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1. Although it is the least favoured option, much global waste still finds its way into landfill.

Waste as a driver of change

Part 2: Approaches to the problem of waste

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"Our enormously productive economy… demands that we make consumption a way of life… We need things consumed, burned up, worn out, replaced and discarded at an ever-increasing rate."[1]

2. Only some 10% of computers are reused and refurbished; the remainder are disposed of.

Introduction

This article is the second of two on the issues of waste. The first[2] looked at why waste is generated and the problems this causes. The present article explores current waste management practices, and the transition required to move towards a more sustainable economy whereby waste becomes a valued resource. It continues the "drivers of change" research theme in *The Arup Journal*, which has so far included water, climate change, energy, demographics and urbanisation[3-7].

Every year more than half a trillion tonnes of materials are dug up, processed, and thrown away. Less than 1% of the materials embodied in the products we consume are still in our possession six months after purchase[8]. All the rest have become waste, be it from construction, commerce, manufacturing or households.

This rapidly increasing volume of waste, generated by economic growth, urbanisation, materialism, and industrialisation, has severe impacts on the global and local environments, natural resources, public health, local economies and living conditions, and is threatening attainment of the UN's Millennium Development Goals[9]. There is much evidence to suggest that today's growing society is using more resources and generating more wastes than the planet can sustain, and that our consumption habits have led us to an environmental crisis point, with depleting resources, the spread of dangerous pollutants, the undermining of ecosystems, and the threat of unhinging the planet's climatic balance.

Radical change is needed to move humanity from the prevailing economic system of manufactured goods and over-consumption to one where people significantly reduce their use of resources. However, the deep divides that exist within humanity make this a hugely complicated task.

An ever-growing body of evidence suggests that the current global consumer class of 1.7bn people needs to significantly reduce its consumption, but an equally large number of people in an emerging global middle class are striving to emulate the perceived "good life" - in stark contrast to the 3bn people who live on less than US$2 a day[10].

Clearly, the solution should not be one that allows the entire global population to consume at the rate current in Western society, nor can it involve moving to a place where Western consumption is accepted whilst the poor are denied a decent standard of living. Instead, the rich need to curb their over-consumptive lifestyles, and industry needs to reduce the resources embedded in products.

Calculations suggest that to achieve the twin objectives of environmental protection and social equity, the developed world may need to cut its use of materials by about 90%[11]. Yet at present it appears that we are moving in the wrong direction. Modern economies produce, at ever-decreasing prices, commodities that consumers regard as little more than goods to be discarded relatively quickly rather than items embodying valuable energy and materials that should be repaired, maintained, and designed to last over a long lifespan.

The good news is that meeting human needs while becoming more resource-efficient can be more profitable and can deliver a higher standard of living than maintaining current practices. A new model of prosperity for an environmentally degraded and poverty-stricken planet may be found in efforts to lower consumption, in practices that increase resource efficiency, and systems that circulate materials through recovery and reuse.

Waste management options

Historically, the amount of waste generated used to be so small that dilution in the environment was seen as a suitable management option. Industrialisation and urbanisation, however, have made this no longer viable, and organised waste management is now a necessity for assisting in environmental protection, in resource management, and in combating global climate change.

Until recently, waste management focused on "end-of-pipe" solutions with landfill as the predominant means of disposal. But in today's society, sustainable waste management relies on managing resources so that wastes can begin to be avoided altogether. The root of this transition requires moving from a mindset of "waste" as unwanted material requiring disposal to one where it is regarded as a raw material to be fed back into the production process as part of a closed loop system.

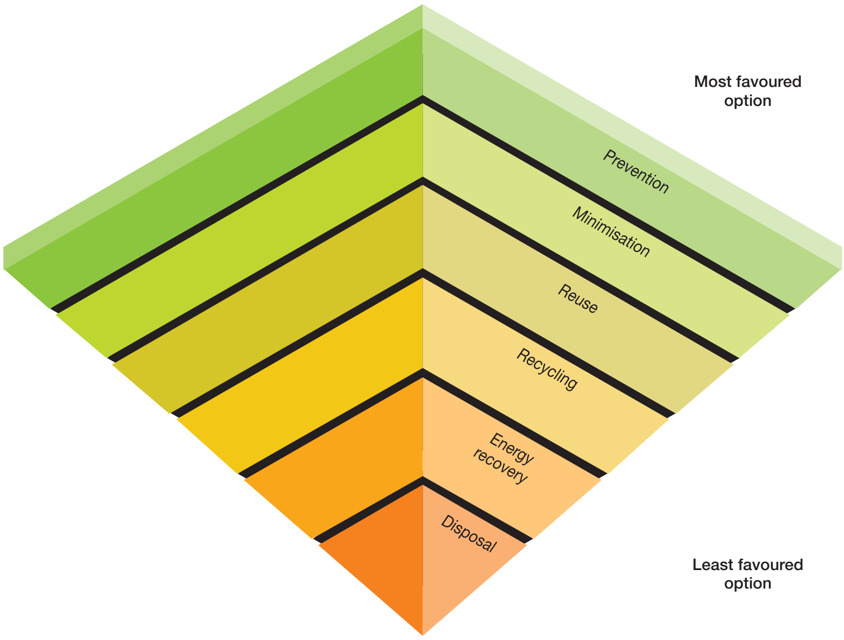
Energy and carbon are also becoming key issues in waste management, with a drive towards systems that maintain the embodied energy or carbon held within the materials.

To effectively manage wastes, therefore, we need to address the issues of sustainable production and consumption using a life cycle-oriented approach. The waste management agenda has recently begun to make this transition, and the focus is shifting from waste towards the sustainable use of natural resources. This is clearly evident in the increasing number of resource management strategies being written to replace waste management strategies. These strategies not only consider physical materials but also seek to reduce the energy required to treat and manage waste and generate an overall reduction in carbon emission. This new focus is encouraging engagement along the entire process chain for products - design, production, and consumption - before finally addressing waste management.

The waste hierarchy

The waste hierarchy[12] (Fig 3) is a useful framework that has, rightly or not, become the cornerstone of modern-day waste management. It sets out the order in which options for waste management should be considered, based on their environmental impact. Although this hierarchy has taken many forms, the basic aim remains the same: to extract the maximum benefits from consumer items and generate the minimum amount of waste.

3. The waste hierarchy.



4. "Light weighting" has resulted in less metal being used in drinks cans.

The hierarchy has been criticised both for being unscientific and not applicable to all countries. It should therefore only be used as a guide. It does not mean that under all circumstances, at all times, a higher option will be better than a lower one. In most cases a combination of options for managing the different waste streams will be needed.

Nevertheless the hierarchy provides a simple rule-of-thumb guide to the relative environmental benefits of different options.

Globally the waste hierarchy has been applied almost exclusively to managing wastes once they have entered the waste stream, but it actually conveys a much broader concept - that end-of-pipe solutions need to be coupled with strategies that look at the essence of the problem, such as how product design and consumption patterns can prevent or reduce waste production. Yet these upper elements of the hierarchy tend to be driven from a waste management perspective without detailed analysis of the overall production cycle of goods and products, and consumer aspirations. Fundamentally this is because waste is still predominantly managed by people employed in the waste management industry who rarely have any control over the waste avoidance techniques placed high in the hierarchy.

Prevention and minimisation

Reduction of waste through prevention and minimisation sit at the top of the hierarchy as they are the most effective ways of both avoiding waste and preventing the associated raw material and energy consumption, as well as any other environmental impacts from the production and consumption activities associated with a product. "Waste reduction" refers to actions taken before waste is generated to either reduce or completely prevent its production, and can be achieved through several mechanisms. In industry a product can be designed thinner and lighter, a process called "light weighting": if a product contains less material, inevitably less waste will be generated at the end of its life. For example, a steel drinks can produced in 1998 was 30% lighter than one manufactured in 1993, and aluminium cans have decreased in weight from almost 100g in 1935 to only 15g[13].

Industries can also reduce waste during manufacturing and through the way a product is transported or a service provided. Some companies, in the UK at least, are getting quite good at waste prevention due to the increasing cost of managing the wastes they generate, ie the recently elevated landfill gate fee of £32/tonne of waste in the UK – to rise to at least £48/tonne by 2010/11[14].

At the consumer level, waste reduction depends on changing our consumption patterns to make us less wasteful and requires significant efforts in public engagement such as education and promotional activities. Changing consumption patterns is notoriously hard to achieve, as it requires modern consumer society to be addressed. To minimise waste, individuals can choose to consume less or choose products with less packaging, for example. They can also choose to buy products designed to last, rather than rely on disposable commodities.

Waste prevention also includes reducing the toxicity of commodities. Removing a heavy metal like cadmium or lead from a piece of electronic equipment lowers the environmental impact of the waste by preventing it from being dispersed into the environment when the equipment itself becomes an item of waste.

Although minimisation should be the top priority in every waste strategy worldwide, most countries have failed to achieve it. In OECD (Organisation for Economic Co-operation and Development) countries, municipal waste has increased approximately 40% since 1980 in absolute terms and 22% on a per capita basis, and projections estimate that waste generation is continuing to grow and increase by a further 43% between 2000 - 2020[15].

Reuse

"Waste reuse" means using an object or material again, either for its original purpose or similar, without significantly altering the object or material's physical form. Recycling, by contrast, does alter the physical form. Reuse is generally preferable to recycling because it often requires less energy and resources.

5. Battery reuse is increasingly common.

6. Composting is a familiar way of managing domestic organic waste.

The major exception is that of electronic appliances where, given a choice between repair and replacement, it may be environmentally preferable to replace appliances such as boilers with new models because of the substantial reduction in energy and/or water requirements.

Reuse has the added advantage of stopping objects and materials becoming waste under its legal definition and can therefore be considered as a form of waste prevention[16]. Charity shops are an example of a reuse service as they take items that are still good for use and resell them to the public.

Composting and recycling

No matter how much effort is put into reduction and reuse, some elements of waste will always be generated from human activities. Composting and recycling are the preferable options for dealing with such wastes.

