air, which is then, for instance, run through the building envelope to discharge the thermal mass (Yannas *et al.* 2006). In order to cool the heat exchange medium consistently below ambient temperature, several types of infrared transparent convection guards have been proposed for radiators (Tsilingris 2003). Daytime radiative cooling has been proposed using convection guards that reflect shortwave solar radiation (Nilsson *et al.* 1992). More attuned spectral selection has been achieved in some radiator materials, enabling exclusive radiant access to the top of the troposphere via the 'atmospheric window' (Granqvist & Hjortsberg 1981; Berdahl 1984).

There has been little commercial development in this area. In the case of convection guards, interest has waned in the face of an apparent mismatch between optical and mechanical properties. Understandably, no one has taken seriously the prospect of spanning a roof with polyethylene wrap. There is nonetheless a clear opportunity for developing technology for cooling below ambient temperature by passive radiative interaction with the sky.

Conclusion

The success of heating, ventilation and air-conditioning systems has enabled a standard blueprint for commercial buildings to be exported around the world, irrespective of climatic context. This 'international vernacular' ignores some remarkable climate adaptation techniques for buildings developed over thousands of years. It also ignores many promising new technological developments which suggest a future ability of buildings for greater thermal responsiveness and selectivity. Some of the thermal conflicts that this 'international vernacular' exacerbates may be solved by building products normally associated with the fit-out of buildings, or multi-functional components that together make-up the envelope of a building.

Chapter 4

LITERATURE REVIEW CONCLUSION

Collectively, buildings are either the largest or second largest consumers of energy in all rich societies, playing a significant role in human interference in the carbon cycle. Technological improvements to reduce energy consumption need to be complemented and reinforced by greater awareness of energy use and behavioural change. But conserving energy in buildings is proving difficult for a number of reasons. The building design process is complex and adversarial, favouring incremental changes to established designs. There is a large discrepancy in performance between buildings as designed and building as built, and – uniquely among producing industries – there is no systematic feedback on performance to designers.

TRIZ may facilitate the transfer of problem-solving strategies ('gambits') across engineering disciplines. Comparisons between biology and engineering suggest that we rely unnecessarily on manipulating energy and matter to solve engineering problems. BioTRIZ shows which alternative 'gambits' to apply when. The tool may help better frame and solve the complex problems at the root of energy consumption in buildings.

The success of heating, ventilation and air-conditioning systems has enabled a standard blueprint for commercial buildings to be exported around the world, irrespective of climatic context. This 'international vernacular' ignores some remarkable climate adaptation techniques for buildings developed over thousands of years. It also ignores many promising new technological developments which suggest a future ability of buildings for greater thermal responsiveness and selectivity. Some of the thermal conflicts that this 'international vernacular' exacerbates may be solved by building products normally associated with the fit-out of buildings, or multi-functional components that together make-up the envelope of a building.

Part I, the literature review, has found two key opportunities for BioTRIZ analysis. The first is the clearly underdeveloped area of radiative cooling. The sky is an abundant heat sink, but its cooling potential has been ignored in modern building design. The second area is thermal storage by building components or products, a prospect enabled in particular by developments in the field of phase-change materials. Both areas involve making better use of locally available thermal resources, which may reduce energy demand in buildings.

Part II of this thesis documents how BioTRIZ has been applied to these areas, how the key problems were framed as a consequence, the range of solutions inspired by the suggested biological 'gambits', and the subsequent development of the most promising concepts into testable prototypes.

PART II

Case-studies

Chapter 5

BioTRIZ ANALYSIS – HOW TO USE THE SKY AS A NATURAL HEAT SINK

Abstract

The sky is a very large but underused heat sink. As the Persians demonstrated hundreds of years ago, radiative heat rejection to cool skies by passive means can be very effective. A building would stay cooler if its roof mass was radiantly coupled to the sky but thermally isolated from ambient and solar gains. This would reduce the need for mechanical cooling in hot climates. But this design challenge has several conflicts nested within in it which have not yet been overcome by existing technology. The biomimetics design tool *BioTRIZ* is used to explore possible solutions. First, an analysis of a standard roof is undertaken, demonstrating that useful radiative cooling will not occur unless particular thermal energy flows are somehow decoupled or rerouted. This problem is formulated in BioTRIZ terms as an 'Energy' vs. 'Energy' conflict. The principles suggested by BioTRIZ to resolve this conflict are used to systematically inspire new roof concepts. Of particular interest are the concepts that require no additional energy input and have no moving parts. These involve somehow giving the roof mass a radiant view of the sky through the insulation component above it. The simplest way of creating this 'heat-selective' insulation is to arrange an existing insulation material around pathways that focus and channel longwave radiation. This structural change could help keep a roof in a hot climate cool for no additional energy costs, perhaps even below ambient temperature. There are several possible configurations of this idea worth pursuing, in particular an arrangement of embedded funnels.

Introduction

This chapter is an edited version of a study published in the Journal of Bionic Engineering (Craig *et al.* 2008). Some sections of the published version have been omitted to make the thesis clearer. A performance estimate of one of the concepts using the simulation software *TRNSYS* has been left out altogether. An additional section describing the mechanism by which radiant energy is exchanged with the atmosphere is included. The results of the BioTRIZ analysis are also reinterpreted, and the conclusions made more explicit. The reader may wish to consult the full published version in the appendix, which is the first independent application of BioTRIZ in the academic literature.

This chapter demonstrates how BioTRIZ was used to analyse and resolve the thermal conflicts in roofs that stop buildings in hot countries benefiting from radiative cooling. This gap in the field of radiative cooling was highlighted in Part I section 3.4.4. The available technologies are more closely reviewed here, after the radiative cooling phenomenon is described in order to demonstrate how it is possible, through passive thermal interaction with the 'sky', to cool a mass below ambient temperature. The remaining sections describe the BioTRIZ study: how it was applied, the results generated, and the concepts arrived at. The original 39x39 TRIZ matrix and its condensed 6x6 version are also used in order to compare results (see Part I, section 2.2).

5.1 Atmospheric radiation

Figure 4 shows the spectrum of the Earth's radiation budget (Kiehl and Trenberth 1997) and the absorption bands of the atmosphere (Smil 2008, pp 29-36). Shortwave (SW) radiation is emitted by the sun and received at the top of the Earth's atmosphere in wavelengths between 0.1 and 5 μm. At sea-level the received range is between 0.2 and 3 μm. All SW radiation that is not reflected and scattered back into space gets absorbed and transformed into longwave (LW) radiation – infrared radiation carried at wavelengths between 5 and 100 μm. The transformation process starts in the stratosphere and continues through the troposphere, but most of it takes place on the Earth's surface. Nearly 40% of the solar energy that reaches the earth's surface is carried by visible wavelengths (0.4-0.7 μm), 8% by ultraviolet (<0.4 μm) and 52% by near infrared frequencies (>0.7 μm) (Smil 2008, pp 29-36).

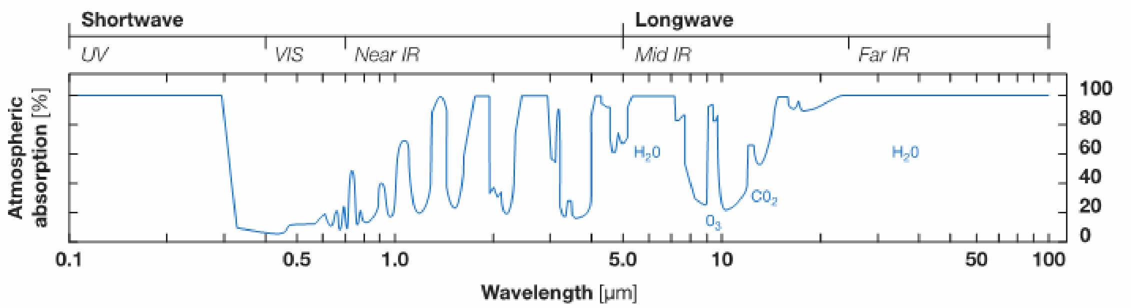


Figure 4. *The scale of wavelengths involved in the Earth's radiation budget and the absorption bands of the atmosphere. Incoming solar radiation is shortwave; outgoing thermal radiation is longwave.*

The atmosphere provides ecosystems with radiant heat that would otherwise escape into space. Down on the ground, we are continually receiving LW energy emitted by the atmosphere above. This incoming flux (the total energy radiated per unit area) is an internal sub-cycle crucial to life on earth; a temporary delay in the outward flow of reradiated heat into space. Smil (2008, pp 29-36) describes the global make-up of this flux. The majority of incoming LW radiation comes from the tri-atomic atmospheric molecules – O_3, CO_2 and H_2O – and arrives in wavelengths between 4 and 50 μm. Stratospheric O_3 contributes 15-20 W/m², CO_2 adds 70-75 W/m² and water vapour emits 150-300 W/m². The annual global mean of incoming flux is around 320 W/m², with mid-latitude continents receiving around 300 W/m² and cloudy equatorial regions up to 400 W/m². Diurnal ranges are mostly between 20 W/m² and 50W/m², with winter flows weakening by 25-30%. Momentary variations can be fairly large: a passing cloud can boost the flux by 25 W/m², and changing levels of green house gases are the major source of its intensification.

While the troposphere's energy transformations are complex, it can still be assigned an effective temperature, by assuming LW radiation received on the ground comes from a large, fictional, blackbody 'sky'. According to the Stefan-Boltzman law, the incident LW flux received from the sky, R_{sky} (W/m²) is proportional to the fourth power of its temperature, T_{sky} (degrees Kelvin, K) (Martin 1989),

$$R_{sky} = \sigma T_{sky}^4 \quad (1)$$

with σ (the Stefan-Boltzman radiation constant) equal to 5.67×10^{-8} W/m²/K⁴ . Applying this equation using the global fluxes outlined above gives a nominal range of possible sky temperatures: humid, cloudy skies are hot at around 293K (+20C); dry, clear skies are cold at around 253K (-20C), falling to as much as 232K (-40C) in winter.

While treating the sky as a blackbody (an object with a continuous radiation spectrum in all wavelengths that absorbs all radiant energy reaching it) can be useful for design, it is important to consider the selective absorption (and hence emission) by atmospheric gases (see figure 4). According to the Wien's displacement law (Vogel 2005a), the peak emissions by a blackbody atmosphere should be around 10μm:

$$\lambda_{\max} = \frac{0.002898}{T} \quad (2)$$

where λ_{max} is the peak wavelength (m) and *T* is the blackbody temperature (K). But this is not the case, as there is a distinct drop in absorption (and hence emission) between 8 and 13 microns by the atmospheric gases, as shown in figure 4. Much of the LW energy from the earth escapes through this so-called 'atmospheric window', since the peak emissions of most terrestrial objects are in this range. The window is at its most open in dry, 'unpolluted' conditions, and clouds block it (Martin 1989).

Under the right conditions, a warm grounded object will cool radiantly if it has an open view of the sky. This phenomenon explains why early morning dew and even frost can occur when ambient temperature is above freezing. The net rate (R_{net}, W/m^2) at which radiation leaves an exposed surface as a result of interaction with the sky will be (Martin 1989):

$$R_{net} = \varepsilon(\sigma T_{rad}^4 - R_{sky}) \qquad (3)$$

where ε is the LW emission coefficient of the radiating surface and T_{rad} (K) is the radiator temperature. Hence a warm emissive flat roof (303K, 30C; ε = 0.9) will reject radiant heat to a fairly cool night sky (If T_{sky} is 283K (10C), R_{sky} = 359 W/m^2 (eq.1)) at a rate of over 100 W/m^2. If the ambient temperature was 20C (293K), when the radiator reached that temperature, there would still be nearly 50 W/m^2 of radiative cooling occurring. If ambient gains were restricted while maintaining the sky view, the roof would cool *below* ambient temperature.

5.2 Radiative cooling

To achieve radiative cooling *below* ambient temperature, there are two basic functional requirements. The first is to emit in the desired spectral range. The second is to do this while stopping convective gains. (Radiative cooling at higher temperatures is a different matter, since the aim is to promote convection)

5.2.1 Spectral selectivity

One of the oldest ways of separating longwave from shortwave radiation – unwittingly or not – is the use of white washes or paints on massive buildings, as it is common in the vernacular architectures in a hot arid region. White reflects the majority of shortwave radiation but lets longwave radiation pass. In the Athens summer, certain off-the-shelf white paints have been shown to keep roof surface temperatures near ambient temperature during day and up to 6 C below at night (Synnefa *et al.* 2006).

Spectral selection has since become more selective. As described in the previous section, the atmosphere is most transparent in the wavelength interval of 8–13 microns – the so-called 'atmospheric window'. If a horizontal building surface had low reflectance in this range and a high reflectance elsewhere, the building mass would effectively have an unrestricted infrared view of the cold upper parts of the troposphere. Coatings and tiles such as SiO, MgO and LiF have been tested with results suggesting the possibility of net radiative cooling day and night (Granqvist and Hjortsberg 1981, Berdhal 1984).

5.2.2 Mitigating convection and bypassing insulation

The Persians understood that wind went counter to their efforts to make ice on clear desert nights, as it would warm the water placed in their shallow, long, exposed troughs. Their solution was to build up the walls of the troughs and arrange them side by side (Bahadori 1976). This simple convection-baffle reportedly allowed the production of ice with ambient night temperatures as high as 9 C (Martin 1989).

Roof ponds are another form of radiative cooling thermal mass design. The most successful ones are those with some form of insulation above the water that is removed at night, for instance sliding panels (Yannas *et al.* 2006). Hence the thermal storage mass is protected from solar and ambient gains during the day and is free to exchange longwave radiation with the sky at night.

Another way of bypassing insulation is to use an intermediary heat transfer medium. In the case of cooling radiators, water is pumped through a roof mounted radiator at night in order to cool the water toward night sky temperature (Meir *et al.* 2006, Yannas *et al.* 2006). This cooled water can then be, for instance, passed through the building envelope in the morning to pre-cool the structure so it is ready to absorb daytime internal heat gains. The performance of cooling radiators can be improved by reducing convective transfer from the surrounding air to the radiator. Open honeycomb convection-baffles with infrared reflective internal walls have been proposed (Yannas *et al.* 2006). So have convection guards made of infrared transparent film or glazing, set parallel to the radiator some millimetres above (Johnson 1975; Nilsson 1992; Tsilingiris 2003). Thin films of polyethylene have been shown to be up to the thermal task, if not up to other mechanical and longevity functions required of building envelopes (Tsilingiris 2003). If the film had a high solar reflectance, the panels might be run during the day to some effect (Nilsson 1992).

5.2.3 Biological analogues

We have found no proven direct biological analogue for radiative cooling. However, a number of plausible examples exist. Vogel (2005a) cites one possibility: the large vascularized ears of desert animals such as the Jack Rabbit (*Lepus spp*) may be used to reject heat to the sky under open shade. Vogel also conjectures that a small Chinese silk tree (*Albizzia julibrissin*) may downturn its leaves at night to reduce the exposed surface area at night to protect them from harmful radiative cooling.

More analogues are available if the search is made more general. For spectral selection, leaves, birds eggs, and desert snail shells reflect most of the near infrared component of sunlight, which accounts for just over half of sunlight's thermal load at sea level (Vogel 2005a). Heinrich (1999) offers an example of mitigating convection in nature: when warming in the sun in preparation for flight, dragonflies have been seen to use their wings as convection baffles to minimize heat loss to the air.

The natural palette appears richer in mechanisms for bypassing heat retention mechanisms, relevant when considering how to bypass roof insulation. Schmidt-Nielsen (1997) tells how dolphins are able to bypass their blubber when the need for heat dissipation increases by rerouting blood through an alternative channel which runs close to the surface of the skin. Heinrich (1999) explains how bumble bees have counter-current heat flow mechanisms that prevent heat loss while they are foraging at low temperatures, but when queens perch upon their brood of larvae to keep them warm, they are able to shunt heat past and through this mechanism to the abdomen by chopping up the flow into alternating pulses.

5.3 Method

A conventional roof is analysed in TRIZ terms so that BioTRIZ may be used to systematically inspire concepts for new roof systems that can utilise the sky as a natural heat sink.

5.3.1 Problem formulation

Figure 5 shows a qualitative model of a roof and its thermal interaction with solar radiation, local ambient temperature and the sky. Useful, harmful and insufficient thermal interactions are indicated. A conventional roof arrangement is assumed, consisting of three subsystems: an exterior white surface, an insulation layer, and the

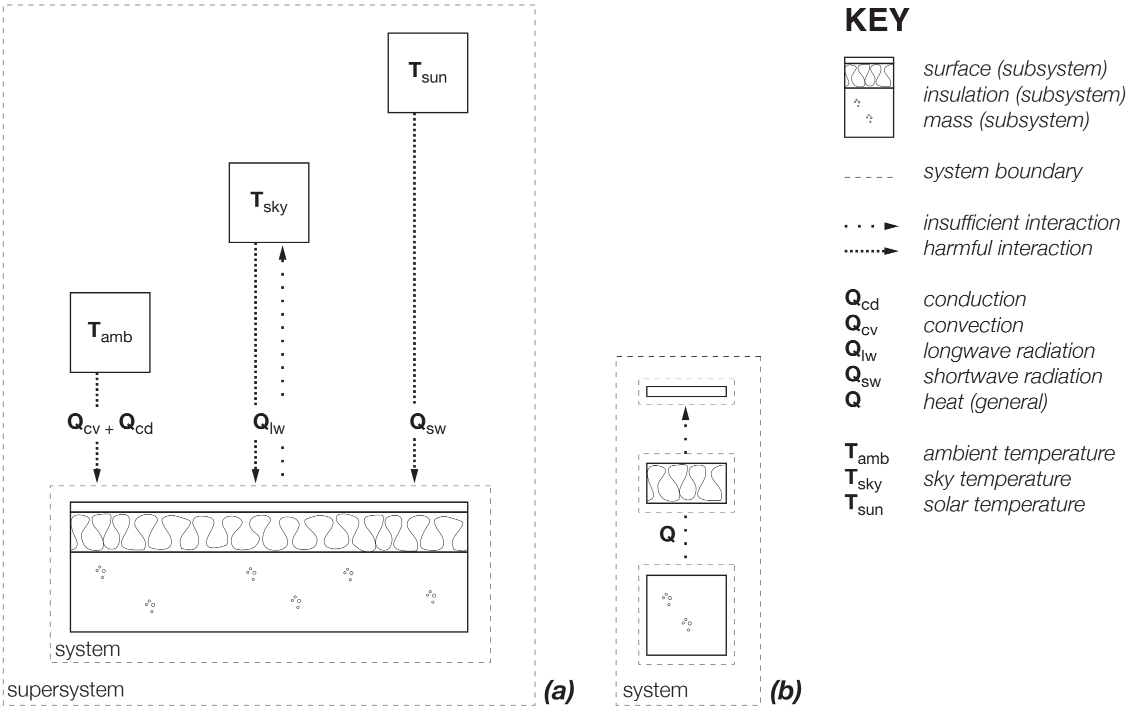


Figure 5. *A roof and its thermal interactions with the sun, sky and external ambient temperature. Insufficient and harmful interactions are shown between the roof and its environment (a), and between the roof subsystems (b). The problem is that with insulation present, there is insufficient interaction between the sky and the mass to bring about radiative cooling. But without the insulation, the mass would be quickly heated by the sun and the ambient temperature.*

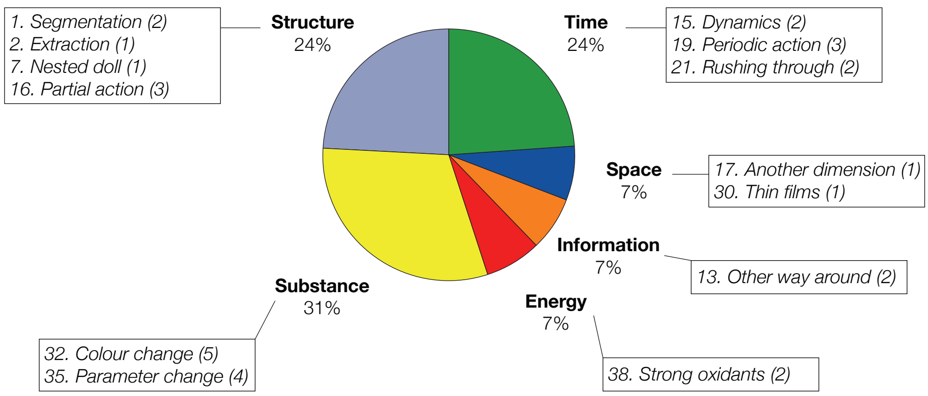


Figure 6. *Inventive principles offered by the standard TRIZ matrix to solve the radiative cooling problem, organised by operational field. Changes in Substance, Structure and Time are strongly suggested.*

envelope mass. Latent heat transfer and the other issues that condensation and evaporation bring are ignored, as are structural and longevity issues.

Ideally, the mass should be radiantly coupled to the sky, but thermally decoupled from solar and ambient gains. The problem lies in the insulation. Usefully, the insulation decouples the mass from the ambient temperature. It also, in conjunction with the white exterior surface, decouples the mass from the sun. But the insulation layer also restricts heat accumulated in the mass from reaching the exterior surface, thereby compromising longwave heat rejection to the sky.

5.3.2 Parameter selection

The parameters that best describe the problem defined above are now chosen from Altshuller's list of 39 features (see table 1). These are:

> 17. Temperature. *The thermal condition of the object or system. Loosely includes other thermal parameters, such as heat capacity, that affect the rate or change of temperature.*
>
> 18. Illumination Intensity. *Light flux per unit area, brightness, light quality, etc.*
>
> 20. Use of Energy by a Stationary Object. *The measure of the object's capacity for doing work; energy required to do a job - includes use of energy provided by the super-system (e.g. heat or electrical)*
>
> 22. Loss of Energy. *Energy that does not contribute to the job being done (reducing the loss of energy sometimes requires different techniques from improving the use of energy, which is why this is a separate category)*

Note that all four parameters fall into the operational field 'Energy' (see table 3). The four chosen parameters can be combined in 12 different ways to describe the problem as conflicts, for instance:

- The mass should be allowed to reach thermal equilibrium with the sky (17) without counterproductive energy inputs from the super system (22)

- Increase the longwave exchange between mass and sky (18) without incoming shortwave radiation and local convection increasing the temperature of the mass (17)

- Increase the longwave exchange between mass and sky (18) without reducing the amount of heat rejected by the mass (20)

- Increase the longwave exchange between mass and sky (18) without counterproductive energy inputs from the super system (22)

5.4 Results

Now that the problem has been formulated in BioTRIZ and TRIZ terms, we can compare the inventive principles that the three matrices suggest for solving the problem. For the standard 39x39 TRIZ matrix, the results come from looking up all 12 conflicts possible from the four chosen parameters (17, 18, 20 and 22). The original TRIZ matrix is available online (see Domb 1997). For the 6x6 BioTRIZ matrix and the 6x6 version of the TRIZ matrix (PRIZM), the results come from looking up 'Energy' vs. 'Energy' (table 3 and table 4).

Operational field	Inventive principle	Source matrix		
		TRIZ	PRIZM	BioTRIZ
Substance	32. Colour change	•		•
	35. Parameter change	•		
	36. Phase change		•	
Structure	1. Segmentation	•		
	2. Extraction	•		
	3. Local quality			•
	5. Merging			•
	7. Nested doll	•		
	16. Partial action	•		
Energy	9. Prestressing			•
	37. Thermal expansion		•	•
	38. Strong oxidants	•	•	
Information	13. Other way around	•		
	22. Blessing in disguise			•
	25. Self-service		•	•
Time	15. Dynamics	•		
	19. Periodic action	•	•	
	21. Rushing through	•	•	
Space	14. Curvature		•	
	17. Another dimension	•		
	30. Thin films	•		

Table 5. *The inventive principles offered by all three matrices. PRIZM offers no changes in Structure, BioTRIZ offers no changes in Time or Space.*

Figure 6 shows the inventive principles suggested by the standard 39x39 TRIZ matrix, organised by operational field. Since several of the inventive principles came up more than once, it is possible to assign percentages to each operational field. It can be seen that the TRIZ matrix strongly suggests changes in Substance, Structure or Time as solutions. Inventive Principle (IP) 32 Colour Change and IP 35 Parameter Change – both changes in Substance – come up most often.

It is not possible to generate charts for the results from the BioTRIZ and PRIZM matrices like in figure 6. This is because they are more general than the standard TRIZ matrix. They capture the 12 possible conflicts in one meta-conflict (Energy vs. Energy), and only one of each of the then suggested principles is given.

Table 5 compares the inventive principles offered by all three matrices. Of most interest is what PRIZM and BioTRIZ exclude (see chapter 2, section 2.2). PRIZM offers no principles from the operational field Structure. BioTRIZ offers no principles from the operational fields Time and Space.