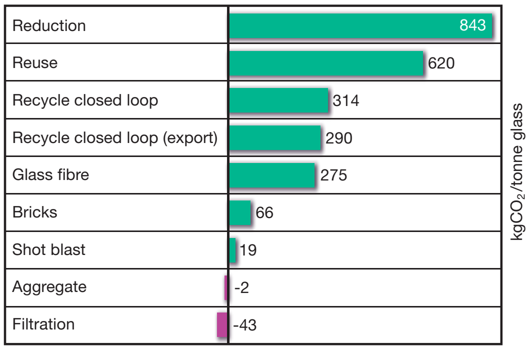
Composting is the controlled biological aerobic (with oxygen) fermentation and decomposition of organic waste (food, garden waste, and paper) by microorganisms into a soil restorer. Composting has huge benefits, primarily in that it keeps organic matter from landfills where it decomposes anaerobically (in the absence of oxygen) producing CO_2 and methane, a greenhouse gas (GHG) with a global warming potential 25 times that of CO_2[17].

Composting organic waste prevents the release of methane and is therefore beneficial in terms of climate change. Composting can be done at many different scales and is particularly effective at the individual household level, eliminating the need for waste transport and further reducing environmental impact.

A second option for managing organic waste treats it in such a way as to encourage the production of GHGs. Biowaste plants use a process called "anaerobic digestion", in which all organic waste (except for liquids) is broken down anaerobically into compost and biogas. The compost is used as a soil improver and the biogas combusted to produce heat and electricity. Such plants are becoming commonplace in many countries.

Recycling uses waste material to manufacture new products, and in doing so alters the physical form of objects and materials. It has the benefit of saving resources as well as preventing impacts from the extraction and transformation of raw materials into products, but appears lower in the waste management hierarchy as additional energy and resources are required to reduce waste levels. Recycling involves collecting, transporting, cleaning, sorting, and then processing of materials so that they may form a new product. Indeed, recycling is not considered to be part of waste prevention because only waste can be recycled.

7. Colour-coding for waste receptacles is now commonplace.



8. Environmental impacts of recycling routes for glass[19].

9. Municipal waste processing plant Spittelau, Austria[20].

The ease and rate at which different materials are recycled vary. Some, such as steel, have been recycled for centuries. Now other metals, paper, glass, some types of plastic, and construction/demolition waste are more or less systematically recycled. Some materials, like aluminium, can be recycled almost indefinitely, but others become increasingly difficult to free from contaminants or – as in the case of paper - may require an addition of virgin material for successful recycling. The economics of recycling vary a lot; metal scrap has been at a very high price for several years, driven by demand from China in particular. Even in the absence of environmental legislation, these materials are recycled where possible.

Recent years have seen a dramatic rise in the export of recyclable materials to markets where it is economically viable to process the waste and where there is a high demand for raw materials. For example, China is the worlds biggest waste importer receiving 4bn tonnes of plastic waste, 12bn tonnes of waste paper and 10bn tonnes of scrap iron and steel in 2004. Within Europe, Germany is the biggest waste importer, receiving approximately 4.15M tonnes of waste in 2003, 98% of which originated in Western Europe.

Although recycling usually consumes less energy and resources than making products from raw materials, it is important to note that some strategies, although well intentioned, can use more energy or themselves produce new wastes or types of pollution. It is therefore important not to assume that recycling is always the best option. Instead a holistic overview, such as a lifecycle assessment (LCA), should be taken to ensure that associated impacts are fully understood. For example, air emissions from aluminium recycling can contain particulate matter in the form of metallic chloride and oxide as well as acid gases and chlorine gas. However, recycling 1kg of aluminium saves 5-8kg of bauxite, 4kg of chemicals, and 14kW of electricity[18]. Because most bauxite is mined in the tropics, recycling aluminium also helps to save tropical rainforests.

Recycling requires the input of energy. LCA enables the comparison of different energy inputs and the associated carbon emissions of recycling methods. One study[19] has demonstrated that some recycling routes offer negligible or even negative benefits in terms of CO_2. For example, recycling glass into aggregate generates more not less CO_2 than using aggregate from other sources. Such information demonstrates the importance of taking a holistic approach and considering the full environmental impacts of waste-related policy rather than just striving for high recycling targets at the consequence of other environmental impacts (Fig 8).

Energy from waste

The term “waste to energy” refers to the process whereby the “energy” content (calorific value) is recovered from waste material. Energy can be extracted from both hazardous and non-hazardous waste streams in several ways. Opinions vary widely on where waste to energy should sit in the waste hierarchy. Some view it as a valid source of renewable energy, substituting for the need to burn fossil fuels as well as diverting waste from landfill. Others, however, regard burning waste as an unacceptable loss of raw materials that may hamper recycling programmes.

Incinerators are the most common mechanism for extracting energy from waste. Incinerators with energy recovery burn waste to produce energy in the form of heat, electricity, or steam to supply other facilities or dwellings. Historically, many badly managed incinerators in Europe have led to a series of scandals and negative public opinion. Today, nearly all such incinerators in the EU have closed, and new ones must comply with strict standards.

Nonetheless, it has been demonstrated that incineration with energy recovery can be very efficient in environmental terms, particularly in Nordic countries where, as well as the electricity produced, incinerators produce heat for local district heating. Currently there are over 600 incinerator plants recovering energy from waste spread over 35 countries[21]. These plants treat nearly 170M tonnes of waste per year and generate energy equivalent to approximately 220M barrels of oil.

10. Waste scavenging is an important but hazardous source of livelihood for the world's poor.

Pyrolysis and gasification are newly developing technologies that use high temperatures to break down waste containing carbon, such as paper, plastics, and organics. Pyrolysis degrades waste to produce synthetic gas ("syngas"), comprising mainly carbon monoxide and hydrogen, with smaller amounts of CO_2 and methane. Other outputs of pyrolysis are pyrolysis oil and char (ash). By using controlled amounts of oxygen, gasification can then break down the remaining hydrocarbons in the pyrolysis oil into syngas. The resulting syngas can used as a fuel to generate electricity or as a basic chemical in the petrochemical and refining industries.

Landfill

The final waste management option is disposal to landfill. Much global waste is still managed in this way, although it is the least favoured option. Indeed, it is likely that with the current patterns of production and consumption and the mix of toxic chemicals entering the waste stream, landfill in some shape or form will be required for many years to come.

Landfills in the EU must be designed to take one of three categories of waste (hazardous, inert, or other), must be separated from the water table, and must have equipment to collect the methane and CO_2 from fermentation of the biodegradable portion. This biogas can then be used to generate electricity.

Informal waste management

In developing countries, waste management is often reduced to what a community can afford. Waste is mostly a big city problem; complications start with waste collection and continue with open dumps and open burning in the middle of towns. In impoverished cities, "waste scavengers" make a living by sorting through landfill sites and collecting recyclable materials.

Such informal systems actually have some environmental and economic advantages. For example they reduce the need for landfill and save natural resources, while providing an important source of livelihood for some of the world's poorest people who are unable to obtain formal employment. In Buenos Aries, informal waste "scavengers" recover 9-17% of municipal waste, representing an estimated saving for the municipality of US$30 000-$70 000 every day, and scavenger households earn about US$58.4 per week[18]. In Asia, whole communities have developed out of the waste industry. Over 60 000 people work on waste dumps in the Philippines. In Brazil 100 000 people earn their living collecting aluminium drinks cans, enabling Brazil to achieve the highest global aluminium recycling rate of 89% in 2003[13].

11. Waste scavengers often endure poor living conditions.

Despite these environmental and economic benefits, scavenging also comes at a huge social cost. The workers are often exploited by waste buyers, have poor health and living conditions, and work day and night without any protective clothing. In Mexico, waste scavengers have a life expectancy of 35 years as opposed to 67 years for the general population[22], a near-50% reduction. It is estimated that children account for roughly half the waste scavengers working in Argentinean cities, with 90% of these minors working more than once a week and for a minimum of three hours per day[19].

12. The plastic bag is omnipresent in our landscape of waste.

Waste as a resource: Can we move beyond waste?

Waste management experts are beginning to think that the present system of waste management may have fundamental flaws, and that a thoroughly effective system may need an entirely new way of looking at waste. As a result, talk about "resource management" rather than "waste management" is becoming increasingly common, as people begin to embrace the "zero waste" philosophy.

The aim of zero waste is to stop thinking of waste as a "waste" and to instead see it as a valuable resource for society. In this sense waste will cease to exist. Put simply, "zero waste" extends current concepts of recycling into a circular system whereby as much material as possible is reused[23].

In this it replicates natural ecosystems that have evolved over millennia so that the waste products of one organism naturally become the resources or feedstock for another, and the major nutrients of carbon, nitrogen, hydrogen, and oxygen are cycled and recycled between animals and plants the planet over.

To move towards such a system will involve breaking away from the current "linear" economy whereby resources are extracted, converted into products, consumed and discarded, and instead embrace a "circular" economy that imitates nature's highly efficient "cradle-to-cradle" system which allows nothing to be wasted.

This will involve fundamentally changing the end-of-pipe way materials are currently managed and instead address wastes and resources along the entire supply/demand chain, starting with product design so that material efficiency and zero waste are in the mind of the designer when pen first hits paper.

It will need an integrated systems approach across all sectors to improve efficiency, avoid all unnecessary waste, and maximise reuse, recycling, and recovery at all stages in the process chain over the lifecycle of goods and services - from sourcing of materials, product design, and production method right through to addressing consumer habits and consumption patterns.

The global consumer class will obviously be key in reshaping the relationship between consumption and sustainability, not only because it is responsible for most material consumption and waste generation, but also because its actions are echoed around the world. Yet solutions will also need to take into account how developing countries are tied into the global economy and their desire to emulate the materials-intensive consumption model that is widely perceived as embodying the "good life".

It is therefore critical to achieve a reduction in the environmental impact associated with consumption, particularly so that increased consumption in developing countries is entirely compatible with global sustainability objectives.

How can we achieve this?

The encouraging truth is that there is no problem without a solution. To move towards a resource-efficient cradle-to-cradle system whereby all the planet's inhabitants live sustainable lives will require the correct balance of economic, social, political, and technological measures. The following list is by no means exhaustive, but sets out some of the ways more sustainable resource management practices can be achieved.

Economic measures

Subsidies and eco-taxation: A key means to achieving more sustainable resource and waste management practices is to send effective pricing signals that encourage more sustainable practices. Numerous subsidies currently make products such as fuels, timbers, and minerals far cheaper than they would otherwise be, encouraging their increased consumption. Although it is difficult to derive an exact value, it is estimated that global subsidies amount to over US$1 trillion per year, with OECD members accounting for three-quarters of the total[24]. Phasing out destructive subsidies and shifting a proportion of the funds to resource efficiency initiatives would help address unsustainable resource consumption practices.

Ecological tax reform is the process whereby market prices are adjusted to reflect the full environmental costs of economic activities. Examples include levies on the use of virgin materials, landfill fees, and other waste and pollution charges that incentivise manufacturers to reduce their generation of wastes and emissions.

In California, a recycling target of 50% diversion from landfill by 2000 was set in 1990, and the state threatened all municipalities with a US$10 000 fine per day for non-compliance. Although it took longer than anticipated to arive at this goal, by 2005 California reached a recycling rate of 52% with some communities diverting over 60% of their waste[25].

Costing externalities: Through incorporating the cost of a wasteful process into the price of a commodity, the total amount of waste generated can be limited. Though plastic bags are still provided free in almost all countries, Ireland has levied a 15c (10p) charge on plastic bags since 2002, a policy that reduced usage by 95%[26]. Similar success was experienced in South Africa where bags were made more durable and expensive to discourage disposal, generating a 90% reduction in usage[26].

Some countries are now beginning to charge for bags in supermarkets, including Austria, Denmark, Germany, Sweden, Finland, Belgium, and the Netherlands. In Mumbai, India, and Bangladesh, governments have gone a step further and banned plastic bags altogether, with fines and prison sentences for people found distributing them.

Another example of incorporating the cost of environmental impact into commodity prices lies in beverage containers. Sweden has achieved an 86% recovery rate for these, driven primarily through an industry-imposed bottle deposit of 10c[27]. Similar success has also been achieved in Michigan, USA, where a 10c bottle deposit has generated a 95% recovery rate[28].

Pay as you throw (PAYT): Charging households for the amount of non–recyclable waste they generate has been a successful way to both increase recycling and reduce the absolute volume of waste generated by a population. The first community to implement PAYT was Richmond, California, in 1916, and since then, over 6000 communities in the US alone have implemented PAYT schemes[29].

PAYT charges residents for collection of waste based on the amount they produce, providing a direct economic incentive to generate less waste and increase composting and recycling. Such schemes have demonstrated huge success in these areas, and additionally decreasing waste collection costs.

Kansas City, Missouri, implemented PAYT in March 2004. Each week residents can dispose of two bags of waste – each additional bag costs $1. To help people maintain this limit, the city actively encourages recycling, and provides residents with free collection of such material. This system is estimated to save the city $2M per year and generates a 30% reduction in waste sent to landfill - 25% of it due to increased recycling and 5% to residents' efforts at source reduction[30].

13. A market stall in Mumbai, where the government has banned plastic bags altogether.

14. Many communities now charge residents for the amount of non-recyclable waste they generate.

Similar success has been seen elsewhere, eg Torrelles de Llobregat, a province of Barcelona, where PAYT has increased recycling from 45% to 83%. In Korea a similar system delivered a 22% reduction in per capita waste volume between 1994 and 2002. The volume sent to landfill fell 43% in the same period and recyclable items rose by 146%[31].

Green procurement: Through the products and services they buy, governmental institutions have great influence. Public purchasing in industrialised countries accounts for up to 25% of GDP. In the EU, government procurement totalled more than $1 trillion in 2001 while in North America it reached $2 trillion[10]. Institutions can therefore have a powerful influence over their suppliers. Through the placement of environmental demands, institutions can shift markets and influence design, efficiency, and durability. This is "green procurement".

In 1998 the US government set a standard demanding the recycled content of all federal paper to be 30%. This generated a shift in recycled content of paper from 10% in 1994 to 30% in 2000 and also increased federal recycled paper consumption from 12% to 90%[10]. The increased government demand also boosted the overall market standard for recycled content in the country. Buying recycled products is the important final stage in the recycling process as it effectively "closes the loop". Many countries are taking this on board: Denmark is a world leader in green procurement with a law in place since 1994 requiring all national and local authorities to use recycled or recyclable products.

15. The average DIY tool is used for just 10 minutes.

Social measures

Influencing consumption: The global consumer class is key in reshaping patterns of resource consumption, simply because it consumes the bulk of the world's resources. Cleaner technologies and more efficient products and production systems will help reduce the impacts of consumption but essentially, consuming better does not alleviate the need to consider moderation in overall consumption levels. In the words of Herman Daly: "To do more efficiently that which should not be done in the first place is no cause for rejoicing"[32].

Influencing consumers is a major challenge. As already noted, a well-designed eco-tax can play a useful role, but the capitalist system leaves decision-making in product purchase almost entirely up to the consumer. More controls on purchasing would be undesirable, but some aspects of individual household consumption can be influenced.

For example, current consumption patterns lead to the production and purchase of many goods that are used infrequently by the consumer. It is estimated that the average do-it-yourself tool is used for just 10 minutes, the rest of life it sits gathering dust[33]. This leads to far greater material consumption than is actually necessary.

Governments and communities can take action to help redress the balance between private and public forms of consumption. Car sharing is rapidly becoming popular in many European cities, and governments can facilitate such initiatives through tax incentives and grant schemes. Similarly, local communities can set up tool and appliance sharing arrangements so that not everyone has to own a separate item.

The "work-spend" lifestyle into which so many are locked drives growth in disposable income, which naturally translates into greater consumer purchases. As the saying goes, "we spend money we don't have, to buy things we don't need, to impress people we don't like". It is clear that consumption goes way beyond satisfying individual's physiological and physical needs. Material consumption is used by many people to create and maintain a sense of identity and to show allegiance with certain social groups. Communication and education will therefore have to play a major role in achieving sustainable consumption. People will change behaviour if they understand the reasons for doing so and it is made easy for them. They need to be informed of the environmental and resource-related consequences of their purchasing and lifestyle decisions. Education is also needed to encourage the use of products made from recycled or recovered materials as well as to inform individuals about the importance of source separation of their household waste.

Developing a recycling culture: Most countries achieving a high level of recycling post-consumer waste have done so by creating a culture of doing so. In Germany, schoolchildren are taught about the importance of properly separating their waste, and separate bins are provided and weighed. The less mixed waste you have, the less you pay. In Vienna airport, for example, all public bins have four different-sized compartments: paper, glass, metal and "other".

The town of Kamikatsu, Japan, has adopted a goal of zero waste to landfill or incineration by 2020, due to the closing of both local incinerators. Although there was initial resistance from the local community, the town now achieves recycling rates of 80% for household waste in the absence of either legislative measures or financial instruments. Local residents take their waste to the local waste centre and separate it into 34 categories. "Recycle Kamikatsu" is a voluntary group set up to help transport waste from senior citizens without cars and also to help people separate their waste at the recycling centre. Anything in good enough condition for reuse ends up at the Kuru Kuru recycling shop where residents can drop off or pick up anything they like, free of charge[34]. Although the success achieved in Kamikatsu may not be transferable to all towns and cities, it clearly demonstrates the success that can be achieved through developing a culture of waste separation and recycling.

Product service systems: A whole new way of thinking about products, the way an economy functions, and what it is supposed to accomplish, has recently emerged. Instead of just selling goods, manufacturers are moving towards the provision of services driven by a transformation of consumer habits. In this, customers do not demand products *per se*, but rather seek the utility that products and services provide. By using a service that meets need rather than a physical object, more needs can be met with lower material and energy requirements. Under such a system the emphasis is on quality retail, advising customers on the best leasing option available, on the quality and upkeep of the products, and on how to extend usefulness while using the least energy and materials.

16. Japan is one of the world's most active countries in initiating the recycling of domestic waste. This example is at Yamaguchi City.

Several companies have already begun to expand on this concept. Xerox already leases over 75% of its equipment, and Dow Chemical and Safety-Kleen have begun to lease organic solvents to their industrial and commercial customers. They advise on the proper use of the chemicals which they recover themselves instead of making their customers responsible for disposal.

Corporate social responsibility (CSR): Many companies are beginning to address environmental issues due to the positive association such moves will have with their brand. Wal-Mart has been pioneering in its approach to addressing sustainability through several initiatives, including one that concerns packaging. In 2006 Wal-Mart set a target to reduce all supply chain packaging by 5% by 2013. Additionally, Wal-Mart has set a target for all transport packaging to be reused and or recycled by 2011 through improved pallets and reusable plastic containers. The sustainable packaging programme is committed to using materials of the highest recycled content without compromising quality. This includes using components the choice of which is based on recyclability post-use.

To achieve these targets Wal-Mart has developed a scorecard system that allows manufacturers to rank their current use of packaging. Scores relate to metrics, including GHG emissions per tonne of packaging, raw material use, packaging size, recycled content, material recovery value, renewable energy use, transportation impacts, and innovation. 60 000 Wal-Mart suppliers use the packaging scorecard, and purchasing decisions are made based on the results.

Through reducing packaging in the Kid Connection toy line, Wal-Mart has reportedly reduced the number of containers required to transport the toys by 427, leading to $2.4m saved annually in shipping costs[8].

Political measures

Governments will play a critical role in moving towards implementing new sustainable waste and resource management processes. Specifically, regulation will allow industry to gain confidence in investing in new technology development, as investing in facilities that are not required to meet regulatory standards under legislation is risky.

Product regulation and labelling: Governments have the potential to influence product development through regulatory mechanisms. National minimum standards for product performance can be set. Minimum standards are complemented by eco-labelling programmes to give purchasers information and encourage manufacturers to design and market more eco-friendly products.

Integrated product policy: At the EU level there is support for integrated product policy (IPP)[35]. This aims to influence the environmental impact of products by looking at all phases of their lifecycles - not just the consequences of disposal but also the impacts of production and factors such as energy use in consumption - and taking action where it is most effective. With so many different products no one simple policy measure can be applied to all. Instead a whole variety of tools - both voluntary and mandatory - can be used to achieve the IPP objective, including economic instruments, substance bans, voluntary agreements, environmental labelling, and product design guidelines.