5.5 Concepts

The inventive principles can now be used systematically to inspire solutions to the problem as formulated in section 5.3: the roof mass should be radiatively coupled to the sky, but thermally isolated from ambient and solar gains. The concepts are presented in order of operational field. The reader may wish to consult the list of inventive principles given in table 2, and the source of each inventive principle shown in table 5.

5.5.1 Changes in Substance

The concepts in this section are inspired by the inventive principles that belong to the operational field 'Substance' (see table 3). A change in Substance involves adding, removing or changing the properties of one of the materials in the system.

IP 32 *Colour Change* and IP 35 *Parameter Change* were the most strongly suggested by the TRIZ matrix. The former suggests adjusting the spectral properties of a substance; the latter suggests adjusting one of the physical parameters. Both could be interpreted as increasing the longwave transparency of the insulation, that is, the use of an insulation material that retards convective and conductive heat transfer, but not radiative transfer.

Clearly the ideal manifestation of this would be the use of a vacuum insulation; the white surface of the roof (we are only assuming changes on the insulation subsystem level) would filter out the shortwave radiation. The use of a vacuum is its own inventive principle, number 39, yet interestingly this was not suggested by any of the matrices. IP 39 is defined as a change in Energy (see table 3)

In summary, the inventive principles belonging to the operational field 'Substance' suggest replacing the existing insulation with one that is transparent to longwave thermal radiation.

5.5.2 Changes in Structure

A change in Structure involves adding, removing or regrouping structural parts. IP 2 *Extraction* suggests extracting the harmful part of the insulation. IP 3 *Local Quality* and IP 1 *Segmentation* combined suggest giving the insulation additional structure on a different length scale. Insulation already exhibits structure on the micrometre level because of its pores. IP 5 *Merging* suggests bringing the pores together in parallel, or making them contiguous. Larger scale vertical pathways through the insulation of millimetre or centimetre scale would give the mass a longwave view of the sky. These pathways could focus and channel longwave radiation. A honeycomb structure may suffice. Or 'funnels' could be arranged in the insulation to channel radiation up and out. Alternatively, infrared fibre optics could be used. Insertion of 'funnels' or infrared fibre-optics also falls under the umbrella of IP 7, *nested doll.* IP 16 *partial action* refers to these pathways being used as a larger damping mechanism.

In summary, the inventive principles belonging to the operational field 'Structure' suggest re-arranging the existing insulation material around pathways that focus and channel longwave radiation.

5.5.3 Changes in Space

These concepts are based on the inventive principles that involve changing the position or shape of the system or its parts. IP 30 *Flexible Shells and Thin Films* suggests replacing the insulation with some membrane that isolates the mass from the harmful heat sources in the environment. This approach already exists within the building technology repertoire in the form of spectrally selective glazing or infrared transparent films such as polyethylene (see 5.2.2) used as convection guards. This is another way of producing a *de facto* longwave transparent insulation. IP 17 *Transition to another* *dimension* suggests layering these longwave transparent membranes in multiple layers to arrest convection further. It also suggests a solution at the supersystem level, best shown with the example of the Jack Rabbit (see section 5.2.3) which has been observed feeding under open shade. Some commentators think its vascularised ears may be rejecting heat to the sky without being warmed by the sun to the rabbit's advantage. An external shading system that followed the sun or even a well placed tree might give a roof system enough open shading for daytime radiative cooling.

5.5.4 Changes in Time

These concepts involve changes to the speed, process or order of actions. The suggested inventive principles that fall under this category all pointed towards solutions that involved bypassing the insulation when it was advantageous to do so, for example at night. Section 5.2.2 showed how this is already done, either with an intermediary heat transfer fluid – as in the cooling radiator example – or with some removable insulation – as seen with the variants of roof pond technology. Alternatively, the roof system as it is could flip round to expose the mass at night. All these approaches can be circumscribed by the three changes in Time offered up by TRIZ and PRIZM. IP 15 *Dynamics* suggests mobilizing the mass or the insulation. IP 19 *Periodic Action* suggests pulsating heat rejection in tune with, for instance, the day and night cycles. In combination with IP 21 *Rushing Through, Periodic Action* suggests chopping up the flow into alternating pulses, like the bumblebee queen described in section 5.2.3

5.5.5 Changes in Energy and Information

A change in Energy refers to a change in energy source or 'field' (e.g. electric to magnetic). A change in Information refers to a change in the interactions or regulation of the system or its elements. Together, changes in Energy and Information suggest a self-adaptive roof.

IP 25 *Self Service* suggests finding some way for the system to regulate itself using either waste resources or energy present in the environment. IP 22 *Blessing in Disguise* suggests turning harmful factors from the environment into a benefit. Both inventive principles are changes in Information. We defined the harmful factors from the environment as solar heat and the local ambient temperature. IP 37 *Thermal Expansion* suggests using the thermal expansion or contraction of a material, or several with different expansion coefficients, to create some useful movement. This is a change in Energy. A combination of these principles suggests some sort of adaptive structure which is able to disconnect and connect the mass to the sky depending on the ferocity of environmental heat sources. For example, surface pores could close when it gets too hot.

5.6 Discussion

The simplest concepts to develop will be those that do not require moving parts or additional energy input. This leaves out some of the concepts based on changes in Space, and all of the concepts based on changes in Energy, Information and Time. The rest of the concepts – based on changes in Substance, Structure and Space – were all some form of ‘infrared-transparent’ or ‘heat-selective’ insulation. Of these, only the changes in Structure gave a clear and simple account of how this was to be achieved: **arrange the existing insulation material around pathways that focus and channel longwave radiation.**

This statement is a significant advance in the radiative cooling field. The absence of such roof system in the market or its development in academic circles is conspicuous. This structural approach is far cheaper than developing a *material* that had infrared transparent properties. There are many possible means with which to achieve it using existing and readily available technology. The breakthrough came about systematically, beginning with a dialectical problem formulation, which enabled focussed and ordered contemplation of a selected range of inventive principles.

The case for whether the concept is biomimetic is however contentious. It certainly embodies biomimetic principles, as defined by Vincent et al (2006). Moreover, had BioTRIZ been used in isolation, it is very possible that the same conceptual breakthrough would have been made. But it also could have been made just as easily by using only the original TRIZ matrix. Both matrices offered changes in Structure (see table 5). The PRIZM matrix – the condensed 6x6 version of the original 39x39 matrix – did not offer changes in Structure. But that outcome is due only to a process of statistical filtering, used to show in very general terms how biology and technology solve problems differently (see Part I section 2.2).

This BioTRIZ analysis has also highlighted the idiosyncrasy and internal logic of such terms as ‘Energy’ to the TRIZ system. Clearly a change in ‘Energy’ does not always equate to an intervention that is detrimental to the environment: in this study, IP 37

Thermal Expansion suggested tapping into the thermal fluctuations natural to the local environment. It is the interpretation of the principles that counts. The matrices are there to assist in selecting which inventive principles to focus attention towards. The fact that none of the matrices suggested using a vacuum (IP 39 *Inert Environment)* emphasises this point.

It would have done just as well to have a list of the 'Structural' principles to hand while tackling this problem. Undoubtedly, BioTRIZ has added another dimension to the TRIZ problem-solving repertoire. But it was the logical framework – *things do things somewhere* - that gave insightful order to this study, upon which the potential of the concepts could be addressed. Arguably it is this framework that can most usefully empower designers interested in low-energy solutions.

Conclusion

For a roof to cool radiatively, its mass should be radiatively coupled to the sky, but thermally decoupled from ambient and solar gains. This problem-formulation was made using the TRIZ dialectical method. The BioTRIZ tool helped generate promising concepts for resolving this conflict. In particular, it was realised that conventional insulation could be restructured around pathways that focus and channel longwave radiation. This type of 'infrared-transparent' or 'heat-selective' insulation has yet to be developed, and there are variants that are suitable for further development as part of the EngD research project, with its emphasis on developing new components for lower-energy buildings to proof-of-principle stage. Comparison of results from the BioTRIZ, PRIZM and TRIZ matrices demonstrated that what constitutes biomimicry can be a contentious affair.

Chapter 6

HEAT SELECTIVE INSULATION FOR RADIATIVE COOLING OF BUILDINGS

Abstract

Proof-of-principle prototypes were built based on some of the concepts for 'heat-selective' insulation presented in the previous chapter. Tests were carried out during April and May nights on an office roof in central London. Test panel temperatures fell to between 6 and 13 degrees below ambient temperature. Radiative cooling powers between 25 and 70 W/m² were recorded when cooling plates were at ambient temperature. At 20 degrees above ambient, total cooling powers of between 90 and 200 W/m² were recorded. Daytime radiative cooling below ambient temperature was evident when clouds blocked direct sunlight. Radiative cooling power was increased by 37% using reflective 'funnels'. The results indicate that a robust, heat-selective roof panel is technically feasible, designed for large enclosures in hot climates, such as transport hubs and exhibition halls. Better focussing and direction of longwave thermal radiation would be required to get useful radiative cooling for multi-storey buildings in built-up areas, because of the small ratio of sky view to floor space.

Introduction

This chapter is an edited version of a paper submitted to the journal Energy and Buildings, going through peer-review at the time of writing. This chapter reports the testing of the most promising concepts arrived at during the BioTRIZ analysis documented in the previous chapter. The first section of this chapter revisits and develops the concept of 'heat-selective' insulation further, commenting on what types of buildings and where in the world its application might be best suited. The chapter then takes on the standard scientific paper format of materials, method, results and discussion.

6.1 Heat selective insulation

The technical challenge of radiative cooling below ambient temperature can be framed as follows: radiantly couple the building mass to the sky; thermally decouple it from ambient and solar gains. Previous proposals for radiative cooling systems have had their mechanical, radiative and thermal properties in conflict. An insulation component that was transparent to longwave radiation would resolve these conflicts. But this need not be a specific material property. Conventional insulation can be restructured around pathways that focus and channel longwave radiation. This section presents three different approaches.

6.1.1 Funnels

The sketch in figure 7a shows a concept for an integrated roof panel made up of LW funnels. By focusing LW IR radiation from the radiator through smaller apertures, several benefits accrue. First, for cooling below ambient temperature, non-radiative losses can be reduced without interfering with LW transmission, by filling the 'dead' spaces between the funnels with high performance insulation. Second, the trade-off between optical and mechanical properties with the selective material is less significant because of the smaller spans: mechanical load can be transferred directly to the structure (UV protected selective high density polyethylene (HDPE) is used for infrared motion detection systems and can be sourced in films or injection mouldable pellets (KUBE 2008)). Third, radiative cooling needn't compete with other functions for roof space. For instance, photovoltaics or natural daylight collectors could fit into the roof space between apertures. Fourth, the radiator is less exposed to solar radiation, increasing the chances for daytime radiative cooling. Lastly, the ability to direct LW means that the concept could work on roofs that were not flat.

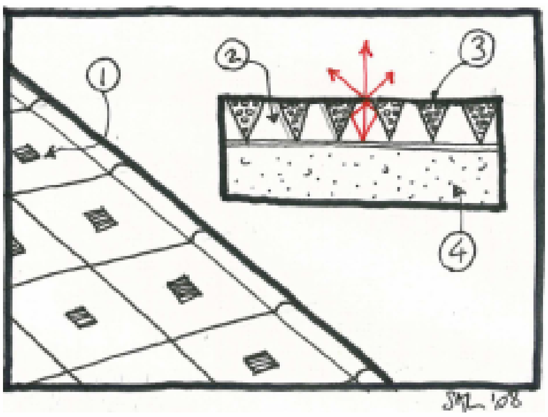


Figure 7a. *LW funnels. (1) Spectrally selective apertures on roof; (2) LW funnels; (3) Insulation; (4) Thermal mass. The funnels give the mass a longwave view of the cool sky, while making more room for insulation. The apertures liberate space for other roof functions and technology, such as solar panels.*

6.1.2 Fibre optics

LW fibre optics (Graydon 2004) could be used to resolve the conflict between thermal and radiative performance, as indicated in figure 7.b. Fibre optics that channel only visible light could also be integrated into the panel, to bring 'cool' light inside. LW Fresnel lenses are another light directing technology that could be implemented (KUBE 2008). Neither LW directing technology is tested in this study.

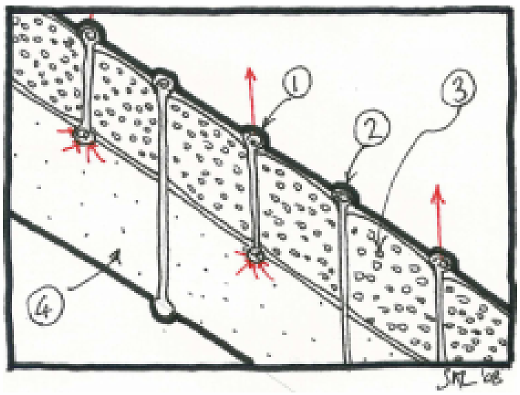


***Figure 7b**. Fibre optics. (1) LW fibre optic bundles; (2) 'cold' visible light fibre optic bundles (channel only visible light, not near IR); (3) Insulation; (4) Thermal mass. LW fibre optics link thermal mass with sky; 'cold' visible light fibre optics bring natural light into the building. No restriction on building shape, or where LW harvested from.*

6.1.3 Sealed hierarchical baffles

Figure 7c shows that an infrared reflective baffle – as used in gas-insulated panels (Griffith *et al.* 1995) – is placed in a cell with rigid walls and an open top and bottom. A group of these cells are stacked and close-packed. Between each layer is a LW transparent film, such as polyethylene. The top layer of cells is covered in a spectrally selective film that reflects SW but transmits LW. A rigid radiator material is put under the cells and the whole component is hermetically sealed. Air might be replaced with a lower conductivity gas, such as argon or krypton (Griffith *et al.* 1995). Composite approaches have been suggested previously (Johnson 1975), but not in a sealed hierarchical format. Nesting the structure in this way could reduce power losses without overly interfering with radiative cooling. The surface can be corrugated or combined with a fibre mesh to make a robust composite (the domed surfaces in the sketch merely demonstrate that the geometry can be manipulated).

6.1.4 Applications

The most straightforward application of heat-selective insulation would be for large enclosures such as airports. Occupants would have a cool radiative link to the thermal mass on the large-span underside, made up of a phase-change material to increase heat capacity and reduce weight. The cool and expansive soffit would radiantly cool occupants. This strategy could allow occupants to remain comfortable in warmer internal air temperatures. It could be supplemented by natural ventilation – which is counterproductive in conventionally air-conditioned spaces – offering the possibility of an energy-saving double-dividend. To keep the thermal mass from heating by convection at the soffit, a similar LW transparent insulation could be placed on the underside. This would maintain the radiant coupling between soffit and occupant, and natural ventilation would not warm the thermal mass.

Better focussing and direction of longwave thermal radiation would be required to get useful radiative cooling for multi-storey buildings in built-up areas, because of the small ratio of sky view to floor space. In the absence of infrared directing technology, such as fibre optics, a fluid medium might needed to bring heat from lower floors to the roof. Infrared directing technology could also make use of the sides of buildings.

The presented concepts do not attend to the possibility of using radiative cooling to create dew (Nilsson *et al.* 1994). Natural evaporative cooling using freely harvested water might supplement radiative cooling. This would be especially useful during the day, as a buffer when the sun is at its strongest.

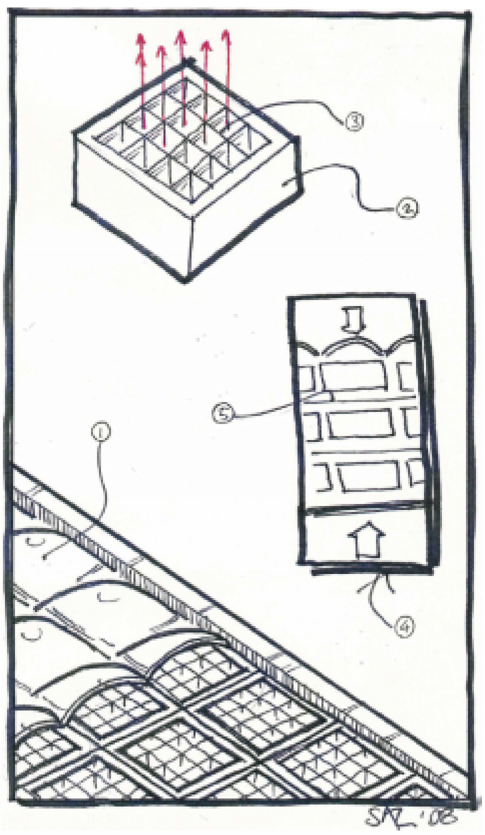


Figure 7c. *Sealed baffles. (1) Spectrally selective domes on roof; (2) Rigid cell; (3) LW reflective baffle; (4) Cells are closed packed and hermetically sealed; (5) polyethylene spacers. LW is allowed to pass vertically in a robust, insulative roof component.*

6.2 Materials and method

A test devised by Granqvist and Hjotsberg (1981) was used to explore whether the first two concepts proposed in section 4 had scope for further development. A coefficient for non-radiative losses for a range of samples was measured indoors. Then total cooling power versus temperature difference was measured during night time rooftop experiments. These two stages allowed radiative cooling power for each sample to be estimated.

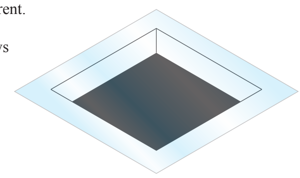
6.2.1 Test panels

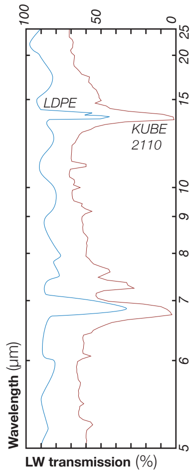
The experiment set-up and the different samples tested are shown in figure 8. Two square aluminium plates (~0.8 mm thick, 250 x 250 mm, ~ 125 grams) were sprayed mat black to approximate blackbody radiators. Measurements with an infrared camera indicated an emissivity of > 0.9 in the spectral range 7.5 – 13 µm. A 30W heating matt was adhered to the underside of each plate. Commercial thermocouples were electrically insulated then glued to the upper (black) side of each plate. The plates were then each placed into a large expanded polystyrene block with a 5cm deep trough cut into the top. A commercial desktop power supply with six DC outputs was connected to each heating mat. These would be used to heat the plates in steps, so the cooling power of each sample could be measured.

The 'clingfilm' sample shown in figure 8 was used as a control for each experiment. Commercial *cling film* is made from low density polyethylene (LDPE), which is noted for its high infrared transmission (Martin 1989). A successful prototype is one that performs well radiatively in comparison to the 'clingfilm' benchmark, but has scope for having its non-radiative losses reduced in a mechanically robust product.

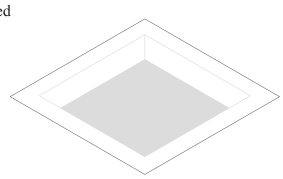
The transmission spectrum of LDPE is shown in figure 8 in comparison with the 'selective' (Kube film 2011 (KUBE 2008)) material also tested. The transmission spectrum for LDPE was redrawn after Martin (1989). According to the manufacturer, the 'selective' film is 0.22 mm thick and has 73% transmission in the 7-13µm range. The material is used for windows and lenses in motion detecting burglar alarms and infrared thermography. Consequently, it has been optimised to block visible light and transmit peak emissions from bodily temperatures, which happen to overlap with the 'atmospheric window', hence showing promise for day and night radiative cooling.

‘Clingfilm’
Low density polyethylene (LDPE) film is LW transparent. Used as a control (prevents convective inflow but allows radiative cooling)
k = **2.8** *W.m⁻².K⁻¹*

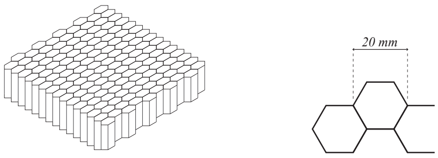




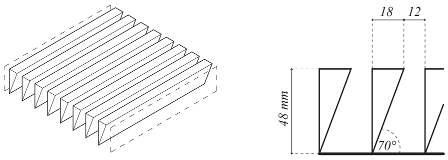
‘Selective’
IR selective film KUBE 2110. Blocks SW, transmits LW. Used for motion detectors and thermography. Vacuum formable. Injection moulding pellets & UV resistance available
k = **2.8** *W.m⁻².K⁻¹*



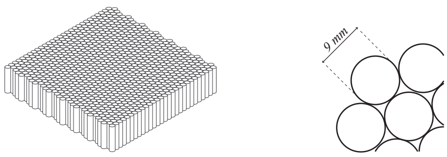
‘Honeycomb’
Aluminium tape folded and glued into honeycomb array. Top of box covered with LDPE film
k = **3.2** *W.m⁻².K⁻¹*
$\tilde{\rho}/\rho_s$ = **0.015** *kg/m³*



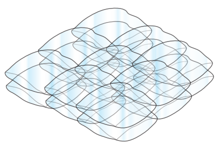
‘Funnel’
Aluminium sheet (0.1mm) cut and folded into 8 rods with slim right-angle triangle sections. Evenly arranged in box, point-side down in parallel array. Top of box covered with LDPE film
k = **3.1** *W.m⁻².K⁻¹*



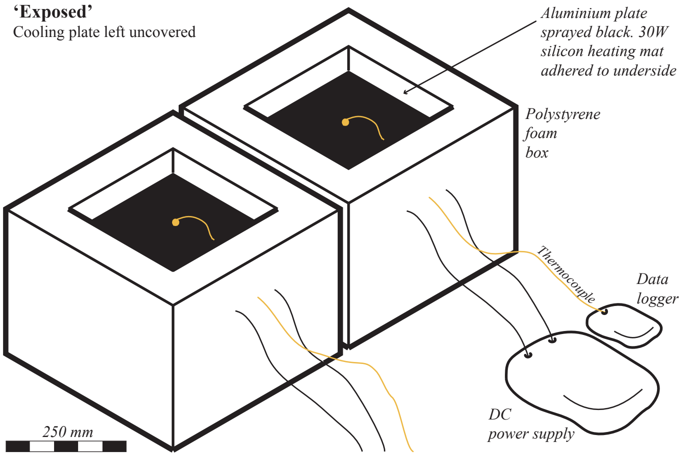
‘Straws’
Large translucent PE drinking straws, closed packed in vertical array. Bundles cut to length using hot-wire for simultaneous weld. Top of box covered with LDPE film
k = **2.7** *W.m⁻².K⁻¹*
$\tilde{\rho}/\rho_s$ = **0.065** *kg/m³*



‘Foam’
24 LDPE self-seal bags blown-up and placed in test box to approximate very low density PE foam. Top of box covered with LDPE film
k = **2.4** *W.m⁻².K⁻¹*
$\tilde{\rho}/\rho_s$ = **0.007** *kg/m³*



‘Exposed’
Cooling plate left uncovered



k = coefficient for non-radiative losses
$\tilde{\rho}/\rho_s$ = relative density

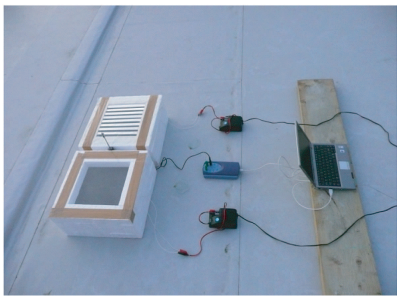


Figure 8
Rooftop tests: experiment setup

6.2.2 Coefficient for non-radiative losses

A very important property of the samples is their non-radiative losses due to conduction and convection, which, if large, will limit net cooling power below ambient temperature, particularly at large temperature differences. A coefficient for non-radiative heat transfer *k* ($W.m^{-2}.k^{-1}$) for each sample was measured, assuming the relationship

$$P_{loss} = k\left|\Delta T\right| \qquad (4)$$

where P_{loss} is the power loss (W/m^2) and ΔT is the difference in temperature between the plate and ambient (K). The plates were electrically heated in a room at constant temperature, measuring the stagnation temperature after an hour of constant heating. The results are shown in table 6. To stop radiative exchange between the plates and cooler walls and ceilings in the room, an aluminium foil 'radiative barrier' was placed over the top of each sample. This made a large difference. For instance, without the radiative barrier, *k* 'selective' was 4.3 $W.m^{-2}.k^{-1}$. (Granqvist and Hjotsberg (1981) did not use any means to minimise radiative exchange with the room). In effect, *k* is a coefficient for conductive and *free* convective heat transfer. The radiative barrier minimised radiative exchange, and the air in the room was still enough to discount the effects of *forced* convection. While the 'foam' sample has the lowest value for *k* (table 6), we expected that it would hinder LW transmission more than, say, the 'honeycomb' sample.