Extended producer responsibility (EPR): Waste can be avoided if manufacturers factor in environmental considerations at the product design phase. EPR laws encourage this by imposing accountability with manufacturers over the entire product/packaging lifecycle and requiring companies to take back products at the end of their useful life.

EPR typically bans the landfilling and incineration of most products, establishes minimum reuse and recycling requirements, and specifies whether producers are to be individually or collectively responsible for returned products. This mechanism shifts the responsibility for waste from government to private industry and encourages the internalisation of waste management costs into product prices. EPR encourages producers to consider waste management and the full lifecycle of the product in the initial product design as it is of advantage for them to do so. They will then ideally eliminate unnecessary parts, reduce unneeded packaging, and generate products with parts that can easily be disassembled, recycled, remanufactured, or reused.

In Europe this concept has been embraced and legislation exists to control waste from electronic and electrical equipment, cars, tires, batteries, office equipment, furniture, construction materials, and packaging. Germany has been the EPR pioneer in tackling packaging, and passed a law in 1991 requiring producers to take packaging back for reuse or recycling.

Over three years, recycling waste paper rose to 54% from 45% where it had stagnated for 20 years[10]. Austria instituted a similar system in 1993 and has achieved 73% recovery and 64% recycling[36]. In both countries the "Green dot" logo (Fig 17) is used by companies to signify the transferral of their obligation to collect, sort, and recover packaging waste to a third party.

17. The "Green dot" logo.

Tradeable permits: Governments can use permits to regulate and reduce resource consumption, waste generation, and environmental pollution over time. The concept behind tradable permits is that all polluters are sold a defined amount of permits allowing them to discharge waste or pollution. If an organisation can reduce their discharge, they can sell their remaining permits. For example, landfill allowance trading schemes (LATS) allocate tradable landfill allowances to each waste disposal authority in England, allowing the disposal of a certain amount of biodegradable waste per year. These authorities can then use their allocations in the most effective way such as trading with other disposal authorities or saving them for future years.

Technological measures

None of today's industrialised economies is truly sustainable and all could be leaner without suffering significant setbacks. Annual material throughputs in America and Europe are estimated as 80 and 51 tonnes/person respectively, but for an average Japanese it is just 21 tonnes. Given the broadly similar living standards of Americans, Europeans, and Japanese, clearly there is considerable room for improvement in both the US and Europe.

Hidden material flows: Much of the material flow in industrialised economies never passes through consumer hands, but these "hidden material flows" account for around 60% of the total in Europe and around 70% in the US. Dealing with these hidden flows requires some of the most destructive practices, ie logging, mining, and smelting in particular, be downsized.

This can be accomplished though numerous technical solutions that improve energy and material efficiency, boost recycling and reuse, and lengthen the lifetime of products, so that the need to extract virgin raw materials is much reduced.

Rethinking product design: 80-90% of products' lifecycle economic and ecological costs are already inevitable once they have been designed, and before manufacture. We must therefore address how we make things, from their design to how they are put together and how they are used.

Products should be designed to last, so that they become "waste" less quickly, and to be easily remanufactured, deconstructed, or recycled when they do become waste. Complementing this, manufacturers should move wherever possible towards using recycled materials.

A major problem, though, is that almost no product on the market is actually designed with recycling in mind. When a car is recycled, the high quality steel is mixed up and contaminated with copper cables, plastics and paints that decrease the quality of the steel and limit further options for its use. Recycled steel sometimes requires high quality virgin steel to be added to make it usable again, and still it will not be of a grade sufficient to produce a new car.

Product design coupled with new technological advancements can help to address this issue. "Active disassembly" makes use of smart materials, such as shape memory polymers, that will change their shape at a "trigger temperature"[37]. This allows for product components to be easily disassembled and separated so that the different materials can be collected and reused, remanufactured, or recycled. For example, mobile phones designed for active disassembly could be dropped into a special tumble dryer and heated to a trigger temperature. Within seconds the phones would be dismantled, allowing plastics to be recycled and toxic components dealt with appropriately.

Dematerialisation: This process is aimed at reducing the amount of raw materials needed to create a product. Advocates have pushed for a "factor 10" reduction - policies that aim at providing a given volume of goods and services with 1/10th of the material input[11]. Indeed there was some success in this area with resource productivity in the EU improving by 30% between 1980 and 1997.

However, this improved efficiency has not translated into an overall reduction in resource consumption which instead has remained essentially constant as consumer wants and needs continue to increase. Although dematerialisation is an important step towards achieving more sustainable economic activity, alone it may be insufficient to contend with humanity's increased desire for consumption and thus must be coupled with strategies addressing consumption.

Clean production: Toxic materials are another matter for concern, yet there are plenty of opportunities to reduce and even eliminate reliance on them in manufacturing to prevent air and water pollution and avoid hazardous waste generation. An innovative example of achieving cleaner production was in a pulp and paper mill in Maine, USA. In the early 1990s it was a major polluter but a shift in management led to active co-operation with local stakeholders. Initial focus on end-of-pipe pollution control was replaced by the implementation of pollution-preventing measures. There was a rapid reduction in the release of organic pollutants and mercury, dioxin and chloroform emissions were eliminated, and particulate emissions reduced by 50%. Hazardous waste generation decreased 95% by 1998 and solid waste to landfill decreased 91%[10].

Industrial ecology: This is the "cradle-to-cradle" system of integrated, closed-loop material flows whereby the byproducts of one organisation become the feedstock of another. The community of Kalundborg in Denmark is widely regarded as the best example of industrial ecology. Here, an increasingly dense web of symbiotic relationships among local companies has slowly evolved over the past three decades yielding both economic and environmental benefits. For example, natural gas from the refinery becomes feedstock in a plasterboard factory, fly ash from the coal-fired power station is used by a cement manufacturer, and sludge containing nitrogen goes to nearby farms for fertiliser. Interestingly, rather than planning for sustainable manufacturing, the business relationships in Kalundborg evolved spontaneously due to their economic benefits.

18. Agriculture is the beneficiary of organic sludge supplied as nitrogen-rich fertiliser.

19. Some new carpets are being made from perpetually recyclable fibre.

Cradle-to-cradle design: The current destructive qualities of our cradle-to-gate system can be seen as a fundamental design flaw rather than the inevitable output of modern-day economies. Good design, based on natural systems and a cradle-to-cradle philosophy, can transform the making and consumption of things into a positive system. Indeed, the traditional approach to sustainability focuses on improving the efficiency of material use and energy consumption and while this is a useful strategy it tends to reduce harmful impacts rather than prevent the harmful activity in the first instance. As Michael Braungart, one of the cofounders[23] of the cradle-to-cradle concept, put it: "By destroying a little less, we are not protecting anything. So it is not about being less bad, but about doing the right thing"[38].

A well-known example of cradle-to-cradle systems is Honeywell's high quality carpet, *Zeftron Savant*, made from a perpetually recyclable nylon 6 fibre[39]. The polymer has been specially designed to be reclaimed and turned back into new carpet without the requirement for extra material or degradation in carpet quality. Additionally, Honeywell can collect carpets made from old conventional nylon 6 and transform it into *Zeftron Savant* - in effect "upcycling" rather than "downcycling", with the material "rematerialised" rather than "dematerialised".

Modular products: Most consumer products are made in ways that render them near impossible to repair and have damaged or broken parts replaced. Even when something can be repaired the cost is often so great that it encourages people to throw the old model out and buy new.

Durability, repairability, and upgradability are essential to lessen the environmental impact of consumption. A modular approach permits access to individual parts and components so that they can be easily replaced. Companies like Xerox have adopted this philosophy and extended the useful life of their products, leading to increased opportunities for maintenance, repair, upgrading, recycling, reuse, and remanufacturing, and thus greater business and employment potential throughout product life.

Xerox, a pioneer of remanufacturing, kick-started its Asset Recycle Management initiative in 1990, which led the company to design products from the outset with remanufacturing in mind and every part reusable or recyclable. As a result, 70-90% of equipment returned to Xerox at the end of its life can be rebuilt[10].

Conclusion: beyond waste

Waste is a crisis of human doing and it is becoming increasingly difficult simply to ignore. It is a result of the ever-increasing population combined with our growing consumerist culture.

Adding to the difficulty in many parts of the world is the endemic corruption – the corner-cutting, local officials' "hands in the till" – that tends to undermine central government efforts to bring in and, more importantly, effectively enforce environmental and waste management legislation. China, for example, has some of the most extensive environmental legislation in the world but currently lacks enforcement. Nonetheless it may be indicative that its State Environmental Protection Department (SEPA) was recently upgraded to the status of Ministry. This now opens the door for more funding, greater power, and more staff to radically strengthen enforcement.

Long-term, viable solutions will require action at every level - personal, corporate, and government, but the solution must start with rethinking the very concept of waste and our relationship with the world around us. Although it is hard for people to make the link between the waste they generate and the global patterns of resource depletion and environmental degradation, this is fundamental for achieving change. Sometimes it is said that thinking such change can be achieved is unrealistic and idealistic, but the true unreality lies in assuming that the global population can continue consuming at its current rate *ad infinitum*.

A movement is beginning that seeks to embrace sustainable consumption through the philosophy behind zero waste. This begins with the design of products that seek to eliminate the concept of waste - through cradle-to-cradle design, industrial ecology, clean production, dematerialisation, modular design, etc.

Changes at this level need to be reinforced with political, financial, and social drivers to encourage people the world over to consume more sustainably and, as a consequence, take better care of our global resources and produce less wastes. If this doesn't happen, we will be limited to solutions that merely slow down our impact on the world around us, rather than dealing with the fundamentals of the problem at hand.

As Einstein is reputed to have said: "The world will not evolve past its current state of crisis by using the same thinking that created the situation."

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Credits

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20. Young girl walking through her backyard at a waste dump in Mexico City.

Damped outriggers for tall buildings

Rob Smith Michael Willford

The St Francis Shangri-La Place development at Manila in the Philippines incorporates the first use of the damped outrigger concept, developed by Arup for safer, more comfortable, and more economical tall buildings.