Sample	***k*** ($W.m^{-2}.k^{-1}$)
'Clingfilm'	2.8
'Selective'	2.8
'Honeycomb'	3.2
'Funnel'	3.1
'Straws'	2.7
'Foam'	2.4

Table 6. *Measured coefficients for non-radiative losses (k)*

6.2.3 *Rooftop tests*

Each sample was tested against a control sample ('clingfilm', see figure 8) on the roof of a 5 storey office in Central London on six separate nights during April and May 2008. One daytime test was conducted. The flat roof was approximately 6x4 metres in area, with a perimeter wall ranging between 0.5 and 1.5 metres in height. Neighbouring buildings were between 4 and 6 storeys. The samples were placed in the middle of the roof for the best sky view, as shown in the photo in figure 8. Four nights were clear and still; two nights started clear and ended cloudy, with gusts of wind. The ambient and plate temperatures were continuously logged at 15 second intervals. The barometric pressure and other weather data were tracked using live online updates from the Meteorological Office (2008). Cooling power versus temperature difference (between ambient and plate temperature) was measured by successively heating the plates and noting the stagnation temperature for each electrical input (P_{el}). The assumption is that

$$P_c \equiv P_{el} = P_{rad} - P_{loss} \qquad (5)$$

Where P_c is cooling power (W/m^2), P_{rad} is radiative cooling power (W/m^2), and P_{loss} is power loss due to ambient gains (W/m^2) (see equation 4). The four electrical inputs from each power supply were measured before the beginning of each experiment using a digital multimeter. For the range of voltages observed, this instrument had a resolution of 10mV at accuracy +/- (0.5%+2), and, for the DC currents observed, a resolution of 10mA at accuracy +/- (2%+5).

After measuring cooling power (P_c), radiative cooling power (P_{rad}) was estimated assuming,

$$P_{rad} \equiv P_c + P_{loss} \qquad (6)$$

noting that the measured coefficients for non-radiative losses (k) do not include the effects of forced convection.

6.3 Results

Six rooftop tests were conducted at night; one during the day. The results are described below and shown in figures 9 – 15.

6.3.1 *'Exposed' vs. 'Selective'*

The cooling performance of these samples was tested both day and night on April 9th 2008.

6.3.1.1 Day

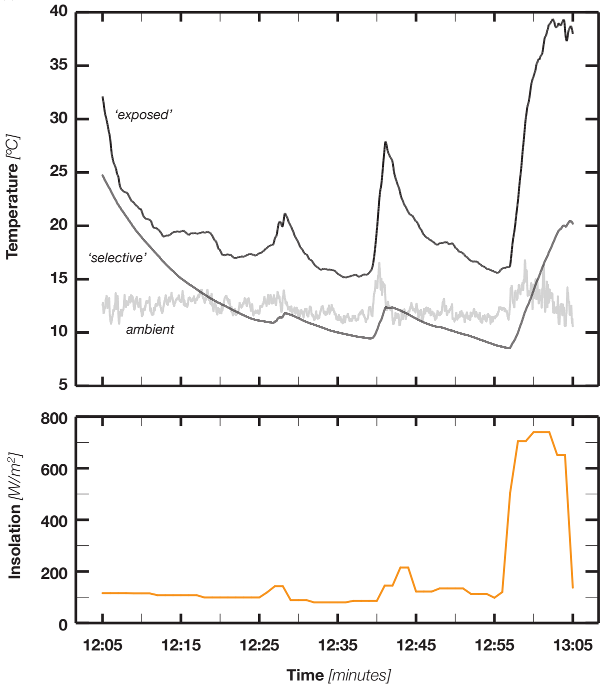
The temperature of both cooling plates was logged for an hour at midday, April 9th 2008. Solar insolation was measured with a handheld meter. Figure 9 shows that the selective window allowed radiative cooling below ambient temperature to occur when clouds blocked direct sunlight. The infrared image taken (figure 9) suggests that the low cumulus clouds – which permeated an otherwise clear sky during the experiment – were at least 25 degrees below ambient temperature. The image was taken assuming a cloud emissivity of 0.9 and distance 1km straight up. The image shows the sky between the clouds to be very cold. The camera's spectral range is 7.5 – 13μm, so the view here is indicative of the temperature of the 'atmospheric window' – the radiative link to the top of the troposphere. The minimum recordable temperature with the instrument is -40C, which was exceeded in this instance.

6.3.1.2 Night

The sky began partly cloudy then completely cleared for the second half of this three hour experiment. Relative humidity stayed near 50% throughout, and the atmospheric pressure rose from 998 to 999hPa. There was a light north westerly wind of 3mph. Figure 10(i) shows the measured cooling characteristics of the plates. Radiative and convective cooling brought the temperature of both plates down from 20C to ambient temperature (10C) at a rate of approximately 2C/min. After 90 minutes, radiative cooling brought the 'exposed' plate to 7.1 degrees below ambient temperature, and the 'selective' plate to 12.9C below. The ambient temperature changed less than 2C in this period. The temperature profile of the 'exposed' plate was clearly more susceptible to changes in wind. But, despite being subject to convective inflow, it still reached a very low stagnation temperature, highlighting the very good sky conditions. It also demonstrates how the Persians were able to make ice in air temperatures above freezing employing only vertical wind guards (Bahadori 1976, Martin 1989), as the sides of the polystyrene box had effectively acted.

The effect of successively heating the plates by increasing the electrical input in four steps is shown graph 10(i). We allowed 20-30 minutes for the plates to reach thermal equilibrium at each step. Each step yielded a larger temperature rise for the

(i)



(ii)

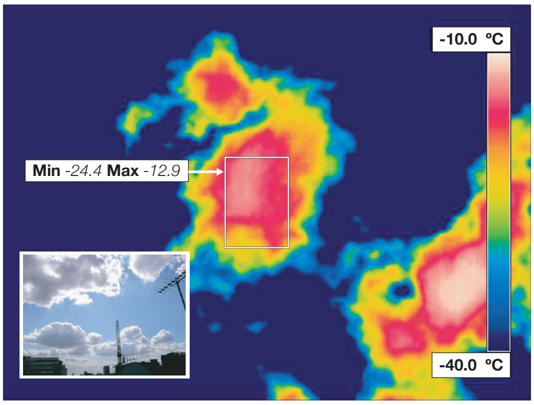


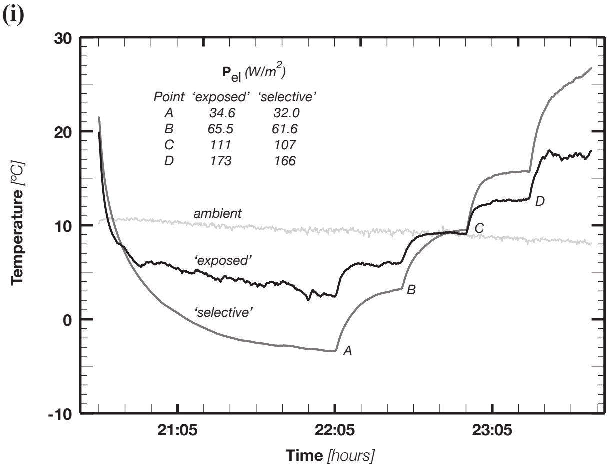
Figure 9. *'Exposed' vs. 'Selective' (daytime)*

(i) Temperature over Time for 'Exposed' and 'Selective' cooling plates, midday April 9th 2008, London W1. Solar radiation received is shown on graph below. The selective window allowed radiative cooling below ambient when clouds moved infront of the sun.

(ii) Low cummulus clouds permeated an otherwise clear sky during the experiment (insert). The infrared image was taken with an assumed cloud emissivity of 0.9 and distance 1km straight up, indicating cloud temperatures of least 25 degrees below ambient. The view between clouds is indicative of the temperature of the 'atmospheric window', as the camera's spectral range is 7.5 – 13µm; unfortunately the minimum recordable temperature with the instrument is -40C.

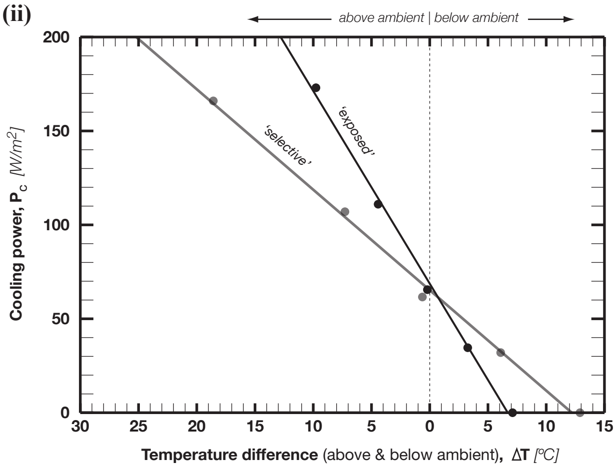
Figure 10. *'Exposed' vs. 'Selective'*

(i)



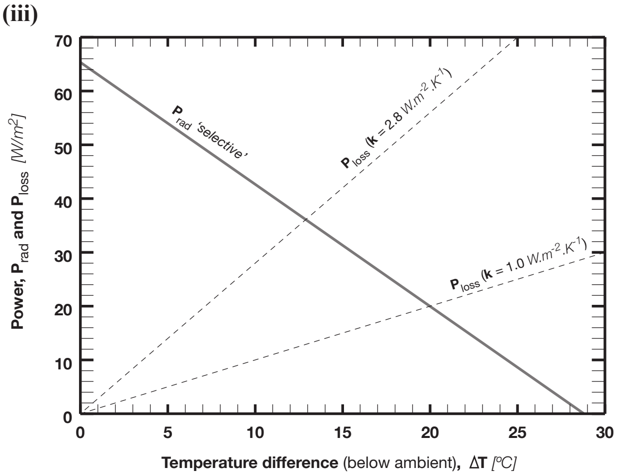
(i) Temperature over Time for 'Exposed' and 'Selective' cooling plates, evening of April 9th 2008, London W1. Points A-D denote electrical powers (P_{el}) fed in.

(ii)



(ii) Measured cooling power (P_c) vs. temperature difference. Data taken from (i). The left side is temperature difference above ambient temperature; the right, below.

(iii)



(iii) Solid line shows estimated radiated power (P_{rad}) vs. temperature difference. Dashed lines show power loss (P_{loss}) caused by non-radiative exchange for two values of heat transfer coefficient.

'selective' plate than for the 'exposed' plate, which was expected since the 'selective' plate was isolated from convective inflow.

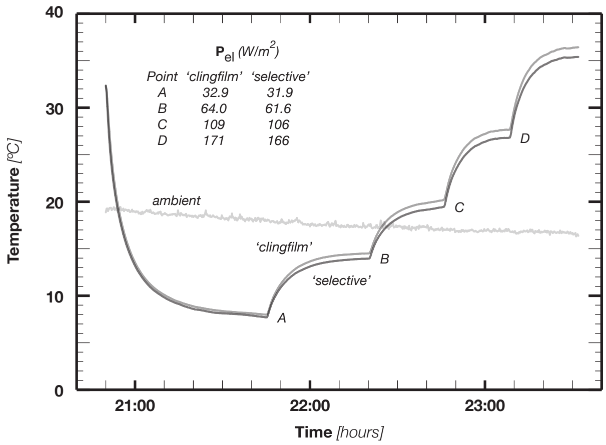
The contrast shows up best when re-plotting the measured data as cooling power against temperature difference (between ambient and plate stagnation temperature). Both plates show linear behaviour, but eliminating convective inflow with the clingfilm reduced the gradient steepness for the 'selective' sample by half. Both the 'exposed' and 'selective' cooling plates share similar intercepts at ΔT=0, 69 and 65 W/m^2 respectively. Clearly only radiative exchange with the sky can account for any losses when ΔT=0. The selective film is estimated to be stopping only 6% of the radiant cooling possible with the cooling plates.

The non-radiative losses are important when considering behaviour below ambient temperature. The upper dashed line in figure 10(iii) shows P_{loss} vs. ΔT for the coefficient *k* found for the 'selective' sample (2.8 W.m-2.K-1, see table 6). The lower dashed line shows the power loss for a lower value of *k* =1, which maybe obtainable. The solid line shows radiative power (P_{rad}), estimated using equation (6). It is at best an estimate, since the measurements for *k* did not account for the effects of forced convection (although on the night of the experiment the wind was only mildly perceptible). The points at which a dashed line intersects with a solid line represent the lowest obtainable temperature for that particular value of *k*. With the lower value (but not unrealistic goal) of *k* = 1, figure 10(ii) predicts a stagnation temperature 20C below ambient. If there were no power losses, ΔT=29C could have been achieved on that night, which, if taken as an estimate for sky temperature depression, indicates an effective sky temperature of -20C.

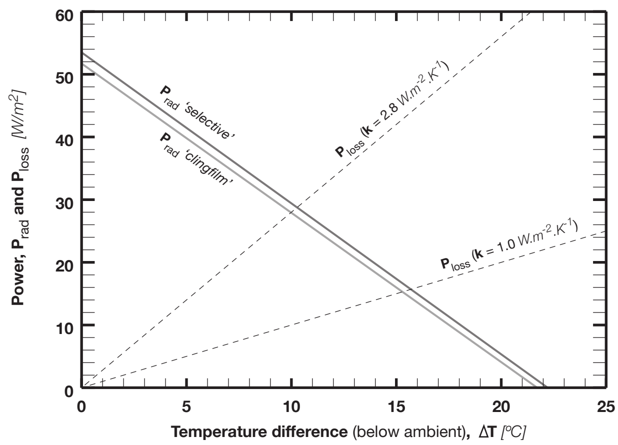
6.3.2 'Clingfilm' vs. 'Selective'

This experiment was undertaken on the evening of May 8th 2008. The sky remained mostly clear, and the local ambient temperature started at just under 20C and did not fall below 16C (figure 11(i)). The air pressure remained at 1017hPa, with easterly winds not more than 8mph, and relative humidity rising from 63% to 76%. With more water vapour in the atmosphere, the conditions were not as good for radiative cooling as experienced during the previous experiment (6.3.1). The 'selective' sample only reached 10.2C below ambient this time (ii), with a smaller sky temperature depression of 22C indicated (iii).

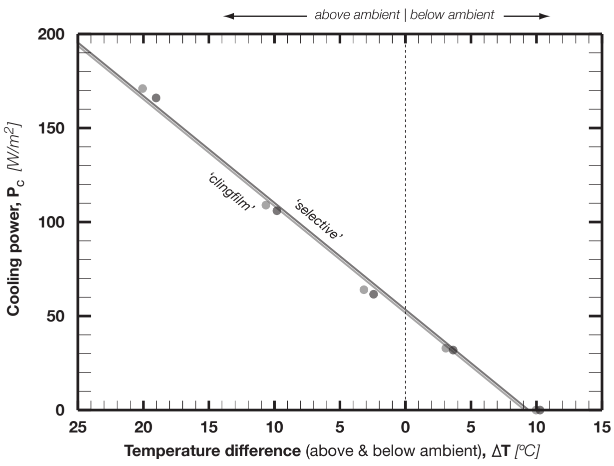
Figure 11. *'Clingfilm' vs. 'Selective'*



(i) Temperature over time for 'clingfilm' and 'selective' cooling plates, evening of May 8th 2008, London W1. Points A-D denote electrical powers (P_{el}) fed in.



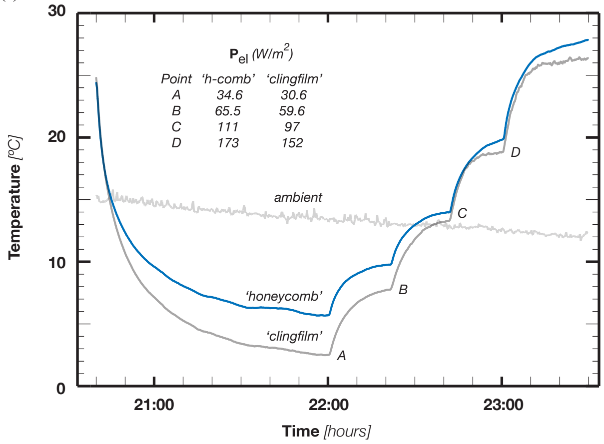
(ii) Measured cooling power (P_c) vs. temperature difference. Data taken from (i). The left side is temperature difference above ambient temperature; the right, below.



(iii) Solid lines show estimated radiated power (P_{rad}) vs. temperature difference. Dashed lines show power (P_{loss}) loss caused by non-radiative exchange for two values of heat transfer coefficient.

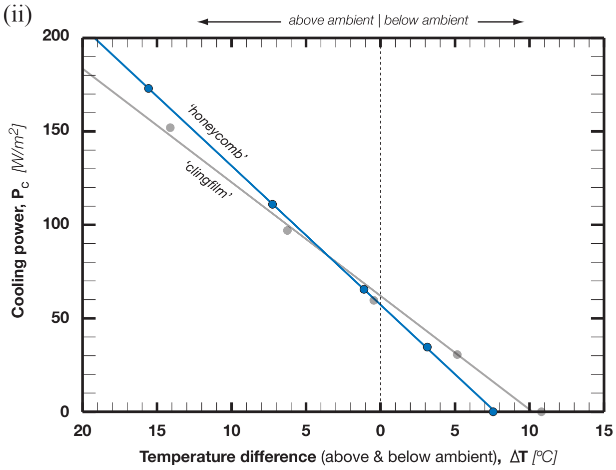
Figure 12. *'Clingfilm' vs. 'Honeycomb'*

(i)



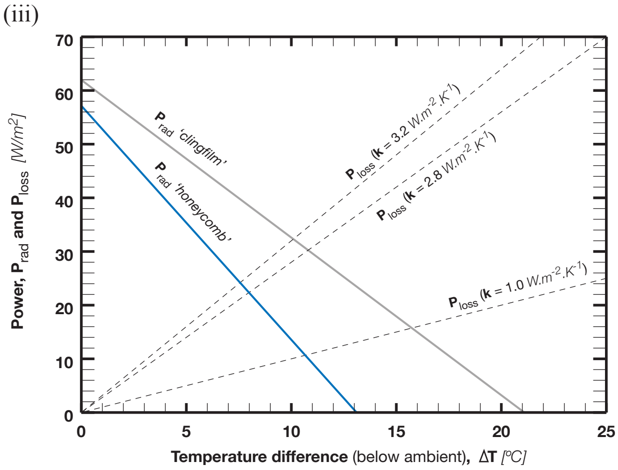
(i) Temperature over time for 'clingfilm' and 'honecomb' cooling plates, evening of May 2nd 2008, London W1. Points A-D denote electrical powers (P_{el}) fed in.

(ii)



(ii) Measured cooling power (P_c) vs. temperature difference. Data taken from (i). The left side is temperature difference above ambient temperature; the right, below.

(iii)



(iii) Solid lines show estimated radiated power (P_{rad}) vs. temperature difference. Dashed lines show power loss (P_{loss}) caused by non-radiative exchange for three values of heat transfer coefficient.

Figure 11 suggests that the selective film performs slightly better than polyethylene, although there is little practical difference. This is unexpected, as the LW transmission of polyethylene is supposed to be superior. Either errors in measurement are evident or this particular brand of polyethylene film is less LW transparent than the selective film.

6.3.3 'Clingfilm' vs. 'Honeycomb'

This experiment was undertaken on a clear evening on May 2nd 2008, when atmospheric pressure rose from 1022 to 1023hPa, relative humidity stayed around 70% with 9mph southerly winds. Recorded ambient temperature dropped from 15C to 12C (Figure 12(i)).

The graph in figure 12(ii) shows the 'honeycomb' and 'clingfilm' share similar intercepts at ΔT= 0 (57 and 62 W/m2 respectively), suggesting that the honeycomb cells are reflecting LW efficiently (92%). The stagnation temperature reached by the 'honeycomb' plate is lesser (ΔT = 7.6C compared to 10.8C for 'clingfilm') because it has a higher k value, attributable to vertical conduction through the aluminium tape. Why the two slopes for P_c diverge is unclear however. Perhaps, below ambient temperature, air stratifies in the cells like Johnson (1975) conjectured, while above ambient, mixing occurs. It would be interesting to see whether in stronger winds the honeycomb is better at stopping convection in the space between plate and film.

6.3.4 'Clingfilm' vs. 'Funnels'

This experiment was undertaken on a still and mostly clear evening on April 2nd 2008. Atmospheric pressure stayed at 1012hPa throughout; relative humidity and wind speed are unknown. Recorded ambient temperature started at 13C and did not drop below 11C (Figure 13(i)).

Unlike the 'honeycomb' sample, the cooling gradient for the 'funnels' sample is parallel to the 'clingfilm' sample. The aperture to base ratio of the 'funnels' sample is:

$$\frac{Total\ aperture\ area\ \left(m^2\right)}{Total\ base\ area\ \left(m^2\right)} = \frac{\left(0.25 - \left(8 \times 0.018\right)\right) \times 0.24}{0.25^2} = 0.41$$

But (when ΔT = 0),

$$\frac{P_{rad}\ '\mathit{funnels}'\ \left(W/m^2\right)}{P_{rad}\ '\mathit{clingfilm}'\left(W/m^2\right)} = \frac{29.9}{53.5} = 0.56$$

Hence the 'funnels' are delivering 56% of the radiative cooling power that the 'clingfilm' sample is delivering, where 41% might be expected. This 37% (0.56/0.41 = 1.37) in radiant flux (the total energy radiated per unit area) is promising for a set of un-optimised funnels. Note that the spaces between funnels can be filled with insulation without infringing on LW transmission (see section 6.1).

6.3.5 'Clingfilm' vs. 'Straws'

This experiment was undertaken on a mostly clear evening on May 6th 2008, when atmospheric pressure remained at 1021hPa, relative humidity rose from 67 to 82%, with an easterly wind of 8mph. Recorded ambient temperature dropped from just under 20C to just over 15C (Figure 14(i)).

The 'straws' took longer to reach stagnation temperature than the other samples. This meant only 4 measurements could be taken rather than the usual 5 for the time allowed (for security reasons the building had to be locked at midnight). Graph (i) shows that three of these were not left enough time to fully plateau. Hence the slope expressed for the 'straws' in graph (ii) is too steep, and the intercept unfairly high, although the minimum temperature reached is reliable. Passing clouds also added to the uncertainty. The last step of the 'clingfilm' temperature profile shows an upward kink where cloud cover increased (i).

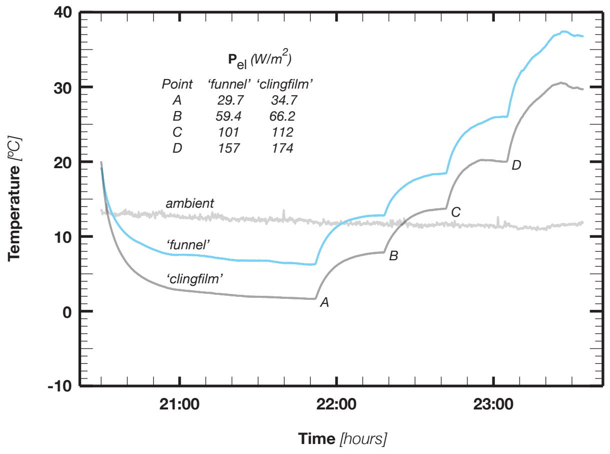
Nevertheless, this experiment does indicate the importance of reflectivity of the cell walls for radiant transfer. The increased time taken to stagnate suggests that a considerable amount of LW energy from the plate was being absorbed into the structure, making heat transfer by conduction more dominant.

6.3.6 'Clingfilm' vs. 'Foam'

This experiment was undertaken on a gusty evening on May 12th 2008. Atmospheric pressure rose from 1016 to 1018 hPa, and relative humidity was in the high 70s. A north-easterly wind of 15mph was punctuated by gusts of up to 26mph, which led to the experiment being abandoned after 2 hours. Ambient temperature fell inconsistently from 16C to 13C. The cloud cover changed throughout also; the effect is most clearly seen for the 'clingfilm' temperature profile before points B and C (Figure 15(i)).

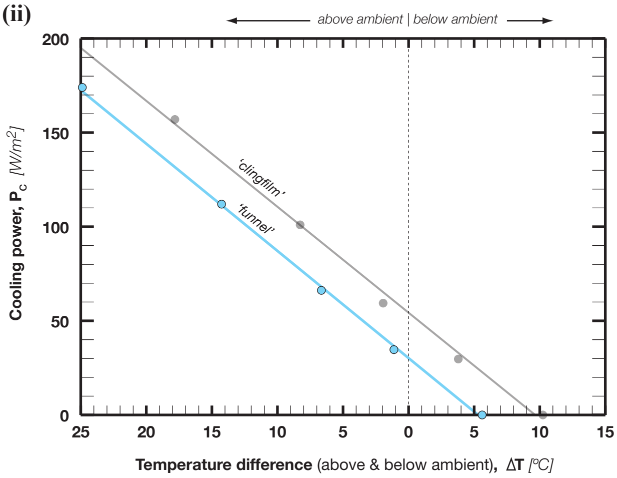
Figure 13. *'Clingfilm' vs. 'Funnel'*

(i)



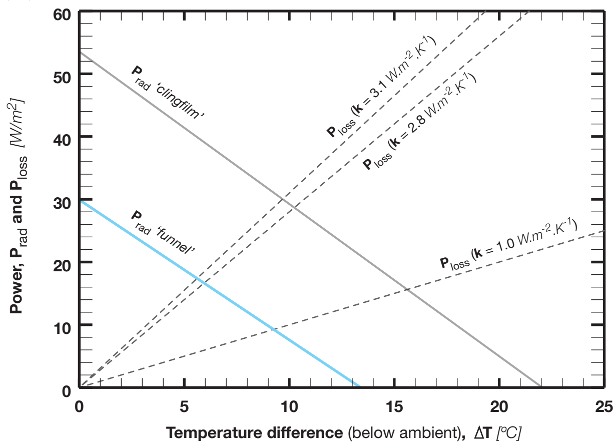
(i) Temperature over time for 'clingfilm' and 'funnel' cooling plates, evening of April 22nd 2008. Points A-D denote electrical powers (P_{el}) fed in

(ii)



(ii) Measured cooling power (P_c) vs. temperature difference. Data taken from (i). The left side is temperature difference above ambient temperature; the right, below.

(iii)



(iii) Solid lines show estimated radiated power (P_{rad}) vs. temperature difference. Dashed lines show power loss (P_{loss}) caused by non-radiative exchange for three values of heat transfer coefficient.

A comparatively low stagnation temperature was reached by the 'foam' sample (ΔT=6.2C compared to 7.3C for 'clingfilm'). This is because of the lower *k* value (2.4 compared to 2.8 W.m-2). Because of the gusty conditions, the 'foam' sample had an unfair advantage over the 'clingfilm', since the measurements for *k* were taken in very still conditions. Still, radiative cooling below ambient temperature was evident, suggesting that there is scope to specify a very low density polyethylene foam for a radiative cooling application, although this may need to be several orders of magnitude less dense than the range of PE foams currently on the market. The measured relative density was 0.007 kg/m^3; (see figure 8); the lowest relative density for a commercial closed cell PE foam we have found was 25 kg/m^3.

6.4 Discussion

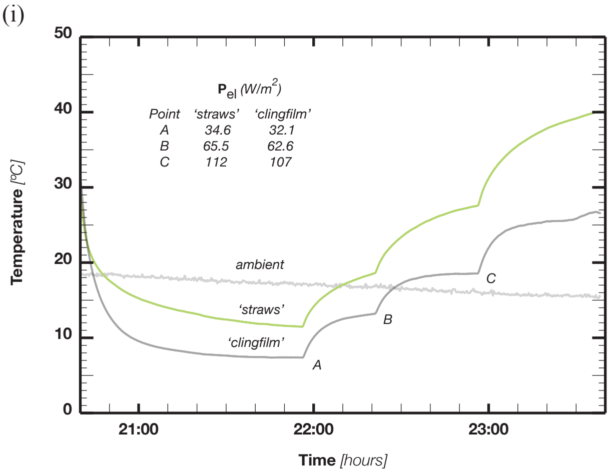
The results were normalised against the experiment that took place on May 2nd (figure 16). Because the selective film performed very similarly to the LDPE (see section 6.2), the 'clingfilm' slope has been removed. The normalised results are divided into two groups: 'reflective' (figure 16.a(i) honeycomb and funnels) and diffusive (figure 16.b(i) straws and foam) for clarity and fairness (the results for the latter group are less reliable). The radiative cooling performance of all samples would be better had the test panels been bigger to lessen edge effects.

The 'reflective' samples are characterised by higher intercepts and steeper gradients for cooling power, while the 'diffusive' samples have lower intercepts and shallower gradients. For cooling below ambient temperature, the ideal is to have a high intercept – a high radiative cooling power – and a shallow gradient – a low possible stagnation temperature. The 'reflective' samples had steeper gradients because they were made out of conductive materials, and hence had higher values for *k*. But there is scope for reducing *k* – perhaps to below 1 – without impinging on radiative cooling power. The conductive mass can be reduced by using reflective film instead of aluminium sheet. Internal convection can be reduced through hermetically sealing and arranging components hierarchically, as described. The 'dead' space between the funnels can be filled with high performance insulation, and the funnel geometry can be optimised to maximise radiative cooling power.

The results suggest that the *funnels* concept, and *sealed baffles* concept (represented by the 'honeycomb' sample in the experiment) have scope for being developed into robust heat selective roof panels for free cooling below ambient temperature.

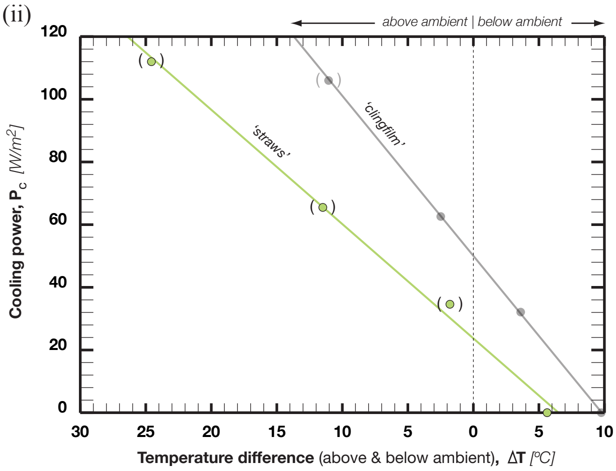
Figure 14. *'Clingfilm' vs. 'Straws'*

(i)



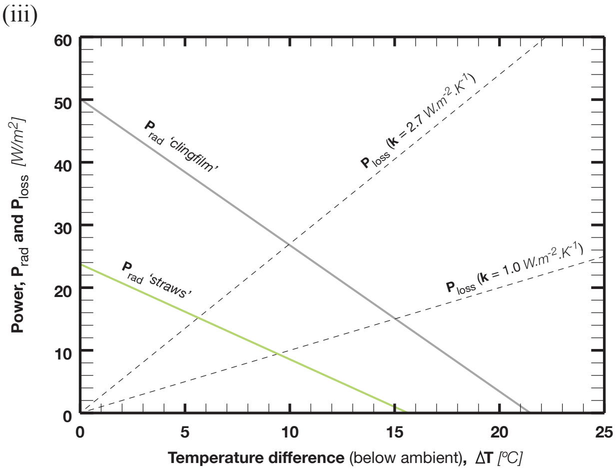
(i) Temperature over time for 'clingfilm' and 'straws' cooling plates, evening of May 6th 2008. Points A-D denote electrical powers (P_{el}) fed in.

(ii)



(ii) Measured cooling power (P_c) vs. temperature difference. Data taken from (i). The left side is temperature difference above ambient temperature; the right, below.

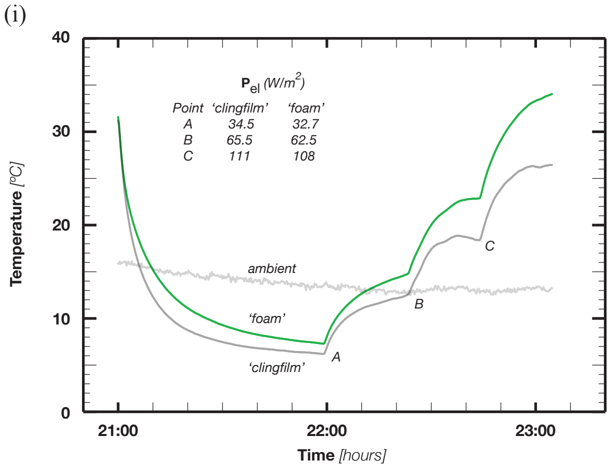
(iii)



(iii) Solid lines show estimated radiated power (P_{rad}) vs. temperature difference. Dashed lines show power loss (P_{loss}) caused by non-radiative exchange for two values of heat transfer coefficient.

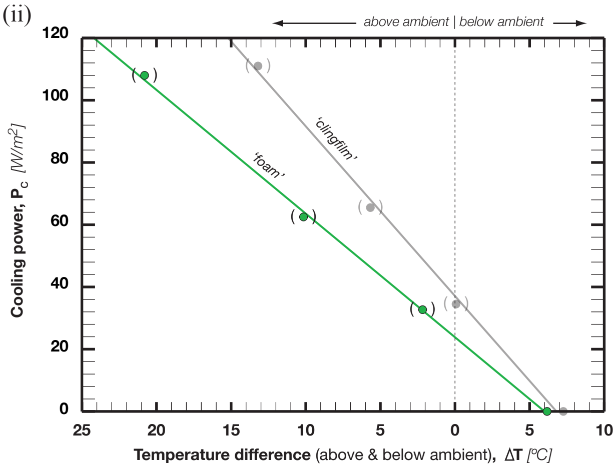
Figure 15. 'Clingfilm' vs. 'Foam'

(i)



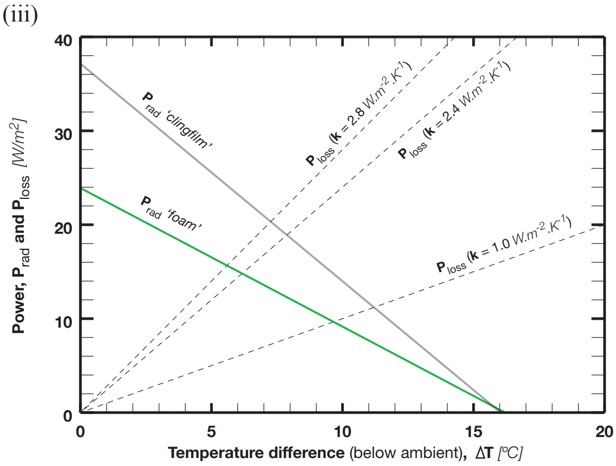
(i) Temperature over Time for 'clingfilm' and 'foam' cooling plates, evening of May 12th 2008, London W1. Points A-D denote electrical powers (P_{el}) fed in.

(ii)



(ii) Measured cooling power (P_c) vs. temperature difference. Data taken from (i). The left side is temperature difference above ambient temperature; the right, below.

(iii)



(iii) Solid lines show estimated radiated power (P_{rad}) vs. temperature difference. Dashed lines show power loss (P_{loss}) caused by non-radiative exchange for three values of heat transfer coefficient.

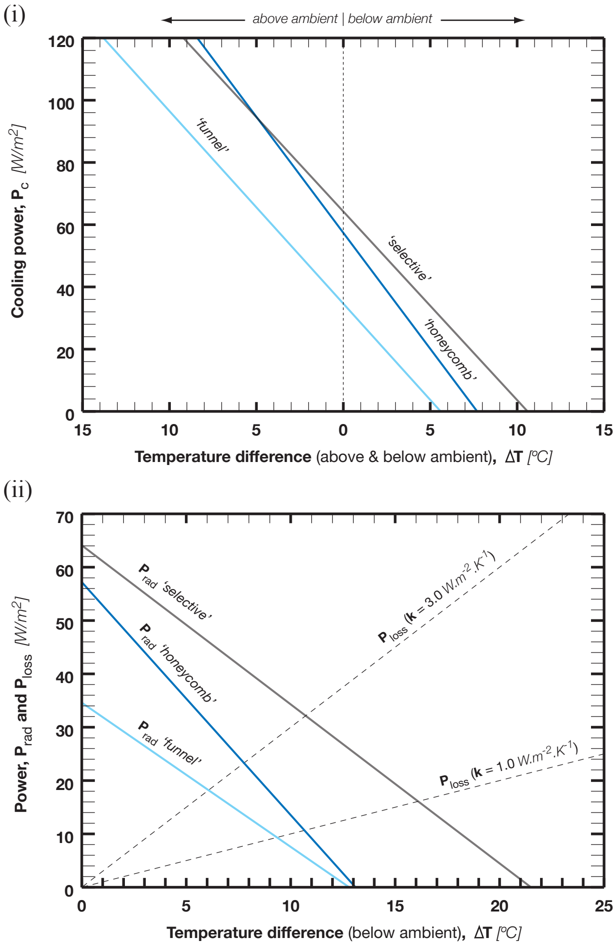


Figure 16a. *Normalised comparison of 'reflective' samples. (i) Normalised cooling power (P_c) vs. temperature difference. The left side is temperature difference above ambient temperature; the right, below. (ii) Solid lines show normalised radiated power (P_{rad}) vs. temperature difference. Dashed lines show power loss (P_{loss}) caused by non-radiative exchange for three values of heat transfer coefficient.*

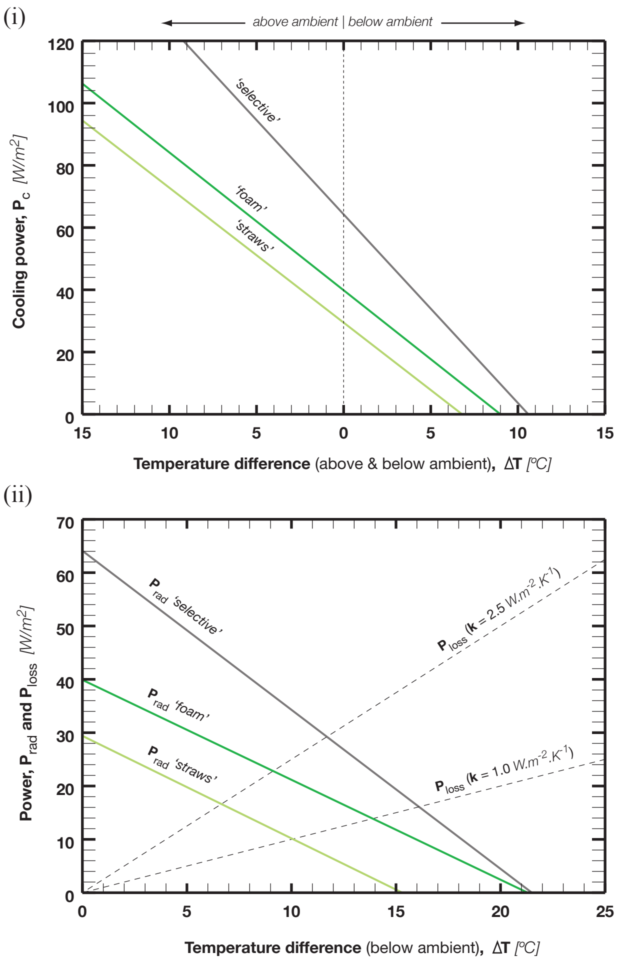


Figure 16b. *Normalised comparison of 'diffusive' samples. (i) Normalised cooling power (P_c) vs. temperature difference. The left side is temperature difference above ambient temperature; the right, below. (ii) Solid lines show normalised radiated power (P_{rad}) vs. temperature difference. Dashed lines show power loss (P_{loss}) caused by non-radiative exchange for three values of heat transfer coefficient.*

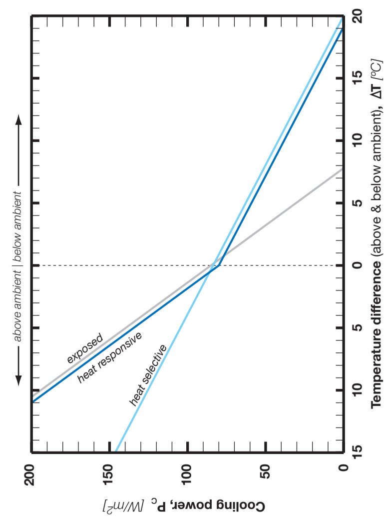


Figure 17. *Ideal behaviour of heat-responsive insulation*

The results also help characterise a more advanced heat *responsive* insulation. When the radiator is at ambient temperature, and the aim is to cool the radiator below ambient temperature, then convective exchange is harmful, hence the motivation to reduce the value for *k*. However, if the radiator is above ambient temperature, convective exchange is useful, because the radiator cools quicker. Ideally, convective exchange could be turned 'on' then 'off' during cooling, as shown in figure 17. Furthermore, both convective and radiative exchange should be turned 'off' during winter.

Conclusion

Proof-of-principle prototypes were built based on some of the concepts for 'heat-selective' insulation presented in the previous chapter. Tests were carried out during April and May nights on an office roof in central London. Test panel temperatures fell to 6 and 13 degrees below ambient temperature. Radiative cooling powers between 25 and 70 W/m^2 where recorded when cooling plates were at ambient temperature. At 20 degrees above ambient, total cooling powers of between 90 and 200 W/m^2 were observed. Daytime radiative cooling below ambient temperature was evident when clouds blocked direct sunlight. Radiative cooling power was increased by 37% using reflective 'funnels'. The results indicate that a robust, heat-selective roof panel is technically feasible, designed for large enclosures in hot climates, such as transport hubs and exhibition halls. Better focussing and direction of longwave thermal radiation would be required to get useful radiative cooling for multi-storey buildings in built-up areas, because of the small ratio of sky view to floor space.

Chapter 7

TWO MORE BioTRIZ CASE-STUDIES

Abstract

Two additional concepts for new building technology based on BioTRIZ principles are presented. Like heat-selective insulation, both case-studies are ultimately about making better use of naturally occurring heat sinks to reduce energy demand in buildings. Unlike heat-selective insulation, these two additional case-studies are examples of *technology-push* innovation, where the aim is to find the right application for a given technology. The first case-study describes the conceptual design of a sacrificial formwork product for concrete structures, made from extruded starch foam. The idea is to use it to 'unlock' the thermal mass in buildings, by creating concrete elements with empty networks inside them, so that cool night air can be passed through to discharge the mass of accumulated heat more effectively. BioTRIZ principles inspired the multifunctional hierarchical spiral-form of the void-former concept. The second case-study describes the design of a range of office products made of phase-change materials which store latent heat. Hitherto this type of material has been integrated with limited success into building fabrics where a thermal compromise occurs. BioTRIZ principles suggested segmenting the required volume and putting each part under the control of occupants. The energy- and material-saving attributes of the concepts presented in each case-study remain to be tested. Nevertheless, the case-studies serve to illustrate how the BioTRIZ method can help translate biomimetic principles into different engineering contexts.

7.1 'Unlocking' thermal mass with biodegradable starch foam

Buro Happold and Brunel University are involved with other industrial partners in a government funded research project to find wider applications for biodegradable expanded starch-foam (ESF) (Song 2001, Song et al. 2007), which is enjoying some success in the packaging industry as an alternative to expanded polystyrene foam (EPS). Planks of starch-foam are made by bringing five square-sectioned rods together in one continuous pultrusion process; only slight wetting of the sides with water is needed to glue the rods together. Figure 18 shows how the planks can be arranged in blocks to form macrostructures that perform differently under compression.

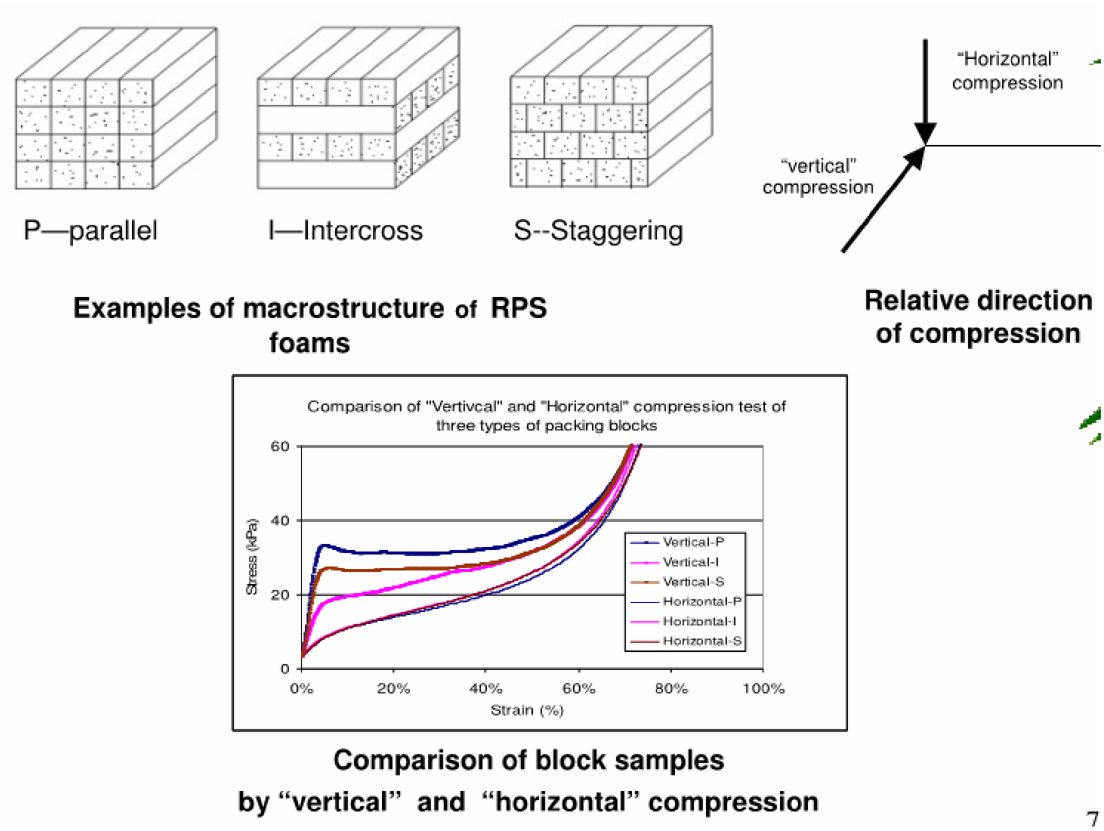


Figure 18. *The effect of interface distribution on compression characteristics of blocks of starch foam planks (Song et al. 2007)*

Concrete formwork was seen as one possible entry point into construction for this technology. There are many different techniques for forming concrete using different materials; the choice of which to use depends on many factors, including the function of the concrete form and cost (The Concrete Society 1995). EPS is used for a wide variety of jobs in building and civil engineering, including complex geometries, and sacrificial formwork for creating internal voids, where wet concrete is poured over the foam, and, depending on the function of the void, it is either left in or flushed out with solvents. Other materials used for void-formers include cardboard, thin sheet metal and plastic (The Concrete Society 1995). Our idea was that ESF might provide an alternative to these and EPS.

Voids in concrete can fulfil multiple functions. One type of pre-cast concrete slab has an internal void-network which plays a structural and thermal role. The voids reduce weight and create a passage way for cool night air to pass through and discharge the slab of heat accumulated during the day, thereby 'unlocking' the thermal mass in a building (Barton *et al.* 2002, see Figure 19). This is the same principle applied by Arup associates in the Central Electric Building (see Part I, section 3.2.2). The pre-cast concrete slabs are formed by pultrusion, which places firm limits on the complexity of geometry achievable (only smooth circular channels) and it has been suggested that measures such as roughening the internal surface and changing the internal geometry might improve performance (Barnard 1995). Internal geometries such as a 'corkscrew' or louvered fins might give better heat transfer for the same pressure drop (Wadley 2006). Our idea was to develop an ESF product to form such internal geometries. To perform this function successfully, it should not dissolve on contact with wet concrete (it is very water-soluble), it would have to hold shape under buoyant load, and it would have to be simple to flushout afterwards with water.

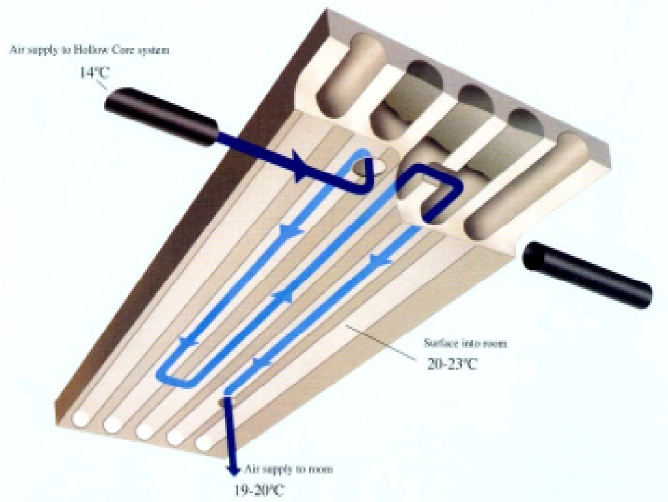


Figure 19. *A Termodeck slab. (www.termodeck.com). Cool night air can be fed through the concrete slabs to discharge them of heat accumulated during the day. This makes the concrete structure function more effectively as thermal mass, and reduces energy demand for cooling. But the slab manufacture process puts limits on the internal geometry. Spirals might exchange heat better than smooth channels without a debilitating increase in fan power.*

7.1.1 BioTRIZ analysis

The multiple functions that the foam will need to perform in this application create several conflicts. The primary function is to create a void in the concrete with a geometry that improves heat transfer without increasing fan power. A corkscrew form is one candidate, which works partly on account of the increased surface area (6 *Area of stationary object,* see table 1) (see Wadley 2006). Another way of describing this attribute is parameter 12, *Shape*. Either way, the attribute is spatial (see table 3). Such forms are often complex to manufacture (32 *Ease of manufacture)*, which is a structural issue according to table 3. In summary, that the desired geometry will be difficult to manufacture is therefore a *Space* vs. *Structure* conflict.