Introduction: the dynamic response of tall buildings

For buildings of about 40 storeys and more, dynamic resonance in wind starts to have a significant effect on the design. A building's dynamic resonance is similar to that of a tuning fork – the higher the building, the lower the frequency. Unfortunately the lower the frequency, the more the building is "excited" or "resonated" by the wind, which has two effects:

- The occupants start to feel the movement, potentially leading to complaints or even panic.
- The design loading due to wind needs to be increased.

The dynamic response of a tall building is governed by several factors, including shape, stiffness, mass, and the damping. While engineers can predict with reasonable certainty the effect of the first three, it is more difficult to do this for the level of damping.

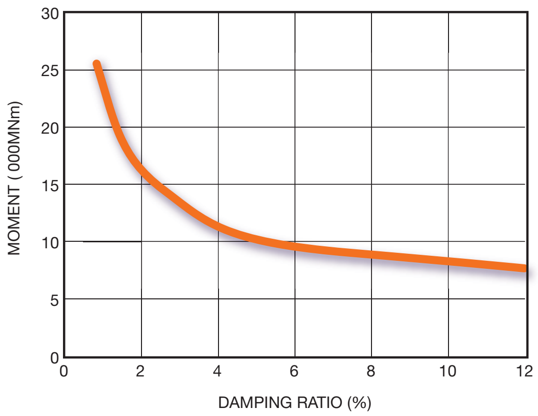
Damping is the degree of energy dissipation that a structure can provide, helping to reduce build-up of the resonant response. It comes from two main sources: intrinsic and supplementary. All buildings have intrinsic damping - from the structural materials, the foundations, the cladding, etc - but it is very difficult to predict as it depends on so many factors. Supplementary damping is added by the engineer and is only currently used in a small minority of buildings. As it is engineered, however, predicting it is much easier. The degree to which damping affects structural loading can be seen in Fig 2, which shows the global overturning load in a 400m high building. By increasing the level of damping from a typical intrinsic level of 1%, it is possible to reduce this overturning load by a factor of three.

By adding an engineered supplementary damping system to a building, it is possible to remove dependence on the low and uncertain intrinsic damping. This improves the reliability of dynamic response predictions and, by supplying higher levels of damping, substantially reduces the required stiffness of the building while at the same time improving the performance.

This article describes a new method – the damped outrigger - by which high levels of dependable damping may be introduced into high-rise building structures, and the benefits that may be realised. The towers of St Francis Shangri-La Place in Manila incorporate the first use of Arup's damped outrigger design. These twin towers, at 217m, are the highest residential buildings in the Philippines. They are within 2km of an active seismic fault, and in an area subject to strong typhoons.

As well as making the buildings safer and more comfortable, the use of the damped outrigger both reduced the capital cost of the towers and increased their floor area.

1. St Francis Shangri-La Place.



2. How overturning moment varies with damping in a tall building.

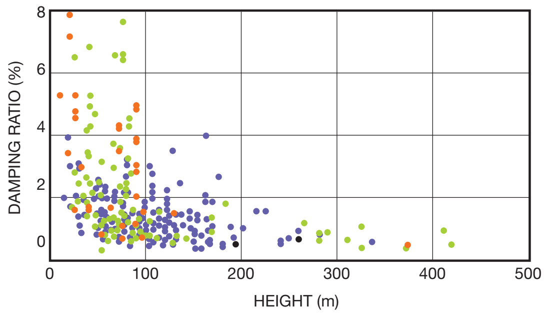
Intrinsic damping in tall buildings

To predict the likely level of damping in a tall buildings, Arup collated data on the measured values for buildings from around the world. Taken from various published academic sources, the data are shown in Fig 3. Three conclusions can be made:

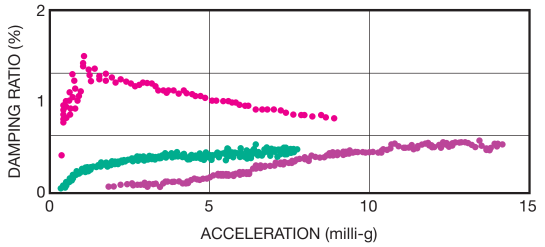
- The measured values show a lot of scatter.
- There is a clear downward trend with increasing height.
- There is no clear difference in levels of damping between steel, concrete, and composite construction.

The decreasing levels of damping with increased building height can be explained by considering the non-structural elements – cladding, partitions, etc – the relative effects of which reduce as buildings increase in height. These non-structural components add significantly to damping for smaller buildings, but not for tall ones.

A common misconception is that damping always increases with amplitude of motion. If this were the case, then the measured values in low and moderate winds could be seen as "lower bound", with expected values in stronger (ie 50-year) winds being higher. However, research has shown that, for tall buildings, this is not always the case, with damping actually decreasing with amplitude in some instances (Fig 4).



3. Measured intrinsic damping of tall buildings.



4. Examples of measured damping vs response level.

Designing for safety

The uncertainty and variability in the data present risks for building design. The measurements suggest that in common practice damping is often overestimated, with the consequence that design wind loads may be underestimated. This leaves the engineer with a choice:

- Be cautious, choose a low level of damping, and design for higher forces.
- Add supplementary damping to remove uncertainty and increase damping.
- Find other methods to reduce sensitivity to dynamic loading.

For most tall buildings, the second option will often be the most economic method of controlling wind resonance.

Supplementary damping systems

Tuned mass dampers

Tuned mass dampers (TMDs) or their variation, tuned liquid dampers, are an established and proven method of adding damping to a building. However, they have several drawbacks.

- They are large, heavy, and take up valuable space at the top of the building.
- They have to be "tuned" closely to the measured natural frequency of the building mode of concern; if there are several modes of concern, then several sets of differently tuned devices are required.
- They are usually introduced at the end of a design, and so form an additional cost. No offset in the structural cost can be made.
- They have no redundancy - there is only one TMD (per mode) and if it fails, resonance will increase. For this reason, TMDs are not relied upon in ultimate wind loads or seismic events.

Viscous/visco-elastic dampers and similar devices

An alternative supplementary damping approach is to add discrete damping elements, such as viscous or visco-elastic dampers, which behave much in the same way as shock absorbers in cars, albeit with much less movement and significantly more durability.

Viscous dampers are commonly used in both new-build and retrofitting of buildings and bridges in areas of seismic activity. Their use to control wind response is less established – the project which forms the subject of this article shows a crossover of technologies between different disciplines within structural engineering.

The damped outrigger concept

How it works

Outriggers are a common method of stiffening and strengthening tall buildings. They work by connecting the inner core to the outer perimeter columns, much as a skier uses his arms and shoulders to hold onto ski-poles, providing extra stability. The method is very effective, and favoured by many structural engineers.

The damped outrigger works by the insertion of viscous dampers between the outriggers and the external columns (Figs 5, 6). When this is done, there is a smaller increase in stiffness of the building, but a significant increase in damping.

For a high-rise building, where resonant wind loading is significant compared to static, this is a huge benefit. The dynamic response of the building to the wind is reduced dramatically, along with the lateral accelerations (which can cause discomfort in building occupants) and the design wind forces.

There are many variations on this concept, but the principle lies in adding and/or connecting structural elements with components primarily to develop damping, rather than primarily to develop additional stiffness.

Damping FAQs

What is damping?

Damping is the physical phenomenon of the reduction of motion through energy dissipation, eg the control of vibration in a car's suspension system, or the vibration of a piano string slowly dying away on its own.

Why is it important to tall buildings?

Tall buildings oscillate with long natural periods (or low frequencies). This makes them particularly susceptible to dynamic resonance in wind, as wind energy is highest at low frequencies. In addition to responding to the natural gustiness of wind, in tall buildings a common form of dynamic response in wind is caused by vortex shedding. This creates movement perpendicular to wind direction.

Where does damping come from?

Tall buildings have two principal sources of damping:

(1) *Intrinsic damping:* this comes from the structural material, connections, cladding, foundation, friction caused by interior fit-out and, in the case of seismic movement, damage to the structure.

(2) *Supplementary damping:* engineered devices such as tuned mass dampers, slosh dampers, viscous dampers, and friction devices.

Why should I worry?

For very tall and slender buildings, dynamic wind response will often dominate lateral loading and the design wind load can be up to three times the static wind loading (ie a dynamic amplification factor of three). Estimates from most wind loading codes will underestimate the dynamic response, and if this happens, it will leave a building susceptible not only to increased acceleration (in the serviceability state), but also to fatigue loading and understrength design in the ultimate wind loading.

Wind tunnel tests enable the dynamic response to be calculated more accurately, but the wind tunnel consultant still needs to make an assumption about what the structural damping is – it cannot be measured before the building is built.

How can dynamic wind response in tall buildings be controlled?

There are three broad methods:

(1) *Shape or sculpt the building:* Vortex shedding is reduced significantly when a building has an irregular shape, is tapered, or has built-in obstructions (eg strakes on chimneys). All these have the effect of breaking up vortices or preventing them from "locking in" simultaneously over the whole building. This may not be appropriate for all buildings, and may increase the cost of construction as well as losing space efficiency.

(2) *Stiffen the building:* This is the traditional approach to controlling wind response and is often appropriate for shorter buildings. However, for taller buildings it can be extremely expensive to provide enough stiffness.

(3) *Add damping:* This is often the most cost-effective method of controlling dynamic response. In addition, by adding supplementary damping, the consequences of uncertainty about intrinsic damping are reduced.

Usually two or three of these approaches are taken in parallel – each project is different.

How do I know what intrinsic damping to assume?

Traditionally a damping level of 1-2% of critical has been assumed for tall buildings. However, recent research and review of measured data shows 0.5-1% to be more appropriate for buildings over 250m tall. Several factors determine the damping, but as yet, there is no foolproof method of predicting damping of a tall building with any accuracy. A cautious approach (say assuming 0.5%) risks overestimating wind loads and increasing the cost of the project. A more conventional approach (say 1.5%) runs the risk of underestimating wind load. Adding supplementary damping removes some uncertainty as the response of an engineered damping system can be predicted with more (although not total) accuracy.

Why is damping in earthquakes bigger?

Damping ratios listed in codes for structures in earthquakes are typically around 5% for concrete structures and 2% for steel. These figures are higher than for wind since they take in energy absorption through damage. It is not possible to consider this energy dissipation in wind (even ultimate wind loading) since wind storms are much longer than earthquakes, and prolonged inelastic behaviour would lead to fatigue failure.

What types of dampers are there?

(1) *Tuned mass damper (TMDs):* These are giant pendula at the tops of buildings. They work by oscillating out of phase with the movement of the building. TMDs are established proven technology and have been used on many buildings around the world. However they have several drawbacks: they are expensive, complicated mechanisms, take up the most valuable part of a building (the top), and have no redundancy so are not usually used to damp earthquakes or ultimate winds.

(2) *Tuned liquid or slosh dampers:* These use the same principle as TMDs but with sloshing water instead of a mass. They are cheaper but bulkier than TMDs.

(3) *Viscous dampers:* These giant shock absorbers dissipate energy by relative movement in them. They have been used to reduce seismic response for many years - many buildings in Japan use distributed viscous dampers. The damped outrigger concept uses viscous dampers.

(4) *Viscoelastic dampers:* These can be used but tend to be temperature-sensitive, and so will lose efficiency as they generate heat in a storm. The best example of their use was in the New York World Trade Center where thousands were installed throughout the buildings to supplement low intrinsic damping.

Can I use a swimming pool as a slosh damper?

Not really. Efficiency is very dependent on the depth, length, shape, and presence of baffles within the water. It would not be an ideal swimming pool.

How stiff should I make my building?

A rule of thumb is to restrict a building's total deflection to height/500 during the 50-year wind. This is a reasonable starting point, but this limit is not absolute. In some cases, where no supplementary damping is added, the stiffness may need to be increased.

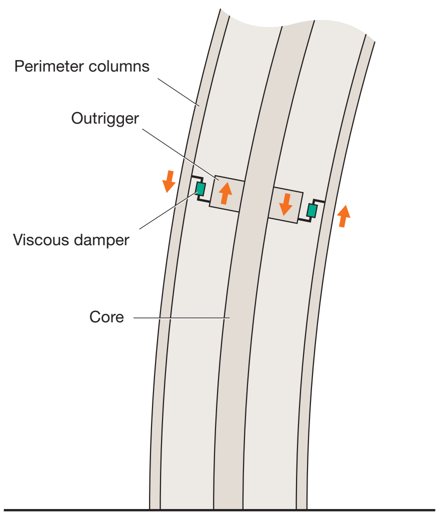
How do I know if I "need" dampers?

Rarely is it a question of whether damping is needed, rather if it is economic. Early in the design stage, the benefit of damping vs stiffness can be estimated and a judgment made of how stiff the building should be. Once wind tunnel testing is complete, the stiffness and damping can be optimised to get the most cost/efficient solution. The wind tunnel testing specification should allow for several design iterations from the structural engineer.

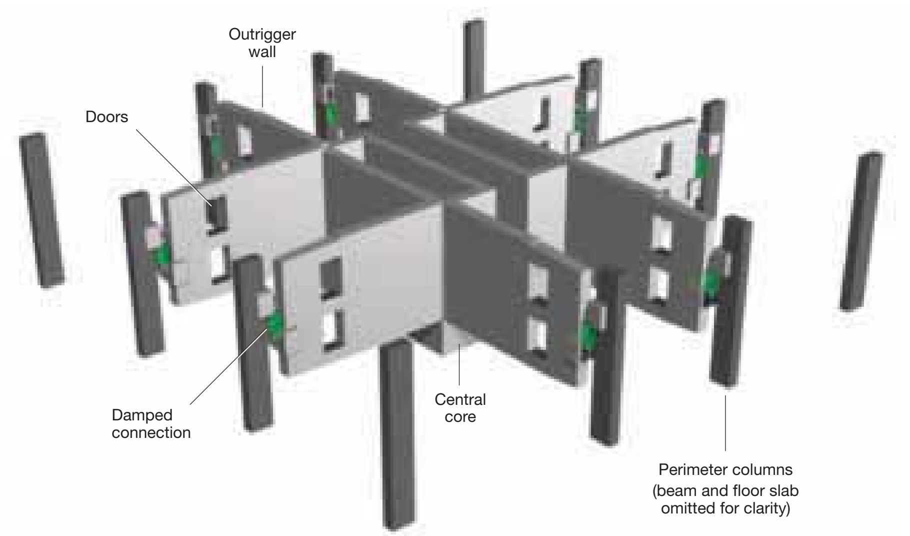
Aren't dampers an extra cost to a building?

If supplementary damping is added late in design, it can be seen as an additional cost. However, the alternative is usually to stiffen the building, which will often cost more. By considering damping early on in the design process, it is possible to exploit its value to the full and optimise the balance of stiffness and damping.

5. The damped outrigger concept.



6. Isometric of core, columns, outriggers, and dampers.



7. The London Millennium footbridge.

8. Viscous damper under bridge deck.

9. Diagonally braced viscous damper under abutment.

Where the idea came from

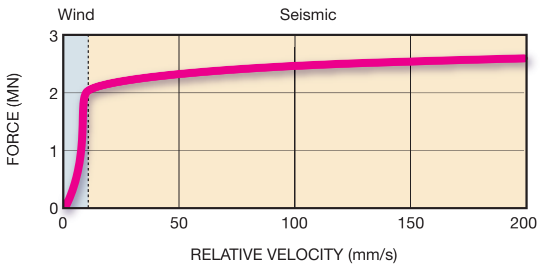
The London Millennium footbridge opened in 2000 but was soon closed following its widely-publicised lateral movement[1]. The solution Arup developed to reduce this movement used damping devices and was extremely effective (Figs 7-9). At the time, Arup was also concerned with a number of tall building projects that were predicted to vibrate in the wind. The ideas put into place on the horizontal bridge were turned around for the use of vertical buildings.

The design

Seismic performance

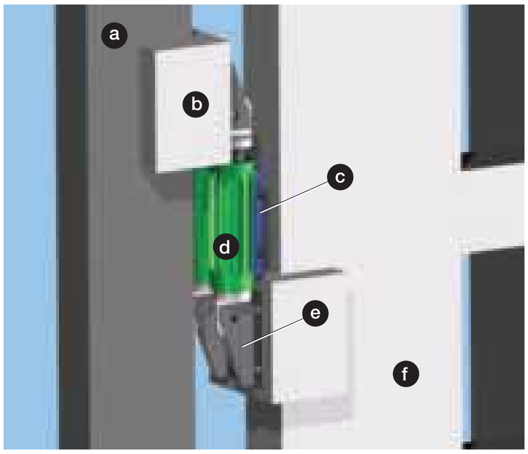
The specification for the dampers on the St Francis Towers needed to consider the effect of earthquakes. Manila is in the same seismic "zone" as California and this being the case, careful attention to the performance of the building and dampers in an earthquake was required.

The dampers were designed to work at optimum level in the "ultimate" wind (31m/s). The velocity of the piston in the damper is up to 10mm/s in wind loading, and up to 200mm/s in an earthquake (Fig 10). Because the force in the damper is a function of the velocity of the piston, the dampers were designed to restrict the force that they would generate by use of a pressure release value (Fig 11). In the unlikely event that this valve fails, the outrigger walls are designed to yield in a ductile manner, but still remain intact. Even if the whole outrigger/damper system failed, the building would remain standing after the most extreme earthquake, although it would be damaged more than if the dampers had worked.

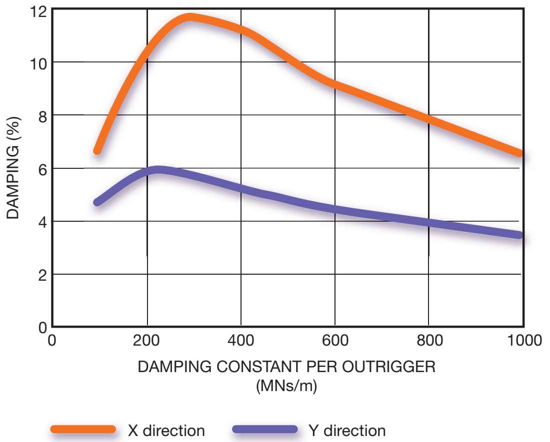


10. Performance of damper under wind and seismic action.

11. Damped connection showing: (a) column, (b) connection block, (c) pressure release valve, (d) damper with cooling fins, (e) steel connection, (f) outrigger wall.



12. Testing the dampers.



13. Variation of global damping with viscous damper coefficient.

Manufacture and testing

The dampers for the St Francis Towers were manufactured and tested by FIP Industriale, based in Italy. The damper design was based on a modification of a standard product produced by FIP with a performance specification written by Arup. A rigorous testing procedure was specified and witnessed by Arup, including a full-scale simulation of the forces induced by earthquakes (Fig 12). This involved a 400kW peak power input into the testing rig, which put a significant strain on the local electricity grid.

Maintenance, inspection, replacement

The specification for the dampers placed a big emphasis on durability, testing, and the use of high quality materials, with the intention that they be maintenance-free. The technology used in the dampers is proven, having been developed over several years for both military and civil applications. The London Millennium Bridge dampers were produced with a 35-year warranty[1] and are maintenance-free, other than repainting.

Nevertheless, it can never be said with absolute certainty that there will be no problems , so inspections are recommended to look out for the unexpected. An analogy can be made with bridge bearings – they need to be inspected, should have no planned maintenance, but will probably need to be replaced during a bridge's lifetime.

Reliability and redundancy

A significant advantage of using multiple viscous dampers to control wind response is that the damping system can be used to reduce the forces that are used in the building design. Without a damping system, the resonant wind response (and hence design forces) would be much higher. Since the ultimate wind loads are being resisted by dampers, there is a safety issue to consider and this is addressed by adding robustness and reliability to the damping system.This is done by:

- adding more dampers than are necessary for "optimum" performance. This means that if some dampers fail, then the performance does not immediately deteriorate (as more dampers fail, the performance point moves to the left on Fig 13).
- using dampers that act in parallel with each other
- physically separating the dampers from each other
- designing for the case when a number of dampers fail
- assuming that the damping system may not act at 100% efficiency
- designing such that even if all dampers fail the building would be damaged, but would not collapse.