Starch-foam is highly water-soluble; wet concrete is wet. The foam needs to be isolated from the wet concrete so that the capillaries don't suck in water. The mechanical properties of the foam change with humidity and it decreases in size. Clearly the foam needs be separated in *space* from water droplets and water vapour. Whatever the make-up of this boundary, it can be thin, on the scale of micrometres or millimetres. And it only needs to function for as long as it takes the concrete to cure; a matter of hours or days. It could also take on some responsibility for making the product robust during transportation and storage.

Operational field	**Inventive Principle**	**Conflict**	
		Space vs. Structure	Energy vs. Substance
Substance *Add, remove, change properties of a material*			
Structure *Add, remove, regroup structural parts*	1. Segmentation 2. Extraction 3. Local Quality 5. Merging	 X X X	X X
Energy *Change energy source or field*			
Information *Change interactions or regulation of a system or its elements*	13. The other way around 25. Self-service		X X
Time *Change speed of process or order of its action*	10. Preliminary action 15. Dynamics 19. Periodic action	X X X	
Space *Change position or shape of system or parts*	4. Asymmetry 14. Curvature 17. Another dimension 25. Porous materials	X	 X X X

Table 7. *BioTRIZ suggests these principles for resolving two conflicts (Energy vs. Structure and Energy vs. Substance) that arise when using starch foam as a concrete void-former. No 'energy' or 'substance' strategies are offered.*

Whatever the external geometry and whatever the form of water-proofing, the foam must hold shape when submersed in wet concrete. The foam will float and like other void-formers will need to be restrained. The buoyancy forces (11 *Stress or pressure;* Energy) experienced by the foam could be used to manipulate the form in some useful manner, but the foam must not fail. (The relationship between buoyancy force and void-former diameter is shown in figure 21). The ability to withstand buoyancy force should be fulfilled using minimum material (26 *Quantity of substance;* Substance) for two reasons. Firstly, material throughput should be minimised generally in order to reduce environmental impact. Secondly, the less material used, the easier it will be to flushout the foam once the concrete has cured. Less water at lower pressures will be required, and less grain, hence less agricultural land, will be taken up in its production. In summary, the need to withstand buoyancy force with minimum material is an *Energy vs. Substance* conflict.

The inventive principles offered by BioTRIZ to resolve space vs. structure and energy vs. substance conflicts are shown in table 7, organised by operational field. No inventive principles were offered that involve the manipulation of substance or energy. This suggests there are alternatives to adjusting the properties of the starch-foam material. Perhaps the conflicting requirements can be met by adding more structure, using the given ESF rod as a building block in combination with shape and space. This result is in line with the lessons learnt by biologists studying hierarchical biological materials and advocated by several practitioners in the biomimetics field (see Part I section 2.2).

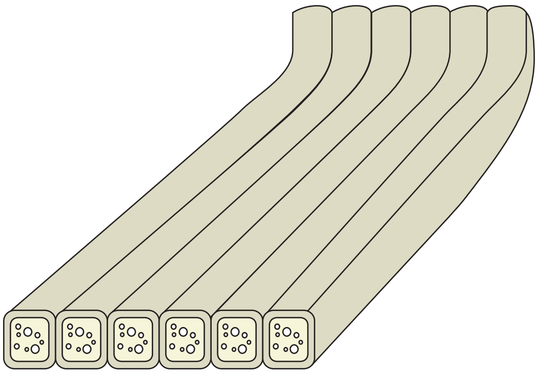
7.1.2 Concept

A concept based on the biological principles arrived at using BioTRIZ is shown in figure 20. The corkscrew void it would leave behind in the concrete may increase the rate of heat transfer without a detrimental increase in fan power. The idea is that this may help buildings reduce their cooling energy demand by making better use of diurnal swings in external temperature.

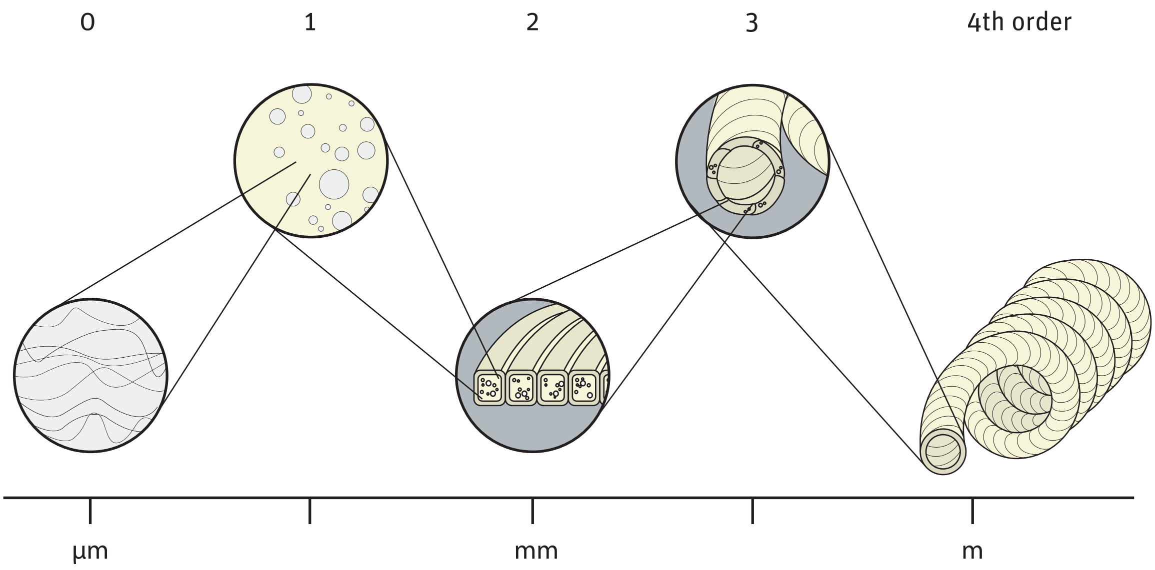
The starch-foam void-former design is meant to hold shape under buoyancy forces for less material than a bulk material equivalent. It is also meant to require less water at lower pressures to flush-out afterwards. The foam can be encapsulated in some film, membrane or 'skin' to isolate it from water and water vapour in order to stop it from dissolving prematurely and decreasing in size when submerged in wet concrete. This membrane could be starch-based, attached or formed as part of the extrusion and pultrusion process. Or it could simply be placed in suitable biodegradable refuse bag and sealed.

The double-hollow spiral is meant to be easy to manufacture and adapt for different requirements. The process of manufacture is meant to be a continuation of the extrusion and pultrusion process already in place to make ESF planks. The sides of the planks are made sticky by wetting them before spiralling the planks into tubes of the required diameter. Then the tubes themselves are wetted so that they can be spiralled once more. This manufacture method would in principle result in very little waste

Figure 20. *Starch void-former concept based on biomimetic principles suggested by BioTRIZ*



The starch foam comes in planks, five rods wide. The rods are extruded then pultruded to make them square and stick together. The heat, pressure and water make the edges denser.



The planks already have at least two structural levels of hierarchy. Twisting a plank twice round – going from plank to tube to spiral – adds two more. Adding structure means it may resist known buoyancy forces for less material than a bulk equivalent. Bagging it makes it waterproof. A length is restrained and concrete poured over it to form a building slab. When the concrete has cured, the foam is flushed out to reveal an empty cork- screw. With several slabs installed in a building, cool night air can be passed though the empty corkscrew channels to discharge the building of heat during the summer. This helps reduce demand for air-conditioning.

Figure 21. *Buoyancy force on different sized cylinders submerged and restrained in wet concrete 250mm deep*

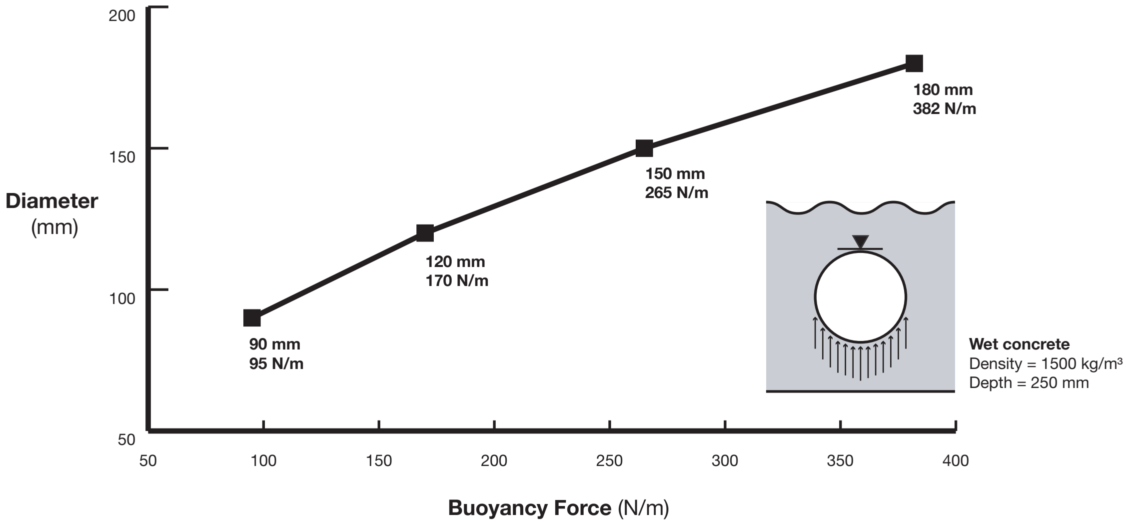
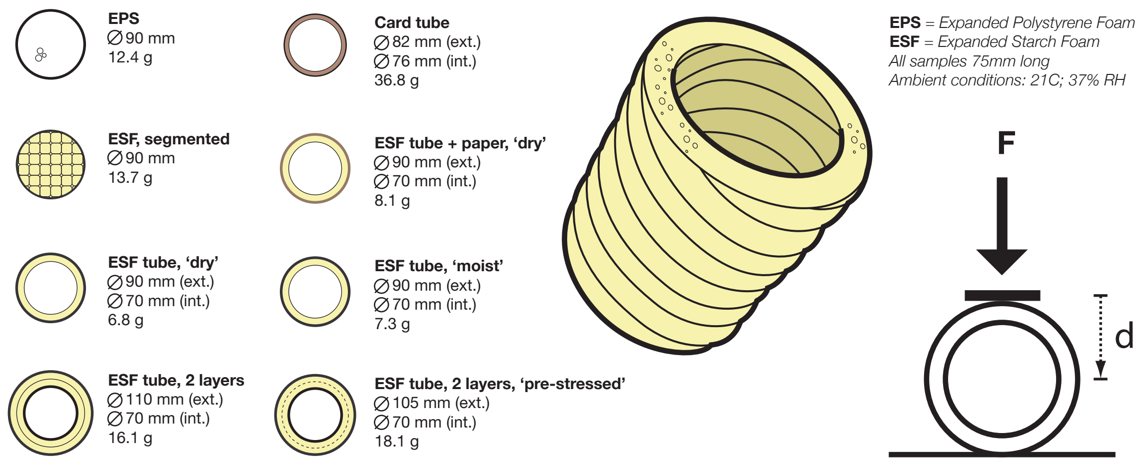
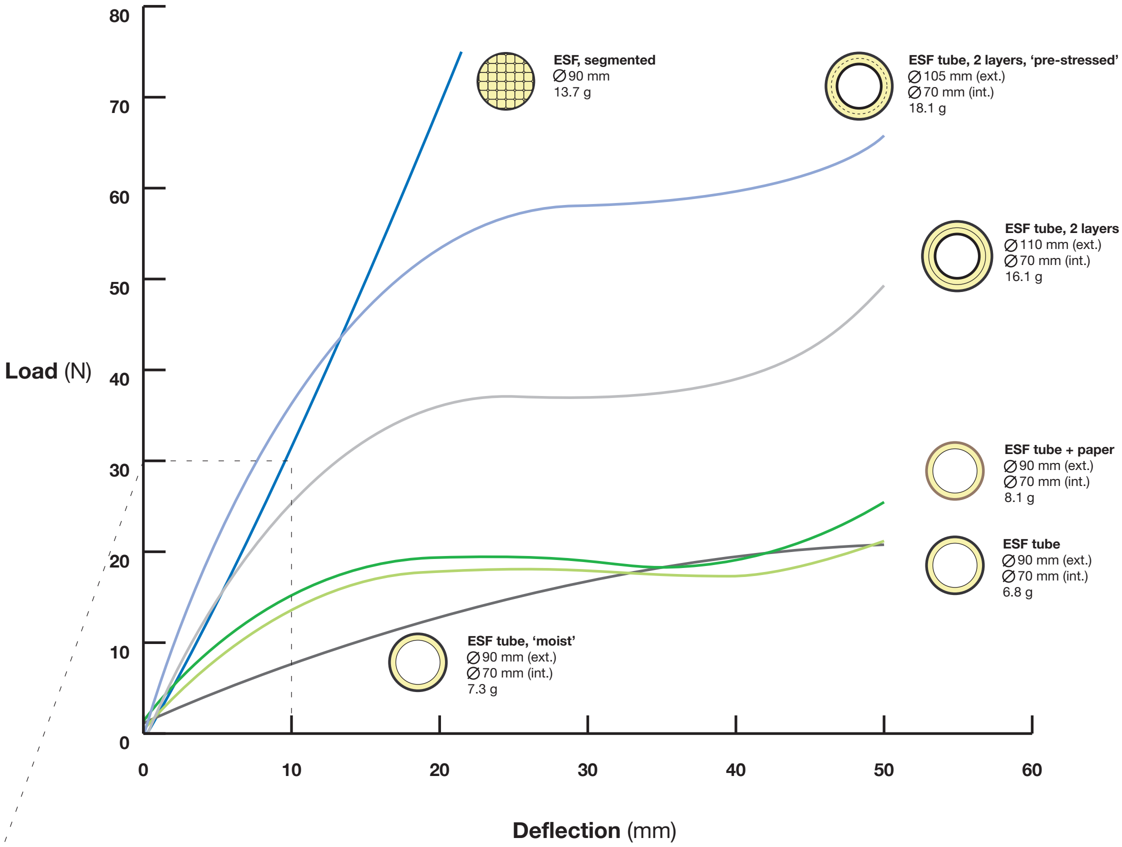


Figure 22. *Samples and set-up of load-deflection test*





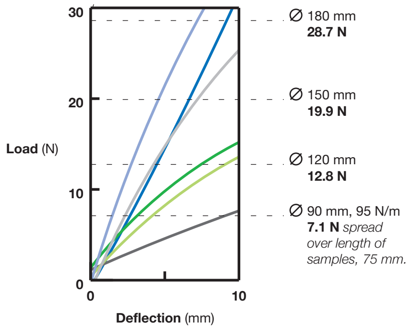
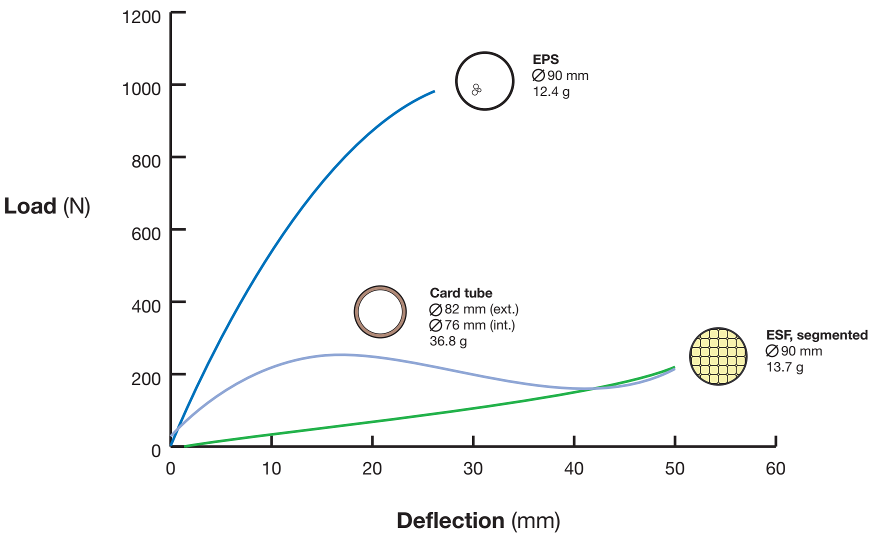


Figure 23. *Load-deflection of tubular concept ESF void-formers (above). Two established void-formers vs. ESF segemented cylinder (below). ESF tubes and spirals (see figure 20) have yet to be tested under hydrostatic pressure. But these results suggest an ESF tube or spiral could be designed to bear hydrostatic pressures when submerged under wet concrete (see insert, left, and figure 22). EPS and cardboard void-formers may be 'overdesigned'.*



material, and the product may have many possible applications where structural protection or support is required temporarily.

A prototype of the concept has been hand-made in a humid room using the ESF planks, but has yet to be tested under the buoyancy forces it would be subjected to in the proposed application. Neither has the idea that an internal corkscrew network could help make night-cooling more effective been tested. However, the load-deflection characteristics of starch-foam tubes are given (see figure 22 and 23) to support the notion that in this case, the manipulation of structure may offer a viable alternative to the manipulation of substance.

7.2 PCM office products

Phase change materials (PCM) and the various ideas for integrating them into buildings were introduced in Part I, section 3.4.3. The advantage of putting PCM into a building envelope compared to conventional (sensible) thermal mass is that PCM can, in spite of external temperature fluctuations, maintain a constant internal temperature for a certain amount of time (Asan and Sancaktar 1998). In contrast, building materials with constant thermo-physical properties will follow the fluctuation in external temperature continuously. It has been suggested that dolphin blubber, with its fatty acid composition, functions as a phase change material (Dunkin *et al.* 2005).

Gideon Susman, a fellow research engineer with Buro Happold and Brunel University who is half way through the Engineering Doctorate program, is looking at, among other things to do with thermal energy storage in the built environment, how PCMs can be better utilised passively and actively in buildings. In collaboration with him and one building services engineer from Buro Happold, opportunities for new applications of PCMs in buildings were categorised. This case-study demonstrates how some of the key problems can be framed using BioTRIZ, and presents some of the concepts generated collaboratively that can be classified as biomimetic according to the results of the BioTRIZ analysis.

7.2.1 BioTRIZ analysis

For PCM to absorb the thermal energy that would otherwise raise the temperature of a room, it needs to be responsive enough to ‘charge’ and ‘discharge’ effectively. Therefore, apart from a high volumetric thermal capacity (by virtue of its high latent heat density), an ideal PCM should have high thermal conductivity (Zhang *et al*. 2006). Unfortunately the building-suited PCM's under study in academic circles and those commercially available have low thermal conductivity. There have been many attempts to increase the conductivity of PCMs without compromising volumetric thermal capacity, including the use of finned tubes, high conductivity particle dispersion, and embedded metal or graphite-matrix structures.

The conflict between volumetric heat capacity and thermal conductivity can be framed in two different ways using BioTRIZ. It can be seen as an 'energy' vs. 'energy' conflict, using the parameters that refer to the thermal condition of the substance and the way the room imparts thermal energy upon it. In this case the problem is the same as that faced and resolved in the heat-selective insulation case study (see chapter 5). Or the problem of conductivity can be seen as a temporal issue, as in the rate of heat transfer. Hence the problem can be framed as 'energy' vs. 'time'.

Operational field	**Inventive Principle**	**Conflict**	
		Substance vs. Space	Space vs. Space
Substance *Add, remove, change properties of a material*	36. Phase transition		X
Structure *Add, remove, regroup structural parts*	1. Segmentation 5. Merging	X X	 X
Energy *Change energy source or field*			
Information *Change interactions or regulation of a system or its elements*	13. The other way around	X	
Time *Change speed of process or order of its actions*	15. Dynamics	X	
Space *Change position or shape of system or parts*	4. Asymmetry 14. Curvature 17. Another dimension 31. Porous materials	 X	X X X

Table 8. *BioTRIZ suggests these principles for resolving two conflicts associated with making use of Phase Change Materials for passive thermal energy storage.*

The problem takes on a different angle when specifying particular commercial products, such as the Energain panel. These are wall-boards developed by DuPont (2007) consisting of a 5mm PCM layer (a shape-stabilised paraffin wax) encapsulated between micron-thin aluminium faces. The panels are meant to be installed behind plaster-board. Because the thickness of panel is standard, the issue becomes that of the ratio of surface area available on the walls to the volume of the room. Long corridors are ideal, but deep plan office spaces are not. The problem framed in this way is a 'space' vs. 'space' conflict.

Being installed inside does not help the panels to discharge and re-solidify at night. Unless the windows are left open or there is an active night-cooling mechanism, the panels are isolated from the cool night air. This problem can also be seen as a 'substance' vs. 'space' conflict, because at that point in time the PCM substance is spatially isolated from the natural heat sink.

The inventive principles that BioTRIZ suggests could resolve 'substance' vs. 'space' and 'space' vs. 'space' conflicts are shown in table 8.

7.2.2 Concepts

Changes to the shape of the PCM panels are strongly suggested to resolve the conflict between available surface area and the volume of the room. For instance, the surface area of the PCM could be increased by shaping it into louvered fins. Interestingly, if the panel was a *sensible* thermal storage product, we would have been pointed towards the idea of employing a phase change material (IP 36 *Phase Transition).* IP 5 *Merging* is here interpreted as looking for surfaces other than the walls to cover with PCM.

This idea is taken further when contemplating IP 1 *Segmentation*, which suggests fragmenting the PCM into independent parts. The question becomes that of how to best distribute the total volume of PCM throughout the room. In combination with IP 5 *Merging,* this represents the idea of distributing the required volume of PCM onto or into any range of objects that will be in the room, thereby increasing the combined surface area. This could include, for instance, desks and chairs, or any office product bought and manufactured in large quantities. This idea is reminiscent of when systems furniture was first designed to help reduce the impact of the acoustic and privacy issues experienced by occupants in densely packed open-plan offices (see Part I, section 3.3.2.).