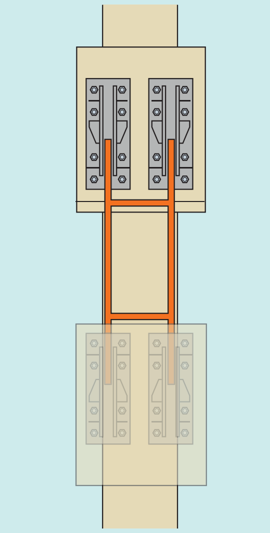
By applying this prudent approach to risk and robustness, it is justifiable to use the dampers in the "ultimate" load conditions, rather than just "serviceability" conditions, as is typically the case with mass dampers.

Installation

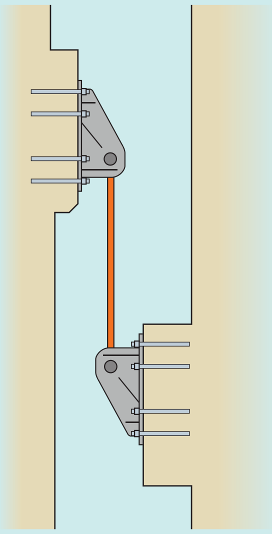
The dampers do not require special equipment to install. Lifting and bolting them - each weighs about 1 tonne - is within the capacity of most competent contractors (Figs 14-18).

14. The dampers do not require special equipment to install.

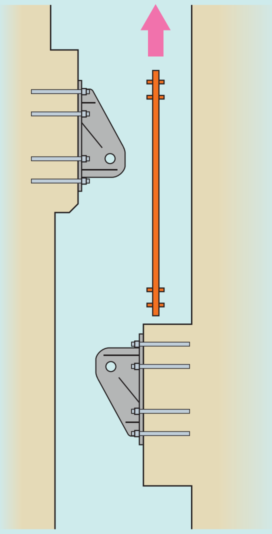
15. Installation procedure.



(a) Anchor frames cast and connected by template.

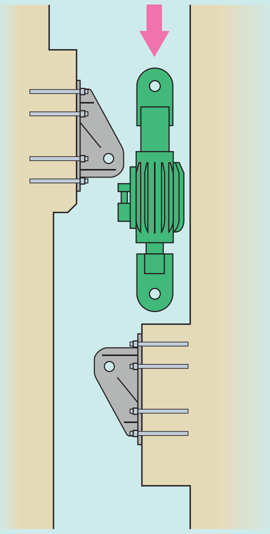


(b) Concrete left to cure.

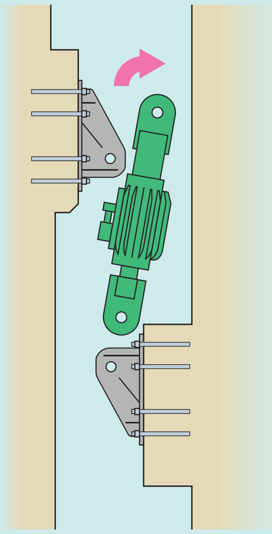


(c) Template removed.

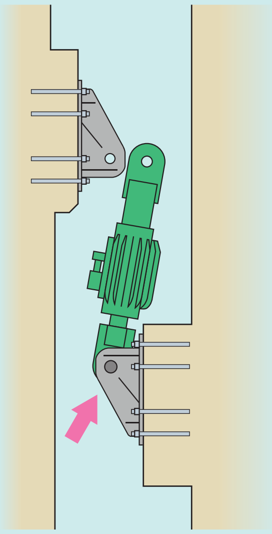
16. Damper being lowered manually using winch.



(d) Damper lowered parallel to anchor frames.

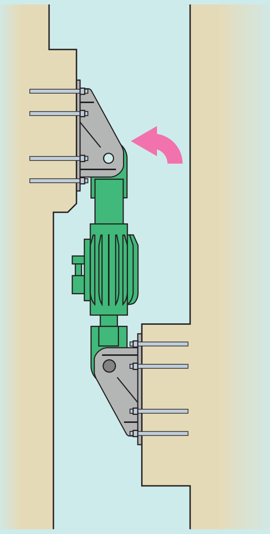


(e) Damper rotated by 10˚.

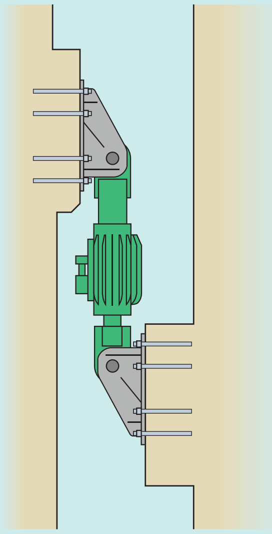


(f) Damper connected to lower anchor frame.

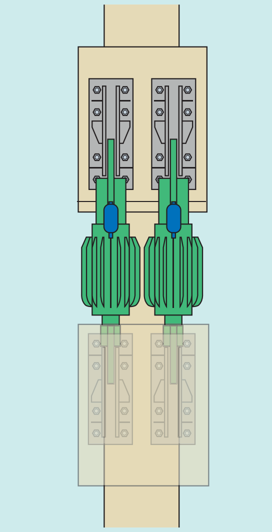
17. Contractor fits first damper to lower anchor frame.



(g) Damper connected to upper anchor frame.



(h) Damper in final position.



(i) Second damper in final position.

18. Both dampers in final position with pressure release valves fitted.

Benefits

Economic benefits

There is a reduction in overall capital cost; since the stiffness and the strength of the structure can be reduced, the costs of structural materials and associated labour are also less. Of course, the cost of dampers, testing, and installation needs to be added, but in the case of the St Francis Towers project, for example, there was a net saving of at least US$4M. For most of the tall building projects over 200m high that have been reviewed by Arup, there would be a net cost saving if a damped outrigger system or similar was used.

The net floor area increases, because with the reduction in design forces, the column sizes can be decreased. This typically leads to 0.5-2% more net floor area. This may sound small, but its value can often exceed the capital cost savings made. Maintenance and inspection costs also are minimal: the dampers are designed to be maintenance free, with inspections only as a measure of prudence.

Finally there is the matter of replacement cost. The owner should plan to replace the dampers once during the building's lifetime. This is obviously expensive, but still fairly small compared to the cost of maintaining and replacing items such as lifts, generators, air-conditioning plants, etc.

Safety and performance benefits

Naturally it is difficult to quantify the reduction in risk of damage from typhoons and earthquakes, but it could mean the difference between having a building that can be repaired instead of having to be replaced following a major earthquake. The more day-to-day occupant benefit is that the motion felt in windy weather is significantly reduced. Again, it is hard to place a value on this, but it could mean the difference between a building that is "comfortable" and one that is not.

The future

Arup has so far specified the use of viscous dampers in five tall building projects around the world: in the Americas, Asia, and Europe. This new technique for controlling the dynamic resonance of tall buildings has a serious future. The damped outrigger concept, the details of which are discussed in more detail in an award-winning journal paper[2], and similar arrangements are subject to patent law. Arup welcomes the use of this concept in other projects, even when the firm is not directly involved. Please contact IntellectualPropertyExecutive@arup.com before proceeding.

References

(1) http://www.arup.com/MillenniumBridge

(2) SMITH, RJ, and WILLFORD, MR. The damped outrigger concept for tall buildings. *The Structural Design of Tall and Special Buildings*, *16*(4), pp501-517, November 2007.
Winner of the "Best Journal Paper of the Year (2007)" award from *The Structural Design of Tall and Special Buildings* journal. http://tinyurl.com/4ccmg3

Credits

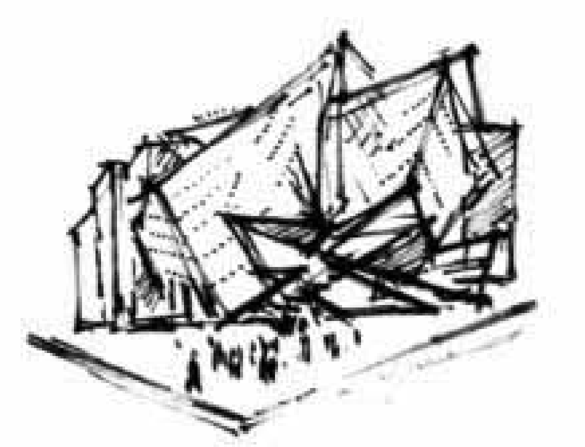
Client (St Francis Shangri-La Place): The Shang Grand Tower Corporation
Architect (St Francis Shangri-La Place): Wong & Tung International Ltd (WTIL)
Structural engineer and damping consultant: Arup – Ronald Aberin, Andrew Allsop, Edmond Asis, Arnel Bautista, Efren Bongyad, Janice Carbonell, Carmina Carillo, Narciso Casanova, Ernesto Cruz, Norbie Cruz, Therese de Guzman, Sheng de Veyra, Mimmy Dino, Xiaonian Duan, Floyd Flores, Bernadette Gajasan, Rico Gomez, Damian Grant, Annie Kammerer, Ana Larin, Chris Lewis, Rob Livesey, Leslie Lucero, Raul Manlapig, Mary Rose Mejia, Anne Navarro, Sarah Owen, Ender Ozkan, Darah Pineda, Rene Ponce, Daniel Powell, Archie Ricablanca, Armie Rico, Kristinah Samy, Rob Smith, Joe Stegers, Chris Villanueva, Michael Willford, Lorraine Yoro, Cesar Zamora **Illustrations:** 1 ©Arup/WTIL/ Shang Grand Tower Corporation; 2-5, 10, 13, 15 Nigel Whale; 6, 11, 14, 16-18 Arup; 7 Grant Smith; 8 Tim Armitage; 9 Mark Arkinstall; 12 Riccardo Merello; 19 Raul Manlapig.

Rob Smith is an Associate Director of Arup in the Advanced Technology and Research group. He led the development in Arup of the damped outrigger concept.