More radical versions of this idea come about when considering IP 13 *The other way around* and IP 15 *Dynamics*. In their own ways, both suggest making each PCM segment mobile. Doing so could bring each part closer to a heat source (an occupant) for charging and closer to the heat sink (the night air) for discharging. This doesn't have

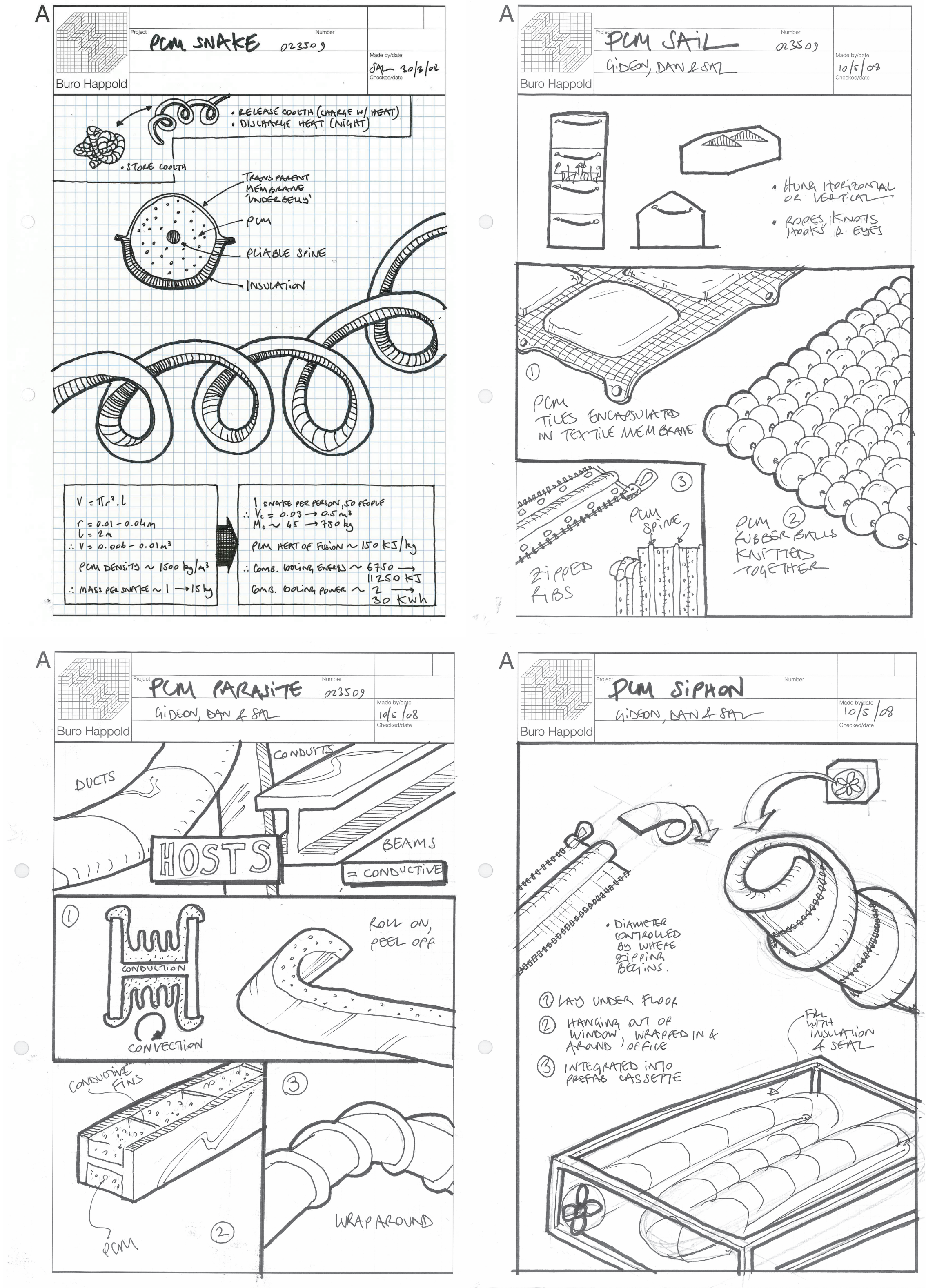


Figure 9. *PCM products based on biomimetic principles arrived at using BioTRIZ (see text). All involve segmenting and distributing a volume of PCM in and around the room when it would usually be integrated into the building fabric at some thermal compromise. PCM snakes (above left) are desktop products given to each occupant, put outside at night to discharge. Charging can be controlled by wrapping and unwrapping. PCM sails (above right) are hung above occupants for radiative cooling effect; they can also be brought outside for discharging. PCM parasites (below left) hug various conductive objects around the office, such as exposed beams and ducts. PCM syphon (below right) is a flexible tube with PCM inside and a fan at one end, that can be placed in many ways around the office or integrated into prefabricated building elements. The fan end can be hung outside the window at night for discharging.*

to be done mechanically. Each occupant could be assigned both a desktop PCM product and the responsibility for taking it on the roof before going home. This localises thermal control, and opens up the possibility of using radiative cooling to the night sky to supplement PCM discharge. The PCM may solidify even if the night ambient temperature was too warm, thus extending its range of operation over the summer.

Figure 24 shows a range of concepts based on these principles, and figure 25 shows the cooling cycle that needs to occur if some of the concepts are to work effectively.

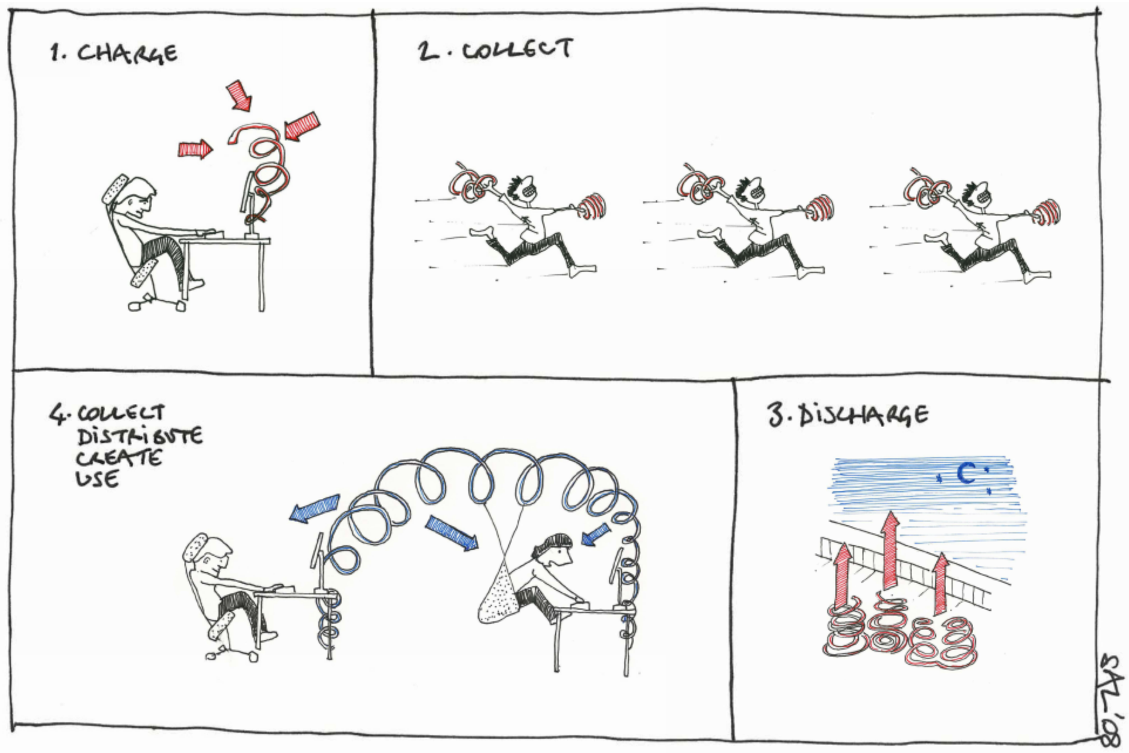


Figure 25. *The cooling cycle for desktop PCM office products*

The concepts for heat-selective insulation become relevant not only to help PCM solidify outdoors (see chapter 5 and 6). They also become relevant indoors. Hung PCM panels with infrared transparent insulation could offer occupants radiant comfort cooling without the PCM melting prematurely on account of warm internal temperatures. The internal air does not necessarily need to be cooled; the occupants do.

Is there anything similar between these concepts and the way 'nature' might do things? Vincent *et al.* (2006) observed that biological solutions were rarely implemented at the same level of the system hierarchy that the problem occurred. Biological solutions are highly contextual, relying heavily on integration between system levels. Highly contextual approaches of this kind are generally avoided by engineers. The aim is usually to avoid conditions from which unpredictable emergent effects can arise (RAE 2007). The inclination is to intervene at that point within the system hierarchy where the problem occurs, and solve it there.

The more radical concepts presented in this section involve the localisation of thermal control. Each individual controls an individual PCM segment, deciding when and where thermal charging and discharging is to occur. For the whole to function, a critical mass of occupants must work in concert. More detailed control is achieved if the modes of heat transfer are distinguished between and selected from, as in the example of tuning solely into radiative flows both inside and out. These are highly contextual solutions – a chain of successful interactions between system levels needs to occur for it to work.

Conclusion

Two additional minor case-studies are presented. They serve to illustrate how the BioTRIZ method can help translate biomimetic principles into different engineering contexts. The energy- and material-saving attributes of the concepts from either study remain to be tested. The first minor case-study describes the concept design of a sacrificial formwork product for concrete structures, made from biodegradable extruded starch foam. The idea is to use it to 'unlock' the thermal mass in buildings, by creating concrete elements with empty networks inside them, so that cool night air can be passed through to discharge the mass of accumulated heat more effectively. BioTriz principles inspired the multifunctional hierarchical spiral-form of the void-former concept. The second minor case-study describes the design of a range of office products made of phase-change materials which store latent heat. Hitherto this type of material has been integrated with limited success into building fabrics where a thermal compromise occurs. BioTriz principles suggested segmenting the required volume and putting each part under the control of occupants.

Chapter 8

CONCLUSIONS AND FURTHER WORK

8.1 Heat selective insulation

The most promising opportunities for developing new environmental technology, discovered while conducting the literature review (Part I), were in the field of radiative cooling, where very little commercial technology exists and academic activity is relatively sparse. Despite successful and ingenious prototypes from civilisations past, the sky is distinctly underutilised as natural heat sink for new developments in hot countries today. Like other renewable resources, suitably cool skies are available only intermittently. Nevertheless, under the right conditions, low-temperature heat can be rejected in the order of 100 W/m^2 without additional energy input.

Conflicting requirements are faced when attempting to cool a mass below ambient temperature through radiative interaction with the sky. This made it suitable for applying the new biomimetic problem-solving tool BioTRIZ. The use of the tool had yet to be demonstrated independently anywhere in the academic literature. In order to access low-energy biological responses to the problem, it was formulated in dialectical terms: the mass should be radiatively coupled to the sky, but thermally decoupled from ambient and solar gains. This statement was then translated according to the BioTRIZ framework into an 'energy vs. energy' conflict. The BioTRIZ look-up table offers seven principles for resolving this conflict. This implies that, based on the study of 3000 examples, biological systems have been seen to resolve this conflict in seven different ways.

Three of these principles inspired a form of infrared-transparent or 'heat-selective' insulation. An insulation that has the bulk property of infrared transparency does not yet exist and would therefore have to be created anew. But two of the three principles suggested that conventional insulation could be restructured around pathways that focus and channel longwave radiation. There is a clear biological analogy implied in this concept. The conflicting functions are resolved by the structural and spatial arrangement of subsystems, rather than the manipulation of bulk material properties or a non-native energy source. However, the results offered by the original TRIZ matrix for the same problem imply that this structural approach is well represented in the human engineering repertoire. On the other hand, the statistically condensed version of the original TRIZ matrix suggests engineers are less likely to adopt a structural strategy for ‘energy vs. energy’ problems.

Proof-of-principle prototypes were built based on some of the concepts for ‘heat-selective’ insulation arrived at by using BioTRIZ. Tests were carried out during April and May nights on an office roof in central London. Test panel temperatures fell to between 6 and 13 degrees below ambient temperature. Radiative cooling powers between 25 and 70 W/m^2 where recorded when cooling plates were at ambient temperature. At 20 degrees above ambient, total cooling powers of between 90 and 200 W/m^2 were observed. Daytime radiative cooling below ambient temperature was evident when clouds blocked direct sunlight. Radiative cooling power was increased by 37% using reflective ‘funnels’. The results indicate that a robust, heat-selective roof panel is technically feasible, designed for large enclosures in hot climates, such as transport hubs and exhibition halls. Better focussing and direction of longwave thermal radiation would be required to get useful radiative cooling for multi-storey buildings in built-up areas, because of the small ratio of sky view to floor space.

The concept that most clearly merits further development is the one that uses reflective funnels to direct longwave radiation. These funnels simultaneously create more space for conventional insulation and other roof-top functions. The geometry of the funnels is yet to be optimised, and improvements on 37% increased flux are expected. Other functions can be integrated into the panel, including ‘cold’ visible light direction from outside to inside.

8.2 Concrete void-former and PCM office products

Two additional minor case-studies were presented to illustrate how BioTRIZ can be used to impose a view on a problem and set-forth a ‘low-energy’ direction in which to follow. Both case studies are about employing a material in a novel way in order to make better use of natural heat sinks and reduce energy consumption in buildings.

The first minor case-study describes the concept design of a sacrificial formwork product for concrete structures, made from biodegradable extruded starch foam. The idea is to use it to ‘unlock’ the thermal mass in buildings, by creating concrete elements with empty networks inside them, so that cool night air can be passed through to discharge the mass of accumulated heat more effectively. BioTriz principles inspired the multifunctional hierarchical spiral-form of the void-former concept. The second minor case-study describes the design of a range of office products made of phase-change materials which store latent heat. Hitherto this type of material has been integrated with limited success into building fabrics where a thermal compromise occurs. BioTRIZ principles suggested segmenting the required volume and putting each part under the control of occupants.

The two case-studies serve to illustrate how the BioTRIZ method can help translate biomimetic principles into different engineering contexts. The energy and material saving attributes from either remain to be tested. Clearly this would be the place to start for further development. It is felt that the PCM office products have a much larger market potential than the starch-foam void-former. But the latter could be developed into a wider range of concrete formwork products to compete with expanded polystyrene in civil engineering applications. The environmental profile of the starch-foam competitor would need to be closely analysed before any environmental benefit was claimed. The PCM office products will continue to develop under the umbrella of Gideon Susman's EngD research project.

8.3 Restatement of theses and contributions

The objective of this research project was to develop a new low-energy building technology into a prototype that demonstrated its principle of operation. An opportunity was found in the field of radiative cooling. A concept for a new 'heat-selective' insulation was developed. Tests showed that a mass can be cooled below ambient temperature by nesting pathways in surrounding insulation that channel longwave radiation toward a cool sky. This result forms the first contribution to knowledge of this thesis.

The second contribution was in demonstrating how the biomimetics design tool BioTRIZ can be used to impose a framework on a technical problem from which solutions that may lead to reductions in energy and material throughput can be conceived and evaluated. A BioTRIZ radiative cooling analysis was published in the Journal of Bionic Engineering. It was the first independent BioTRIZ study in the academic literature. Two other minor case-studies were presented in this thesis to further illustrate how the tool can be used to solve problems faced during low-energy building design.

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APPENDIX A

BioTRIZ radiative cooling analysis published in the Journal of Bionic Engineering

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BioTRIZ Suggests Radiative Cooling of Buildings Can Be Done Passively by Changing the Structure of Roof Insulation to Let Longwave Infrared Pass

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Abstract

This paper demonstrates the application of a design tool called BioTRIZ. Its developers claim that it can be used to access biological strategies for solving engineering problems. Our aim is to design a roof for hot climates that gets free cooling through radiant coupling with the sky. The insulation in a standard roof stops the sun and convection from warming the thermal mass. But it also restricts the mass's longwave view of the cool sky. Different solutions to this conflict are offered by BioTRIZ. The chosen solution is to replace the standard insulation component with an open cell honeycomb. The vertical cells would allow longwave radiation to pass, while arresting convection. The solutions offered by BioTRIZ's technological counterpart include no such changes in structure. It is estimated that the thermal mass in the biomimetic roof would remain on average 4.5˚C cooler than in a standard roof over a year in Riyadh, Saudi Arabia.

Keywords: biomimetics, TRIZ, BioTRIZ, radiative cooling, building design, passive design

1 Introduction

1.1 Sky temperature and radiative cooling heat balance

In hot climates, to save energy for cooling, buildings should be designed to cool down passively faster than they heat up. This requires protective measures against heat gain, mechanisms for maintaining cool temperatures, and mechanisms for rejecting heat into available heat sinks. One important natural heat sink to consider is an open sky – a very large "object" at a low effective temperature[1]. Sky temperature is a meteorological construct, based on measurements of incoming longwave radiation at ground level. Longwave radiation refers to infrared (thermal) radiation between 5 and 100 microns in wavelength, which is the bandwidth at which the earth rejects heat into space via the atmosphere. Shortwave radiation refers to radiation below 5 microns in wavelength, that is, the incoming solar radiation[2,3].

The sky temperature is often much lower than ambient air temperature at ground level, particularly in clear and dry conditions. The sky emits longwave infrared radiation downwards; a building emits longwave infrared radiation upwards: if the latter outweighs the former, net radiative cooling occurs. A low warm cloud settled above a building will cut off infrared access to the cold sky above it while radiating its own heat down[4]. But if the sky is clear and dry enough, it can be used as a natural cooling resource. This cooling resource is taken to the best advantage if the heating effects of the sun (shortwave radiation) and the local ambient temperature (conductive and free and forced convective heat transfer) are avoided somehow. There are several existing building techniques and technologies that take advantage of the radiative cooling effect – old and new, passive and active[5]. Careful design with certain systems can bring about a net rejection of 20 W·m^{-2} to 100 W·m^{-2} in clear night sky conditions, with the aim of cooling a building mass below ambient temperature[4].

1.2 Available radiative cooling technologies

To achieve net radiative cooling, the radiative,

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convective and conductive components of the total heat balance need to be resolved in some form. Clearly conductive and convective heat transfer from the surrounding air is counterproductive if the aim is to cool a mass below ambient temperature. As for the radiative transfer component, some way of separating shortwave radiation from longwave radiation is required, even if this means radiative cooling is initiated only at night; specific selection of certain bandwidths within the longwave spectrum can also be advantageous.

1.2.1 Spectral selectivity

One of the oldest ways of separating longwave from shortwave radiation – unwittingly or not – is the use of white washes or paints on massive buildings, as it is common in the vernacular architectures in a hot arid region. White reflects the majority of shortwave radiation but lets longwave radiation pass. In the Athens summer, certain off-the-shelf white paints have been shown to keep roof surface temperatures near ambient temperature during day and up to 6 ˚C below at night[6].

Spectral selection has since become more selective. The atmosphere is most transparent in the wavelength interval of 8−13 microns – the so-called “atmospheric window”. If a horizontal building surface had low reflectance in this range and a high reflectance elsewhere, the building mass would effectively have an unrestricted infrared view of the cold upper parts of the troposphere. Coatings and tiles such as SiO, MgO and LiF have been tested with results suggesting the possibility of net radiative cooling day and night[7,8].

1.2.2 Mitigating convection and bypassing insulation

The Persians understood that wind went counter to their efforts to make ice on clear desert nights, as it would warm the water placed in their shallow, long, exposed troughs. Their solution was to build up the walls of the troughs and arrange them side by side[9]. This simple convection-baffle reportedly allowed the production of ice with ambient night temperatures as high as 9 ˚C [10].

Roof ponds are another form of radiative cooling thermal mass design. The most successful ones are those with some form of insulation above the water that is removed at night, for instance sliding panels[5]. Hence the thermal storage mass is protected from solar and ambient gains during the day and is free to exchange longwave radiation with the sky at night. Another way of bypassing insulation is to use an intermediary heat transfer medium. In the case of cooling radiators, water is pumped through a roof mounted radiator at night in order to cool the water toward night sky temperature[5,11]. This cooled water can then be, for instance, passed through the building envelope in the morning to pre-cool the structure so it is ready to absorb daytime internal heat gains.

The performance of cooling radiators can be improved by reducing convective transfer from the surrounding air to the radiator. Open honeycomb convection-baffles with infrared reflective internal walls have been proposed[5]. So have convection guards made of infrared transparent film or glazing, set parallel to the radiator some millimetres above[12–14]. Thin films of polyethylene have been shown to be up to the thermal task, if not up to other mechanical and longevity functions required of building envelopes[14]. If the film had a high solar reflectance, the panels might be run during the day to some effect[13].

1.2.3 Biological analogues

We have found no proven direct biological analogue for radiative cooling. Vogel cites one possibility: the large vascularized ears of desert animals such as the Jack Rabbit (*Lepus spp*) might be used to reject heat to the sky under open shade[1]. Vogel also conjectures that a small Chinese silk tree (*Albizzia julibrissin*) may downturn its leaves at night to reduce the exposed surface area at night to protect them from harmful radiative cooling.

More analogues are available if the search is made more general. For spectral selection, leaves, birds eggs, and desert snail shells reflect most of the near infrared component of sunlight, which accounts for just over half of sunlight’s thermal load at sea level[1]. Heinrich offers an example of mitigating convection in nature: when warming in the sun in preparation for flight, dragonflies have been seen to use their wings as convection baffles to minimize heat loss to the air[15].

The natural palette appears richer in mechanisms for bypassing heat retention mechanisms: such analogues are salient to the problem of how to bypass roof insulation, or how to maximize the performance of cooling radiators. Schmidt-Nielsen tells how dolphins are able to bypass their blubber when the need for heat dissipation increases by rerouting blood through an alternative channel which runs close to the surface of the skin[16]. Heinrich explains how bumble bees have countercurrent heat flow mechanisms that prevent heat loss while they are foraging at low temperatures, but when queens perch upon their brood of larvae to keep them warm, they are able to shunt heat past and through this mechanism to the abdomen by chopping up the flow into alternating pulses[15].

1.3 TRIZ, PRIZM and BioTRIZ

All these technological examples, biological ones included, resolve one or more tradeoffs inherent in the radiative cooling task. The building mass should be coupled to the sky but decoupled from the sun and local air temperature. As far as the authors are aware, a simple passive roof system that resolves the tradeoffs without moving parts isn't available for purchase or specification.

TRIZ, the Russian system of problem solving, offers several tools with which to formulate and resolve such conflicts[17]. One of the most popular tools is a look-up table made up of 39 opposing features (parameters, variables) of engineering systems such as strength, weight, speed, volume, temperature, ease of manufacture and versatility. The claim is that if you define your problem in its terms, the TRIZ contradiction matrix will point you to a handful of principles that have been found to resolve the trade-off. Altshuller and his colleagues found 40 such principles from the study of reportedly 3 million patents[17].

More recently, a condensed version of this matrix was made by rearranging the 39 features and 40 inventive principles into 6 meta-categories, or "operational fields" – Substance, Structure, Energy, Information, Space and Time[18]. This new 6×6 matrix was called PRIZM. The PRIZM framework was then used to capture evolution's solutions to engineering problems in the so-called BioTRIZ matrix[19]. Vincent and his colleagues then compared the two 6×6 matrices, taking them as representative of innovation strategy in engineering and nature. There was only a 12% similarity. One of their conclusions was that human technology solves problems largely by manipulating the use of Energy, whereas biology uses Information and Structure – two factors largely ignored by technology.

1.4 Aim of paper

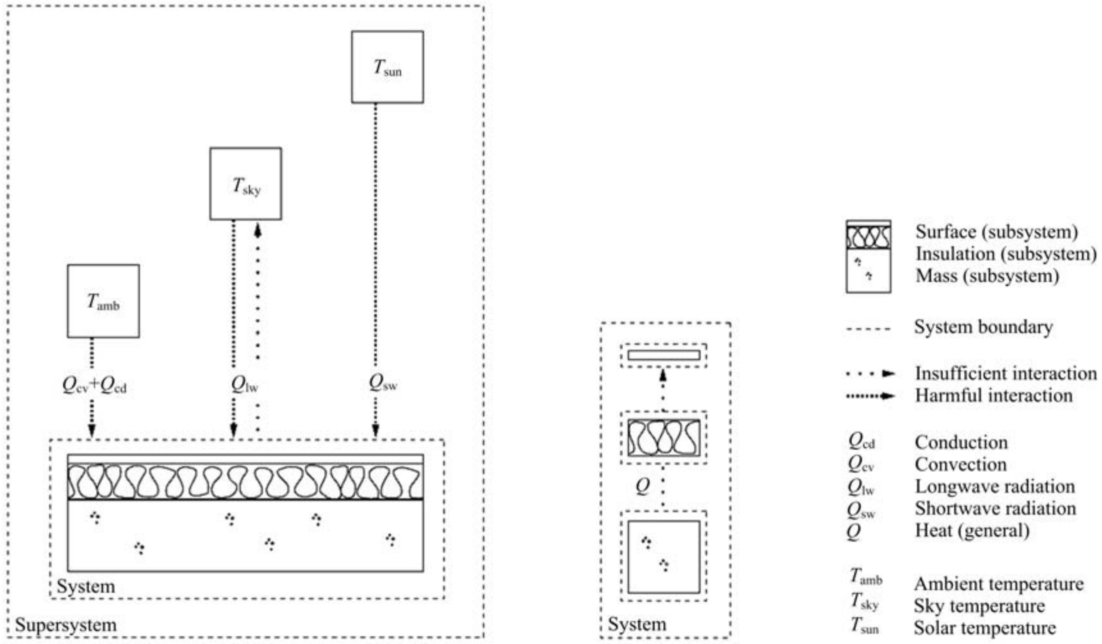
This paper demonstrates how the BioTRIZ matrix has been applied to resolve the tradeoffs inherent in the radiative cooling task. It describes how BioTRIZ was applied to model the problem, interprets the inventive principles that the BioTRIZ matrix offered as solutions and compares the results from the original TRIZ matrix and its condensed version PRIZM. Finally it details a concept applying changes in Structure as suggested by the BioTRIZ matrix. An estimation of its performance in a hot arid climate using the dynamic simulation software TRNSYS is presented and some conclusions are drawn regarding the success of the BioTRIZ trial, whether or not the concept can be called biomimetic or new, and what else needs to be done to develop the design further.

2 Method

2.1 Problem formulation

Fig. 1 shows a qualitative model of a roof, and its thermal interaction with solar radiation, local ambient temperature and the sky. Useful, harmful and insufficient thermal interactions are indicated. We assume a conventional roof arrangement consisting of three subsystems: an exterior white surface, an insulation layer, and the envelope mass. Latent heat transfer and the other issues that condensation and evaporation bring are ignored, as are structural and longevity issues. Ideally, the mass should be thermally coupled to the sky, but thermally decoupled from the sun and the external ambient temperature.

Fig. 1 shows that the problem lies in the insulation. Usefully, the insulation decouples the mass from the ambient temperature. It also, in conjunction with the white exterior surface, decouples the mass from the sun. But the insulation layer also restricts heat accumulated in the mass from reaching the exterior surface, thereby compromising longwave heat rejection to the sky.



(a) (b)

Fig. 1 A roof and its thermal interactions with the sun, sky and external ambient temperature. Insufficient and harmful interactions are shown between the roof and its environment (a), and between the roof subsystems (b).The problem is that with insulation present, there is insufficient interaction between the sky and the mass to bring about radiative cooling. But without the insulation, the mass would be quickly heated by the sun and the ambient temperature.

2.2 Parameter selection

The parameters that best describe the problem defined above are now chosen from Altshuller's list of 39 features[19]:

17. Temperature. The thermal condition of the object or system. Loosely includes other thermal parameters, such as heat capacity, that affect the rate or change of temperature;

18. Illumination Intensity. Light flux per unit area, brightness, light quality, *etc*.;

20. Use of Energy by a Stationary Object. The measure of the object's capacity for doing work; energy required to do a job – includes use of energy provided by the super-system (e.g. heat or electrical);

22. Loss of Energy. Energy that does not contribute to the job being done (reducing the loss of energy sometimes requires different techniques from improving the use of energy, which is why this is a separate category).

Note that all four parameters fall into the operational field "Energy"[19]. The four chosen parameters can be combined to describe the problem as conflicts in 12 different ways, for instance:

- The mass should be allowed to reach thermal equilibrium with the sky (17) without counterproductive energy inputs from the super system (22);
- Increase the longwave exchange between mass and sky (18) without incoming shortwave radiation and local convection increasing the temperature of the mass (17);
- Increase the longwave exchange between mass and sky (18) without reducing the amount of heat rejected by the mass (20);
- Increase the longwave exchange between mass and sky (18) without counterproductive energy inputs from the super system (22).

3 Results

With the PRIZM and BioTRIZ matrix, the results come from looking up all 12 conflicts possible from the four chosen parameters (17, 18, 20 and 22). With the latter two, the results come from looking up Energy versus Energy, because all the four chosen parameters fall into the Energy operational field[19]. (The TRIZ matrix is available in Ref. [20]. The PRIZM and BioTRIZ matrices are available in Ref. [19]. The definitions of the inventive principles are available in Ref. [19].)

3.1 Suggested inventive principles

Fig. 2 shows the inventive principles suggested by the standard TRIZ matrix, organised by operational field. Since several of the inventive principles come up more than once, it is possible to assign percentages to each operational field. It can be seen that the TRIZ matrix strongly suggests changes in Substance, Structure or Time as solutions. Inventive Principle (IP) 32 *Colour change* and IP 35 *Parameter change* – both changes in Substance – come up most often.

It is not possible to generate charts for the results from the BioTRIZ and PRIZM matrices like in Fig. 2. This is because they are more general than the standard TRIZ matrix. They capture the 12 possible conflicts in one meta-conflict (Energy vs. Energy), and only one of each of the then suggested principles is given.

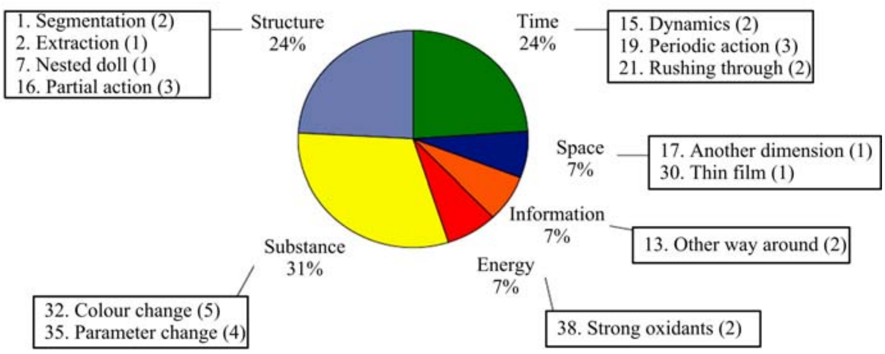


Fig. 2 Inventive principles offered by the standard TRIZ matrix to solve the roof problem, organised by operational field and frequency. Changes in Substance, Structure and Time are strongly suggested.

Table 1 The inventive principles offered by all three matrices

Operational field	Inventive principle	Source matrix		
		TRIZ	PRIZM	BioTRIZ
Substance	32. Colour change	•		•
	35. Parameter change	•		
	36. Phase change		•	
Structure	1. Segmentation	•		
	2. Extraction	•		
	3. Local quality			•
	5. Merging			•
	7. Nested doll	•		
	16. Partial action	•		
Energy	9. Prestressing			•
	37. Thermal expansion		•	•
	38. Strong oxidants	•	•	
Information	13. Other way around	•		
	22. Blessing in disguise			•
	25. Self-service		•	•
Time	15. Dynamics	•		
	19. Periodic action	•	•	
	21. Rushing through	•	•	
Space	14. Curvature		•	
	17. Another dimension	•		
	30. Thin films	•		

Table 1 compares the inventive principles offered by all three matrices. Of most interest is what PRIZM and BioTRIZ exclude. PRIZM offers no principles from the operational field Structure. BioTRIZ offers no principles from the operational fields Time and Space.

3.2 Interpretation

The inventive principles are general indicators for solutions – "models" for ideal solutions. The interpretation of them is paramount – how they could be applied to resolve the defined conflicts. This subsection interprets some of the suggested inventive principles in order of operational field. The place in the system where each principle is applied is indicated in the subheadings – it will either be a change on the subsystem, system or supersystem level (see Fig. 1). (refer to Ref. [19] to see the full characterisation of each inventive principle discussed. Table 1 shows the source matrix of each inventive principle discussed.)

3.2.1 Changes in substance suggest longwave transparent insulation (subsystem level)

IP 32 *Colour change* and IP 35 *Parameter change* are the most strongly suggested by the TRIZ matrix. The former suggests adjusting the spectral properties of a substance; the latter suggests adjusting one of the physical parameters. Both could be interpreted as increasing the longwave transparency of the insulation, that is, the use of an insulation material that retards convective and conductive heat transfer, but not radiative transfer.

Clearly the ideal manifestation of this would be the use of a vacuum insulation; the white surface of the roof (we are only assuming changes on the insulation subsystem level) would filter out the shortwave radiation. The use of a vacuum is its own inventive principle, number 39, yet interestingly this was not suggested by any of the matrices. IP 39 is defined as a change in Energy[19].

3.2.2 Changes in structure suggest longwave transparent insulation (subsystem level)

Instead of changing the material make up of the insulation, we might offer longwave radiation a clear pathway by introducing voids through the insulation, bottom to top. IP 2 *Extraction* tells us to extract the harmful part of the insulation; IP 3 *Local quality* tells us to change the insulation from uniform to non-uniform. A typical insulation component is porous, and so it is already heterogeneous, but only locally – in our model we assumed it to be globally homogenous. “Empty” vertical pathways in the insulation would give the mass an infrared view of the sky. A honeycomb structure, for instance, might allow air to stagnate during radiation cooling to form an infrared transparent insulator. Alternatively, infrared fibre optics would let longwave radiation pass, and heat gain from the ambient would be purely from conduction.

3.2.3 Changes in space (subsystem and supersystem level)

IP 30 *Flexible shells and Thin films* suggests replacing the insulation with some membrane that isolates the mass from the harmful heat sources in the environment. This approach already exists within the building technology repertoire in the form of spectrally selective glazing or infrared transparent films such as polyethylene (see Section 1.2.2) used as convection guards. This is another way of producing a *de facto* longwave transparent insulation.

IP 17 *Transition to Another dimension* suggests layering these longwave transparent membranes in multiple layers to arrest convection further. It also suggests a solution at the supersystem level, best shown with the example of the Jack Rabbit described in Section 1.2.3. Here the desert rabbit feeds under open shade, hence its vascularised ears are able to reject heat to the sky without being warmed by the sun. An external shading system that followed the sun or even a well placed tree might give a roof system enough open shading for daytime radiative cooling.

3.2.4 Changes in time suggest bypassing insulation (system level)

Changes in Time, as suggested by PRIZM but not BioTRIZ, point towards solutions that involve bypassing the insulation when it is advantageous to do so, probably at night. Section 1.2.2 shows how this is already done, either with an intermediary heat transfer fluid – as in the cooling radiator example – or with some removable insulation – as seen with the variants of roof pond technology. Alternatively, the roof system as it is could flip round to expose the mass at night. All these approaches can be circumscribed by the three changes in Time offered up by TRIZ and PRIZM. IP 15 *Dynamics* suggests mobilizing the mass or the insulation. IP 19 *Periodic action* suggests pulsating heat rejection in tune with, for instance, the day and night cycles. In combination with IP 21 *Rushing through*, *Periodic action* suggests chopping up the flow into alternating pulses, like the bumblebee queen described in Section 1.2.3.

3.2.5 Changes in energy and information suggest adaptive structures (system level)

IP 25 *Self service* suggests finding some way for the system to regulate itself using either waste resources or energy present in the environment. IP 22 *Blessing in Disguise* suggests turning harmful factors from the environment into a benefit. Both inventive principles are changes in Information. We defined the harmful factors from the environment as solar heat and the local ambient temperature. IP 37 *Thermal expansion* suggests using the thermal expansion or contraction of a material, or several with different expansion coefficients, to create some useful movement. This is a change in Energy. The combination of these principles suggests some sort of deployable structure[21] which is able to disconnect and connect the mass to the sky depending on the ferocity of environmental heat sources. For example, surface pores could close when it gets too hot.

3.3 Discussion

A distinction between two main types of solutions generated can be drawn: passive and active solutions. A passive thermal storage system is one that has its storage mass in contact with its intended environment. An active system has its storage mass in isolation from its intended environment, therefore requiring an intermediate heat transfer fluid.

All changes on the subsystem insulation level – changes in Substance, Structure and to some degree Space – suggest a form of infrared transparent insulation. If any of the suggested changes to the insulation were implemented, it would end up an entirely passive solution to the problem, with no moving parts. This would be true even if the standard insulation component was replaced with a vacuum insulation component – IP 39, the principle omitted by all matrices – which is defined as change in Energy[19].

Most changes on the system level suggest an active system of sorts. The suggestion is the strongest with the changes in Time, which the PRIZM matrix includes but the BioTRIZ matrix omits.

Interestingly, changes in Structure are suggested by BioTRIZ and TRIZ, but not by PRIZM. The PRIZM matrix is made on the basis of the finding that certain inventive principles in the standard TRIZ matrix show a statistical preference to some of the 36 meta-conflicts (Energy vs. Time, Space vs. Space, *etc.*)[18]. The PRIZM matrix is made up the principles that show such a statistical preference. This explains the omission of structural principles by the PRIZM matrix. It implies that none of the inventive principles that fall into the operational field "Structure" show a statistical preference to the conflict "Energy vs. Energy".

Clearly changes on the subsystem level, particularly the structural changes IP 2 and IP 3, are simpler to implement than the whole system changes.

4 Concept design and performance estimate

The simplest solution to the problem at hand seems to be a structural change in the insulation, as described in Section 3.2.2.

4.1 Concept description

Fig. 3 depicts one possible manifestation of the changes in Structure discussed in Section 3.2.2. Spectral profiles of various construction materials, mostly weathered, such as marble, concrete, and different coloured surfaces, tiles and paints, are given in the ASTER spectral library[22].

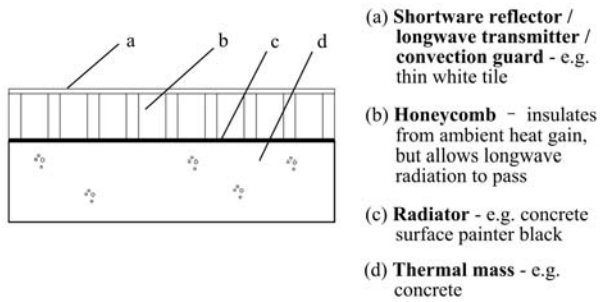


Fig. 3 A cool roof for hot countries (not to scale). By swapping conventional insulation with an open honeycomb, the concrete mass will reject thermal radiation to the sky, and be protected from solar radiation and the warm surrounding air. The solution, a change in structure, was suggested by the BioTRIZ and TRIZ matrices, but not the PRIZM matrix (see Section 3.2.2 and Table 1).

If net radiative cooling is to occur, it will most likely occur at night. When the radiator (c) is cooler than the mass (d), heat conducts upwards through the mass to the radiator. The radiator is able to reject this heat to the cooler sky because the honeycomb (b) and the convection guard (a) let longwave radiation pass. At the same time, the honeycomb arrests conductive transfer from outside to inside, and the convection guard arrests convective transfer from outside to inside. This means the mass has a chance of cooling below ambient temperature. The more radiative cooling occurs, the more each column of air in the honeycomb will stagnate, and the greater the resistance to conductive and convective heat transfer is.

Since the convection guard is not perfectly transparent to longwave radiation, some longwave energy is radiated back to the radiator, thus decreasing cooling efficiency. Hence it acts as a "weak" radiator. During the day, net heating will probably occur, because the convection guard will not reflect all solar radiation, and the ambient and sky temperatures increase. The concept will be successful if more night time cooling occurs than day time heating.

4.2 Cooling performance at night: steady-state model

An estimate of the net radiative cooling power of the roof at night in steady-state conditions can be made by adapting a model empirically verified by Johnson[12]. The expression

$$Q_{\text{net radiation}} = Q_{\text{mass}} + Q_{\text{ambient}} \tag{1}$$

is depicted in Fig. 4a, where temperatures of various bodies are also indicated. It is assumed that the mass is not in thermal contact with the room below. Heat from the night air (Q_{ambient}) is transferred to the radiator by conduction only, since the radiator is protected from forced convection (wind or non-still air). In addition, a temperature inversion layer forms, arresting free convection in the trapped air cells. (The radiation component is dealt with in the $Q_{\text{net radiation}}$ term). Therefore,

$$Q_{\text{ambient}} = h(T_{\text{air}} - T_{\text{radiator}}), \tag{2}$$

where h is the conduction parameter (W·m^{-2}·K^{-1})for a stagnant 40 mm air layer. Upon substituting the correct value for h (conductance = conductivity / length), Eq. (2) becomes

$$Q_{\text{ambient}} = 0.6(T_{\text{air}} - T_{\text{radiator}}), \tag{3}$$

since the conductivity of still air is 0.024 W·m^{-1}·K^{-1}. Heat conducts through the mass to the surface of the mass, which is painted black. Assuming the mass to be a concrete slab 0.3 m thick,

$$Q_{\text{mass}} = h_{\text{slab}}(T_{\text{mass}} - T_{\text{radiator}}), \tag{4}$$

where h_{slab} is conduction parameter for 0.3 m of concrete. We ignore the specific heat of concrete, since the calculation is steady state. Upon substituting the correct value for h_{slab}, Eq. (4) becomes

$$Q_{\text{mass}} = 6.1(T_{\text{mass}} - T_{\text{radiator}}), \tag{5}$$

assuming the conductivity of concrete to be 1.83 W·m^{-1}·K^{-1}[23]. The net longwave radiation to the night sky ($Q_{\text{net radiation}}$) is found by subtracting the heat emitted by the convection guard to the radiator and the incoming sky radiation transmitted by the convection guard to the radiator from the energy emitted by the radiator as shown in Fig. 4b. It can be assumed that the temperature of the convection guard is the same as the temperature of the night air (T_{air}) since any wind will convect the local ambient heat to the guard.

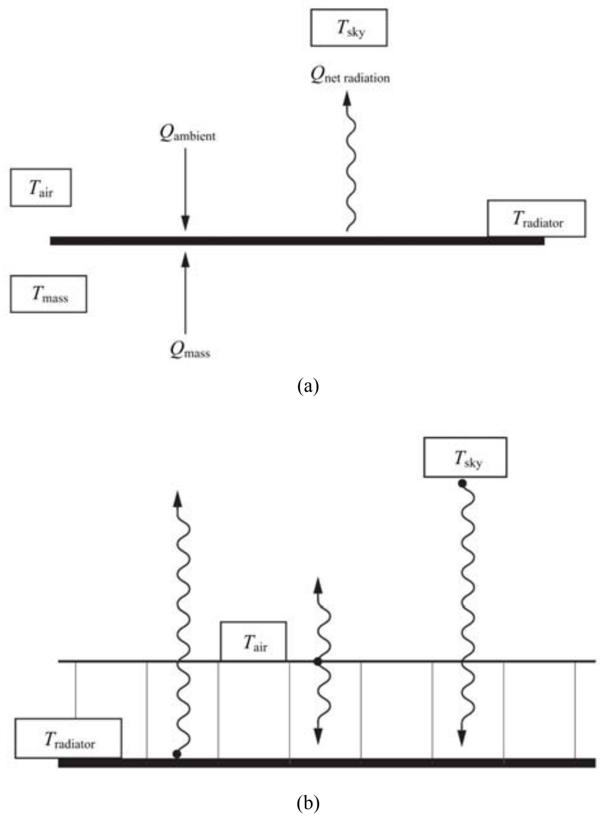


Fig. 4 (a) Radiator heat flow model (b) Convection guard radiation exchanges. The guard is at ambient temperature, and the radiator is coupled to external air temperatures by conduction only.

The energy emitted by the radiator is $\varepsilon\sigma T_{\text{radiator}}^4$, where σ is the Stefan-Boltzmann constant 5.67×10^{-8} W·m^{-2}·K^{-4} and ε is the emissivity of the radiator in the longwave spectrum (approximately 0.9). The energy transmitted by the convection guard is $M\varepsilon_{\text{es}}\sigma T_{\text{sky}}^4$ where ε_{es} is the equivalent emissivity of the night sky, and M is the percentage of longwave radiation transmitted by the convection guard. Sky emissivity varies markedly with humidity levels, cloud cover, and vapour pressures. A worst case condition of $\varepsilon_{\text{es}} = 0.9$ is representative of conditions of high humidity and dense cloud cover. The energy reradiated by the convection guard is $\varepsilon_{\text{cg}}\sigma T_{\text{air}}^4$ where ε_{cg} is the emissivity of the convection guard. Since emissivity + reflectivity + transmission = 1, and the longwave reflectivity of the convection guard is low, $\varepsilon_{\text{cg}} = 1 - M$,

$$Q_{\text{net radiation}} = \varepsilon\sigma T_{\text{radiator}}^4 - M\varepsilon_{\text{es}}\sigma T_{\text{sky}}^4 - (1-M)\sigma T_{\text{air}}^4 . \quad (6)$$

This equation in linearized form is sufficient to gauge the performance with small temperature ranges encountered,

$$Q_{\text{net radiation}} = T_{\text{radiator}} - MT_{\text{sky}} - (1-M)T_{\text{air}} , \quad (7)$$

With the air temperature re-expressed as the sky temperature plus an offset temperature T_0,

$$T_{\text{air}} = T_{\text{sky}} + T_0 ,$$

the net radiation becomes,

$$Q_{\text{net radiation}} = T_{\text{radiator}} - MT_{\text{sky}} - (1-M)\times(T_{\text{sky}} + T_0) ,$$

or

$$Q_{\text{net radiation}} = T_{\text{radiator}} - \left[T_{\text{sky}} + T_0(1-M)\right]. \quad (8)$$

This shows that the equivalent sky temperature is raised when transparency M is decreased.

With all three components of the total heat balance (Eq. (1)) defined, we can now estimate the cooling power of the roof in night time steady state conditions. Thermal equilibrium will occur when the temperature of the mass reaches the temperature of the radiator $(T_{\text{mass}} = T_{\text{radiator}})$. Thus Eq. (5) cancels, and Eq. (1) becomes $Q_{\text{net radiation}} = Q_{\text{ambient}}$. If $M = 0.7$, $T_{\text{sky}} = 283$ K (10 ˚C) and T_{air} = 299 K (26 ˚C), then the system reaches steady-state when the mass reaches 292 K (19˚C). If M = 0.9, this falls to 290 K (17 ˚C).

Clearly a night of cooling would not be enough for a thick concrete slab and a room underneath to reach steady-state. But useful cooling would occur: if the bottom of the mass was 299 K and T_{radiator} = 290 K, then heat will flow upwards through the slab at a rate of 54.9 W·m^{-2} (Eq. (5)). Assuming T_{sky} and T_{air} remain the same, and the transparency M = 0.9, if the radiator heated up through contact with the mass to 299 K, it would cool back down at a rate of 14.4 W·m^{-2} (Eq. (8)).

4.3 Estimation of dynamic performance, night and day

To get a better idea of whether the new roof might bring appreciable benefits, it needs to be modelled in transient weather conditions, and to include the inertial effects of the concrete.

4.3.1 Model and assumptions

A dynamic model of the concept was built using the dynamic simulation software TRNSYS (Transient Systems Simulation)[24]. The assumed time step was one hour and the length of the analysis was one year, using weather data for Riyadh, Saudia Arabia. Fig. 5 shows the basic set-up. A standard 0.3 m concrete fabric component from the TRNSYS library was chosen, set-up to be adiabatic on the underside. The non-linearized version of the heat balance $Q_{\text{net radiation}} = Q_{\text{mass}} + Q_{\text{ambient}}$ (see Section **4.2**, Eq. (1) and Eq. (6)) was used to simulate the honeycomb and convection guard. Only longwave radiation was dealt with through this balance however. As Fig. 5 shows, solar radiation energy, direct and diffuse, enters the fabric after 80% is reflected away. This simulates a white surface with 80% shortwave reflectance. Since solar radiation effectively "bypasses" the honeycomb and convection guard, the convection guard only heats up through interaction with longwave radiation.

Convection, as explained in Section **4.2**, is assumed to keep the convection guard at ambient temperature. However, a default constant wind speed affects the surface that interacts with solar radiation. TRYNSYS computes a fictitious sky temperature using ambient and dewpoint temperature data. The feedback loop between mass and heat balance is indicated in Fig. 5 – every hour, a new $T_{radiator}$ is taken from the mass component and fed back into the heat balance, and so on and so forth.

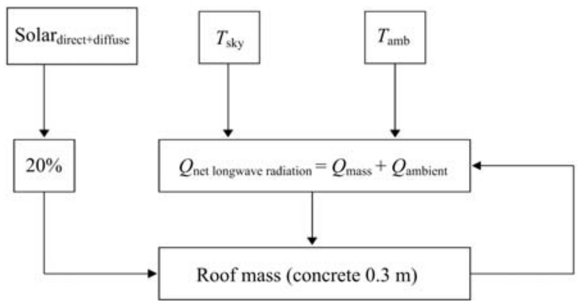


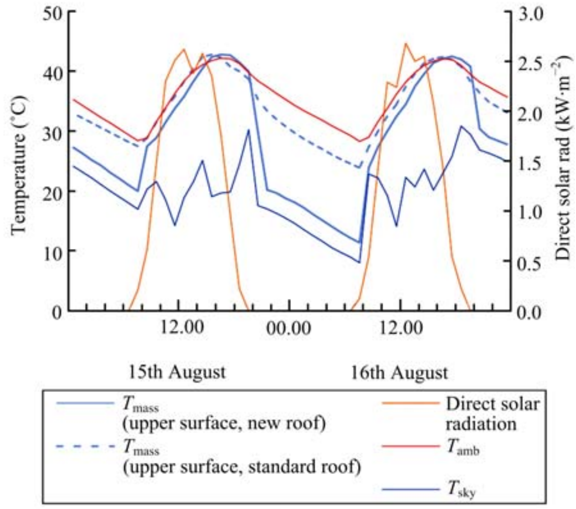
Fig. 5 Basic set-up of the dynamic model in TRNSYS. The arrows show the direction of information, which is either temperature or, on the far left, solar radiation.

4.3.2 Results

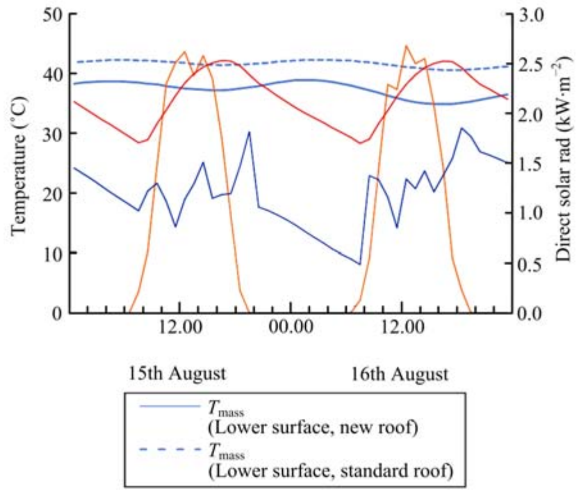
The set-up allows a comparative estimate of two types of roofs to be extracted. A "standard roof", made up of 0.3 m of concrete fabric painted white, is indicative of the vernacular found in Middle Eastern regions. The "new roof" is the concept described in Fig. 3. The performance of these two roofs over two hot days in August is shown in Fig. 6. Their average annual performance is summarised in Table 2.

Fig. 6a compares the upper surface temperature of the concrete fabric for both the standard and new roof. The upper surface of the standard roof closely follows ambient temperature, and dips below a few degrees at night. This behaviour is indicative of that tested by Synnefa *et al.*[6], where the temperature changes after the application of off-the-shelf white paints did not much stray above ambient temperature during the day, and dipped below ambient at night due to longwave interaction with the sky (see Section 1.2.1).

As expected, the upper surface of the mass in the "new" roof is more closely coupled to sky temperature, as the larger temperature fall at night shows. This extra temperature fall is translated into extra cooling, as shown in Fig. 6b, which compares the temperatures of the underside of each roof. The inertial effects of the concrete are clear in both circumstances, but the new roof stays a few degrees cooler than the standard roof.



(a) Upper surface mass temperatures



(b) Lower surface mass temperatures

Fig. 6 Performance estimate of the "standard" roof and "new" roof in Riyadh, Saudi Arabia.

Table 2 Performance of the "standard" and "new" roof over a whole year in Riyadh, Saudi Arabia, as modelled in TRNSYS

	T_{sky} (°C)	T_{amb} (°C)	Solar rad* (kWh·m^{-2})	Standard roof, T_{mass}(°C)			New roof, T_{mass}(°C)		
				Upper	Middle	Lower	Upper	Middle	Lower
Mean Max	21.9	31.7	2.4	32.2	31.5	31.9	32.0	29.1	28.3
Mean	11.7	25.6	0.63	24.2	27.7	31.2	19.6	23.2	26.9
Mean Min	4.1	19.0	0	17.1	24.4	30.7	8.0	17.7	25.8

*Direct only, annual total = 5494.2 kWh·m^{-2}.

The annual performances of both roofs are summarised in Table 2. If the averages of the mid points of both masses are compared, it can be seen that the new roof is 4.5 ˚C cooler than the standard roof. Also note that the new roof is 2.4 ˚C cooler than the average ambient temperature, while the standard roof is 2.1 ˚C hotter.

Since the surface temperature never goes above ambient temperature, the cooling period is on average longer than the heating period. Note that heat from the underside of the mass can only flow upwards via conduction. We might expect both mass temperature profiles to be cooler if the fabric was in thermal interaction with a room below.

5 Conclusions

Section **1** introduces radiative cooling in terms of its central challenge: coupling a mass to the cool sky, while decoupling it from the sun and ambient temperature. A brief survey of the available technologies and techniques is organised around this conflict. A brief introduction to TRIZ, PRIZM and BioTRIZ problem-solving matrices is also given. Section **2** shows how a conventional roof meant for radiative cooling could be described by some of the parameters that make up these matrices. Section **3** compares the inventive principles suggested by each matrix. The BioTRIZ matrix offers changes in Structure, the PRIZM matrix did not. The simplest solution is to let longwave radiation pass through the insulation by changing its structure. Section **4** describes a concept based on this principle. It is estimated that this roof would remain on average 4.5˚C cooler than a standard roof over a year in Riyadh, Saudi Arabia.

The concept is not radically new. The principles on which it functions – the way it decouples the mass from the sun and the ambient temperature while allowing longwave thermal exchange with the sky – are all evident in the radiative cooling literature and are manifest in the available building technology repertoire in some form. However, as far as the authors are aware, the entirely passive roof system proposed has not yet been studied and is not available for purchase or specification.

The selection of an appropriate material for the convection guard, which must also function as a solar reflector and a longwave transmitter, is likely to be the source of the next trade-off to resolve. Which ever material is selected, there will be an optimal thickness regarding spectral functions[7]. This spectral optimum may be mismatched with some mechanical optimum – it may be too thin, for instance, to resist fracture, or environmental degradation during the life time of a building. Similarly, the honeycomb component has an important mechanical role in the system, which will have much to do with the size and shape of its cells, which also determine how well the component arrests ambient heat flow. A new round of TRIZ and BioTRIZ may help resolve tradeoffs when the non-thermal requirements are defined. Or another solution avenue might be pursued from the ones already generated in Section **3** – infrared fibre optics for instance.

It can be argued that this particular application of BioTRIZ is successful, because it results in a new concept that is worth further empirical investigation and development. It can also be argued that the concept is biomimetic, because it is based on changes in Structure suggested by the BioTRIZ matrix. Furthermore, these changes are not offered by the PRIZM matrix, suggesting that a change in Structure would not be a typical engineering solution in this case. This is a contentious point however, since the PRIZM matrix is a meta-version of the TRIZ matrix, and as Fig. 1 shows, the TRIZ matrix strongly suggests changes in Structure.

Acknowledgement

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APPENDIX B

Heat-selective insulation poster presented at EngD conference, 2008, Surrey University

Heat selective insulation for radiative cooling of buildings

Salmaan Craig [1,2], Prof. David Harisson [1] & Dr. Andrew Cripps [2]

[1] Brunel University, [2] Buro Happold Ltd.

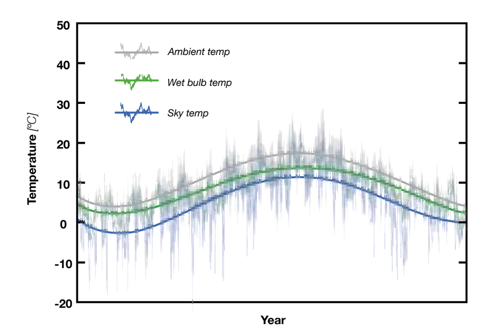
Tapping into cool skies could reduce energy & water demand

The sky is an abundant but under used heat sink. With good design in the right climate, radiative cooling could reduce or even replace the need for mechanical cooling. If a building envelope was radiantly coupled to the sky but thermally isolated from ambient and solar gains, it would remain cool during the hottest parts of the year. Different prototypes for such a heat selective insulation were tested during April and May nights on an office roof in central London. Stagnation temperatures between 6 and 13 degrees below ambient temperature were achieved, with radiative cooling powers between 25 and 70 W/m2 at ambient temperature. At 20 degrees above ambient, total cooling powers of between 90 and 200 W/m2 were observed. Daytime radiative cooling was evident with direct sunlight blocked by clouds. The results show that two design concepts have scope to bear mechanical loading and reduce convective and conductive losses without impinging on radiative cooling power.

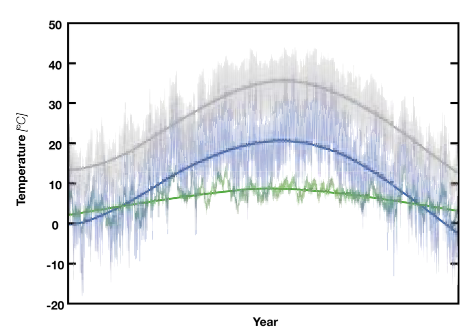
[01] Climate analysis: scope for radiative cooling

The atmosphere continually emits longwave (LW) heat energy down to earth. It can be assigned an effective 'sky' temperature by assuming the radiation received comes from a blackbody. The 'sky' is always cooler than local ambient temperature. The drier, clearer, and less 'polluted' the sky, the colder it gets. The Persians used this phenomenon to make ice at night.

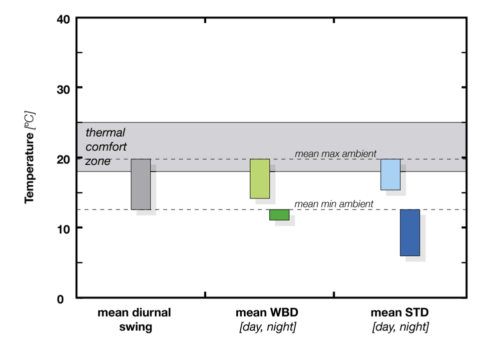
London's annual temperature trends



Riyadh's annual temperature trends

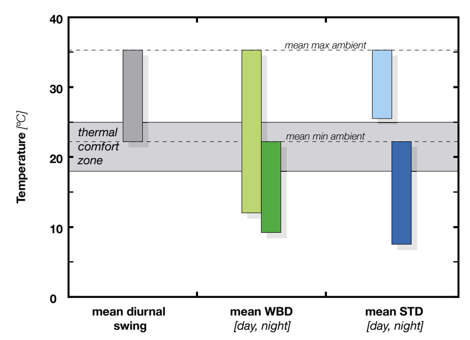


London's natural heat sinks [May-Sep inc.]



There is good scope for thermal mass and night ventilation (grey column), daytime evaporative cooling (light green) and night radiative cooling (dark blue)

Riyadh's natural heat sinks [Mar-Oct inc.]

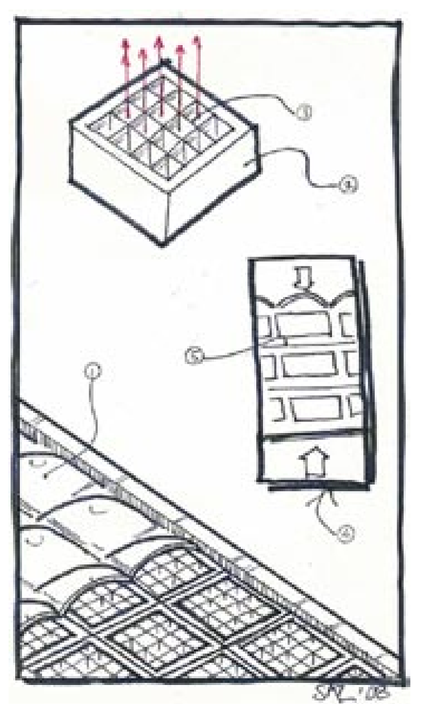


Thermal mass and night ventilation (grey column) can be supplemented by evaporative (green) and radiative (blue) cooling both day and night.

[02] Heat selective insulation: some concepts

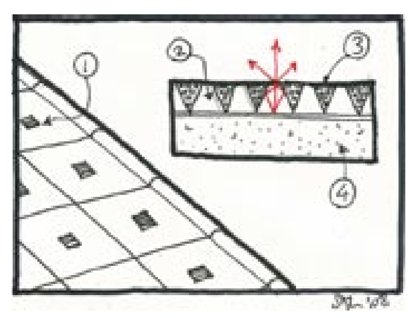
Previously proposed mechanisms for radiative cooling below ambient temperature have had their mechanical, radiative and thermal propeties at loggerheads. Here are three concepts that in principle resolve this conflict.

(i)



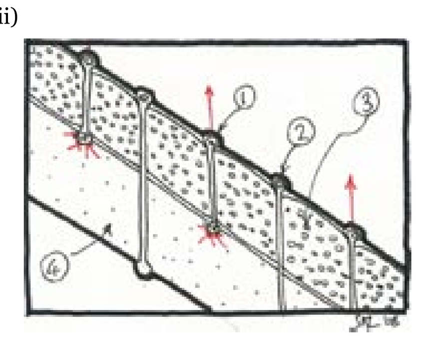
Sealed baffles (1) *Selective PIR domes on roof* (2) *Rigid baffle shell* (3) *LW baffle* (4) *Containers are closed packed and hermetically sealed* (5) *Polyethylene separators*. LW is allowed to pass vertically in a robust, insulative roof product.

(ii)



LW funnels (1) *Selective PIR apertures on roof* (2) *LW funnels* (3) *Insulation* (4) *Thermal mass*. Funnels free up space for insulation and e.g solar panels on roof. Small apertures and structure make it robust.

(iii)



Fibre optics (1) *LW fibreoptic bundles* (2) *VIS fibreoptic bundles* (3) *Insulation*. (4) *Thermal mass*. LW fibreoptics link mass with sky; VIS fibre optics bring natural 'cold' light into building. No restriction on buiding shape, or where LW harvested from

[03] Experiment

A test was devised to compare the radiative cooling power of different prototypes. The 'funnels' sample shown below is a first version of concept (ii) shown in section [02]. Elements of concept (i) are explored with the 'honeycomb', 'straws' and 'foam' samples. A coefficient for non-radiative losses *(k)* of each sample was measured indoors. Then total cooling power versus temperature difference was measured during night time rooftop experiments. These two stages allowed radiative cooling power for each sample to be estimated.

'Clingfilm'
Low density polyethylene (LDPE) film is LW transparent. Used as a control (prevents convective inflow but allows radiative cooling)
k = **2.8** $W.m^{-2}.K^{-1}$

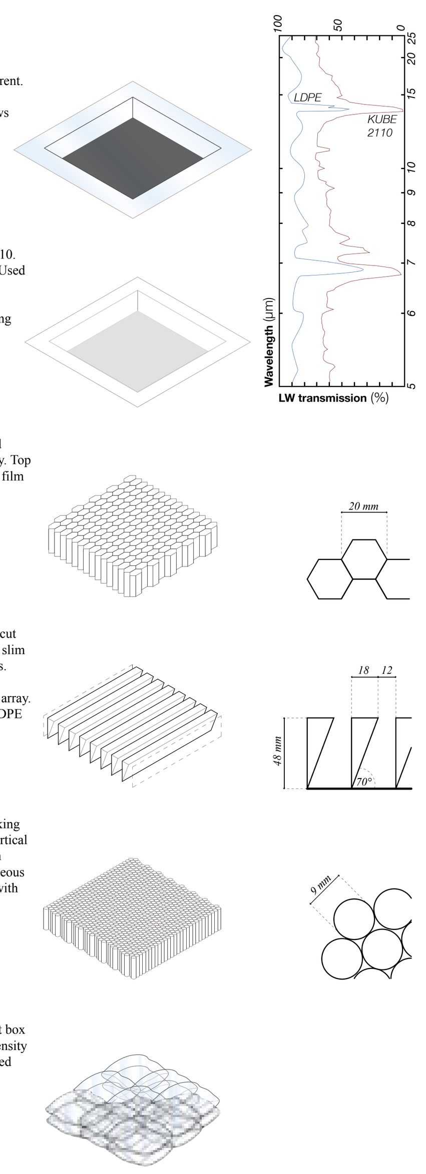
'Selective'
IR selective film KUBE 2110. Blocks SW, transmits LW. Used for motion detectors and thermography. Vacuum formable. Injection moulding pellets & UV resistance available
k = **2.8** $W.m^{-2}.K^{-1}$

'Honeycomb'
Aluminium tape folded and glued into honeycomb array. Top of box covered with LDPE film
k = **3.2** $W.m^{-2}.K^{-1}$
$\tilde{\rho}/\rho_s$ = **0.015** kg/m^3

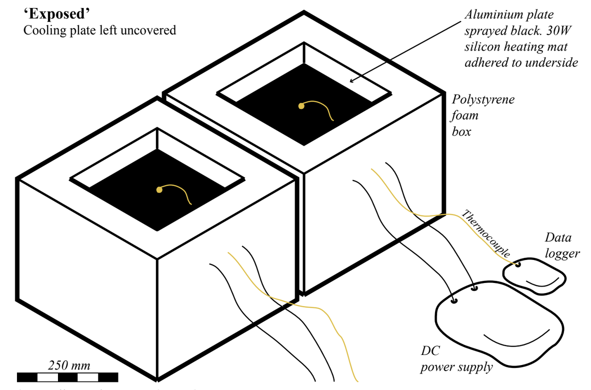
'Funnel'
Aluminium sheet (0.1mm) cut and folded into 8 rods with slim right-angle triangle sections. Evenly arranged in box, point-side down in parallel array. Top of box covered with LDPE film
k = **3.1** $W.m^{-2}.K^{-1}$

'Straws'
Large translucent PE drinking straws, closed packed in vertical array. Bundles cut to length using hot-wire for simultaneous weld. Top of box covered with LDPE film
k = **2.7** $W.m^{-2}.K^{-1}$
$\tilde{\rho}/\rho_s$ = **0.065** kg/m^3

'Foam'
24 LDPE self-seal bags blown-up and placed in test box to approximate very low density PE foam. Top of box covered with LDPE film
k = **2.4** $W.m^{-2}.K^{-1}$
$\tilde{\rho}/\rho_s$ = **0.007** kg/m^3



'Exposed'
Cooling plate left uncovered

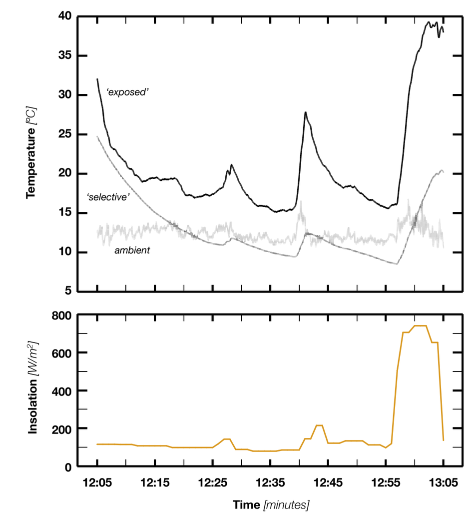


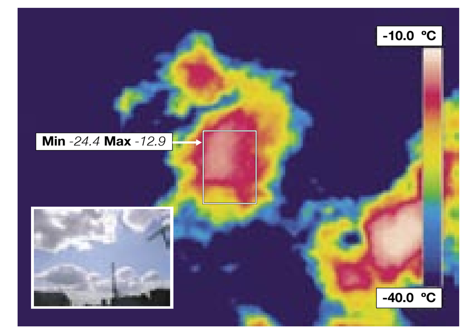
k = coefficient for non-radiative losses
$\tilde{\rho}/\rho_s$ = relative density

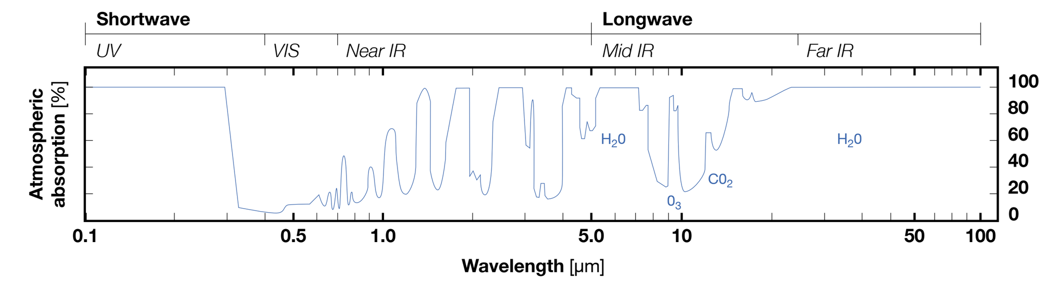
[04] Daytime results: 'exposed' vs. 'selective'

The low cummulus clouds were at least 25 degrees below ambient temperature. Between the clouds is a thermal view of the top of the troposphere, through the 'atmospheric window' (spectral range of camera = 7.5-13μm)

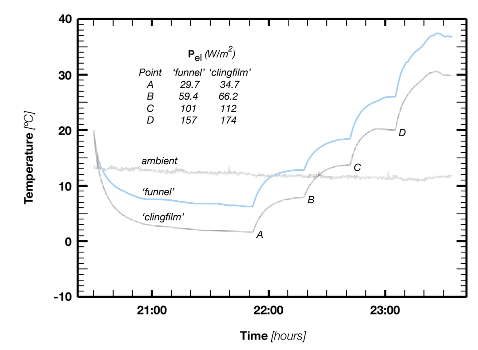
Midday April 9th 2008, London W1. The selective window allowed radiative cooling below ambient when clouds moved infront of the sun.



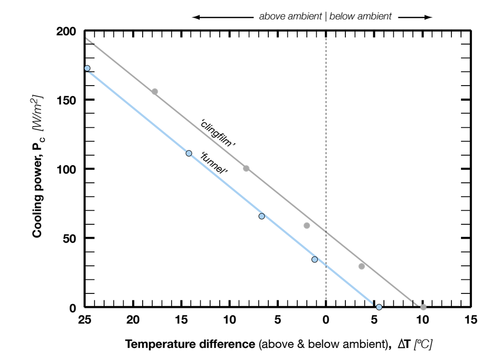




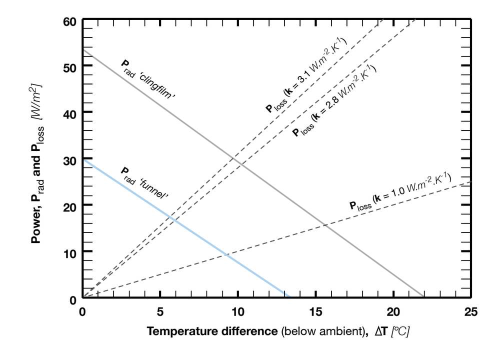
[05] Example night results: 'clingfilm' vs. 'funnels'



Temperature over time for 'clingfilm' and 'funnel' cooling plates, evening of April 22nd 2008. Points A-D denote electrical powers (**P**el) fed in. The 'clingfilm' sample is used as a control. Both cool below ambient temperature.

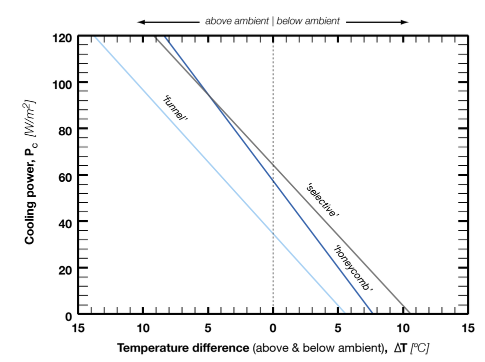


Measured cooling power (**P**c) vs. temperature difference. (data taken from the graph adjacent left; **P**c ≡**P**el). The 'funnels' are delivering 37% more radiative cooling than a straight walled version would.

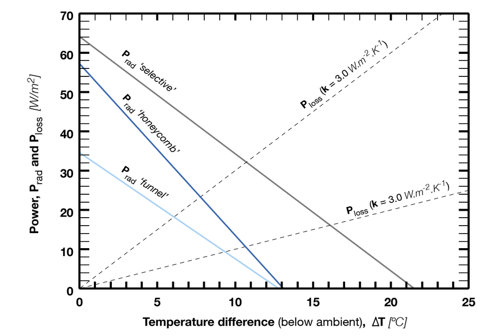


Solid lines show estimated radiated power (**P**rad) vs. temperature difference [**P**rad ≡ **P**c + **P**loss]. Dashed lines show power loss (**P**loss) caused by non-radiative exchange for three values of heat transfer coefficient. The spaces between the funnels can be filled with insulation, reducing power losses without reducing radiative cooling power, making lower temperatures possible.

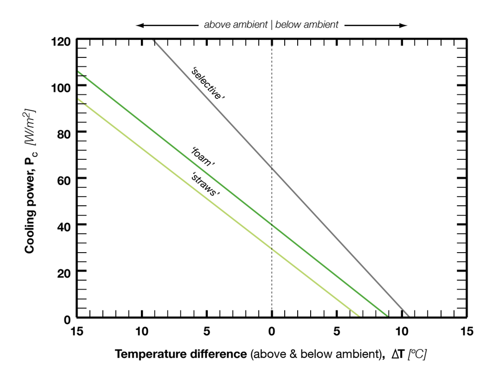
[06] Nomalised comparison (night)



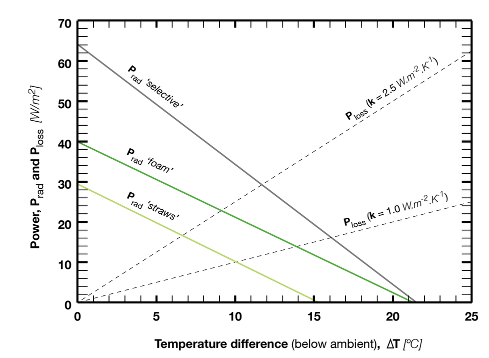
'Reflective' samples. Normalised cooling power (**P**c) vs. temperature difference. The left side is temperature difference above ambient temperature; the right, below.



Solid lines show normalised radiated power (**P**rad) vs. temperature difference. Dashed lines show power loss (**P**loss) caused by non-radiative exchange.



'Diffusive' samples. The data for the diffusive samples are less reliable because of unstable weather conditions



[07] Conclusion

Versions of concept (i) and (ii) could be developed with low values for *k* and high LW transparency in a structurally robust product. Possible applications include large enclosures such as airports: permanantly cool radiative soffits would allow for less emphasis on mechanical evaporative cooling and more on natural ventilation. Another possible application is high rise urban developments, although the multiple floors mean that some heat exchange medium would be required to bring heat to the radiator (if concept (iii) works, a heat exchange medium might not be required). A heat 'responsive' insulation would be able to turn convection 'on' when cooling above ambient temperature, and turn radiative cooling 'off' in winter.

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