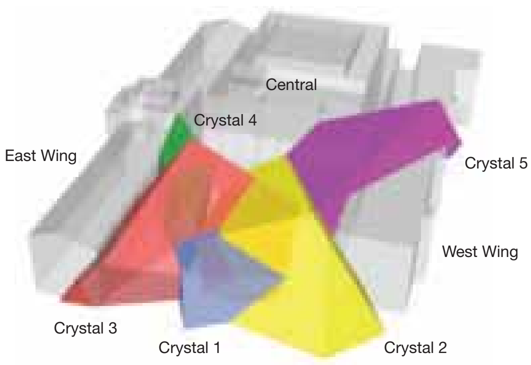
Michael Willford is an Arup Fellow and Global Leader of the Advanced Technology and Research group. He is the inventor of the damped outrigger concept.

19. The St Francis Shangri-La Place development under construction, October 2008.

1. Architect's concept of the "Crystal" extension within the existing museum.



2. Original "napkin sketch" by Daniel Libeskind.



3. The five "crystal" volumes.

The Royal Ontario Museum, Toronto

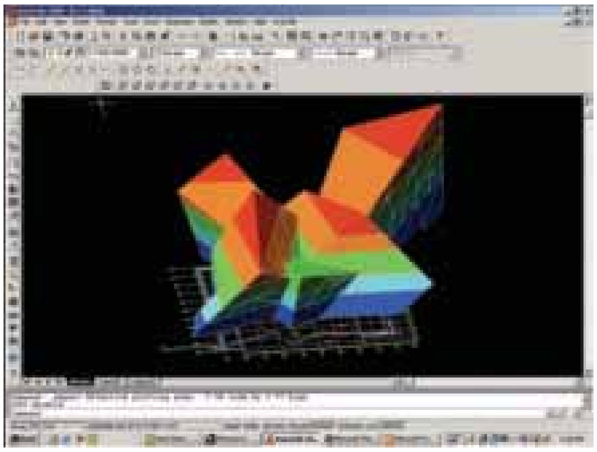
Florence Lam David Lewis Julian Sutherland

The Crystal extension designed by Daniel Libeskind is a spectacular and iconic new building for Toronto.

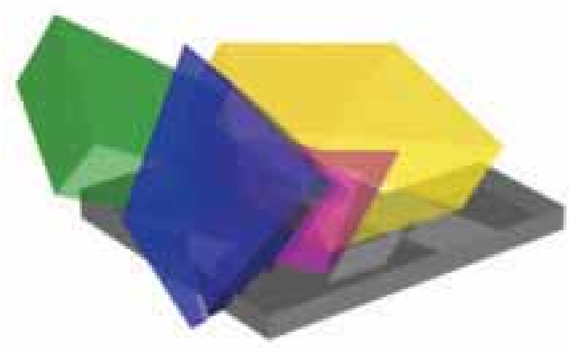
Background

Toronto's original Museum of Natural History and Fine Arts opened in 1857 at the Toronto Normal School ("normal school" is a now little-used term for a teacher-training college). The enactment of the Royal Ontario Museum Act by the provincial government in 1912 re-established the museum as the Royal Ontario Museum (ROM), with a new building designed by Toronto architects Frank Darling and John A Pearson in the then-fashionable Italianate neo-Romanesque style.

This opened in March 1914, since when the ROM has undergone three major expansions. In 1933 the first of these added an east wing fronting onto Queen's Park, including an elaborate art deco Byzantine-inspired rotunda and new main entrance. Both this wing, designed by Alfred H Chapman and James Oxley, and the original building are listed as heritage buildings of Toronto.



4. Main structural frame from *GSA* program.



5. Crystal geometry study.

The second wave of expansion began in 1964 with the addition of the McLaughlin Planetarium to the south. This was followed by a new multi-level atrium in 1975, and then the Queen Elizabeth II Terrace Galleries on the north side of the building and a curatorial centre built on the south. This second major addition to the ROM, begun in 1978 and completed in 1984, was designed by Toronto architect Gene Kinoshita, with Mathers & Haldenby.

The third expansion

A major donation by the Jamaican/Canadian investor, Michael Lee-Chin, enabled the museum to implement a further much-needed expansion, beginning in 2002. After an international search, Studio Daniel Libeskind was selected as architect for the new Renaissance ROM project, in a joint venture with the Toronto practice Bregman + Hamann Architects.

On his first visit to the museum Libeskind saw some wonderful mineral crystal displays and, with pen and napkin (Fig 2), the “crystal” form of the new building, and its challenge, were established. His architectural vision developed into a set of six “colliding prisms” clad in brushed aluminium (one of them later removed for cost reasons). This overall form (Figs 1, 3) contrasts spectacularly with the existing buildings, but the Michael Lee-Chin Crystal, named for the principal sponsor, has provided dynamic new architecture, a great public attraction, and 100 000ft² (9290m²) of new exhibition space.

Situated on one of the most prominent intersections in downtown Toronto, the Crystal established itself as a dynamic centre for the city when it opened in June 2007.

Arup, working with local engineering consultants, was appointed to engineer the architectural vision, the scope of which also included renovating 10 galleries in the existing buildings on either side of the Crystal.

Structural engineering

Methodology

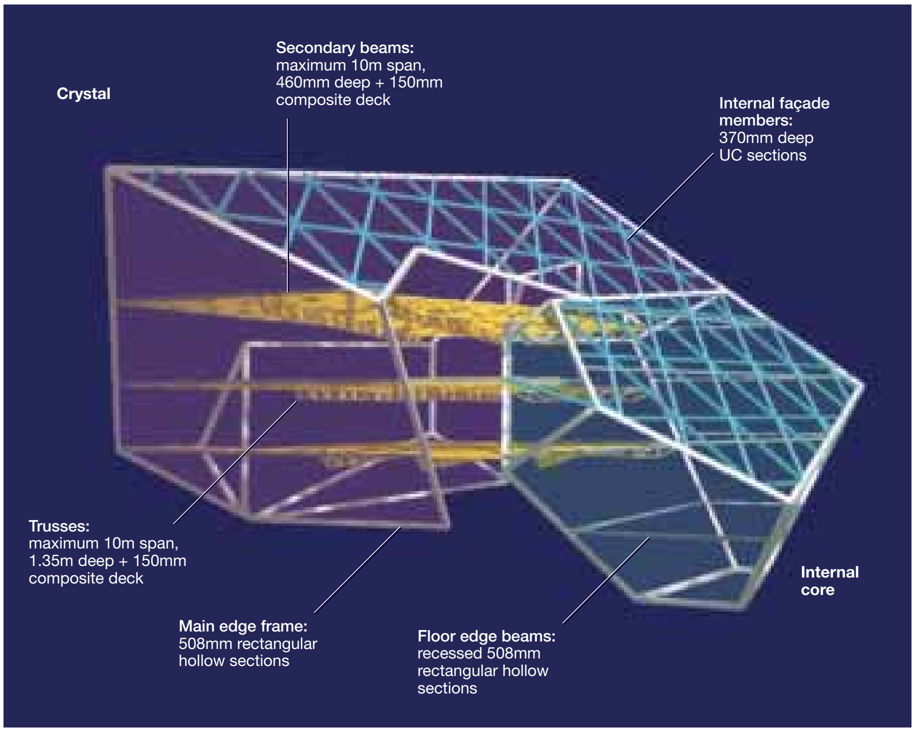
Libeskind’s buildings are well known for their unusual shapes, and the challenge to the Arup team to form the structure started at the competition stage, a challenge heightened by the desire to insert the new construction within the form of the original buildings and match to their existing floors.

On earlier projects with Libeskind, such as the Imperial War Museum North in Manchester, England, a joint working methodology had been established using 3-D programs such as *Form Z*, *Rhino*, and Arup’s own *GSA* to enable rapid transfer of information between architect and engineer. For the ROM, this provided a base structural concept and graphics for the competition entry. By demonstrating to the client and his technical team how the work would be carried out, the 3-D modelling was vital to securing the commission.

These programs were used extensively throughout the design phases, including to establish the building services routes and compatibility with the structural frame (Fig 4). The *GSA* output was returned to the architects’ *Form Z* model to ensure that agreed boundaries of structural zones were not transgressed and avoid clashes with the existing building. Eventually the model was transcribed to *X-Steel* (Tekla Structures), and SAP 2000 for final analysis and results compatibility check. These were then given to the contractor for use during fabrication and erection.

GSA’s graphical output capability also demonstrated how the structure would fit together (Figs 5, 6), and together with the architect, the Arup team used renderings of inside and outside surfaces to demonstrate internal finishes and external cladding.

6. Main structural components.



7. Crystal 5 oversailing the original building.

Arup's local structural engineering partner was Halsall Associates, and design work was shared between the two offices. Generally superstructure concept and scheme work was begun in London and then completed in Toronto. All works associated with foundations, infrastructure, and interventions to the existing buildings, including seismic modifications, were undertaken by Halsall.

Structural integration with the existing building

The new structure's relationship to the existing building was crucial (Fig 7), particularly regarding seismic design. No increase in lateral load had to be transmitted to the sensitive original masonry structure, which would have needed a complete and relatively costly upgrade. As a result, much care was taken in positioning supports and bearings when they were unavoidable.

The new building's very unusual shape necessitated wind tunnel tests to determine with greater accuracy the effects of applied wind forces including drag, as well as whether any unforeseen changes would affect the existing building. This modelling was also used to review performance of gaseous laboratory extract from the museum's conservation departments, and to predict snow drifting and ice formation on both the new and existing buildings. As the existing roofs had relatively poor capacity, snow drifting needed to be avoided.

Substructure

The area to be occupied by the new building included the traditionally concrete-framed Queen Elizabeth II Terrace Galleries building. This had become unsuitable for the museum's use, as well as masking some façades of the earlier buildings deemed desirable to re-expose to public view, and so was demolished to make way for the new reinforced concrete basement construction, designed to avoid the foundations of the original buildings and the need to underpin their footings (Fig 8). New piled foundations were installed and the structure designed with air intake and extract trenches to suit the location of the main building services plantrooms.

The basement space is for guest exhibitions, the type of "blockbuster" shows of national and international importance for which additional entrance is charged. It is thus as column-free as possible, though structural support for the superstructure had to pass through it, aligned and angled with the walls of the "crystals" above to visually connect the underground and overground architecture (Fig 15).

Superstructure

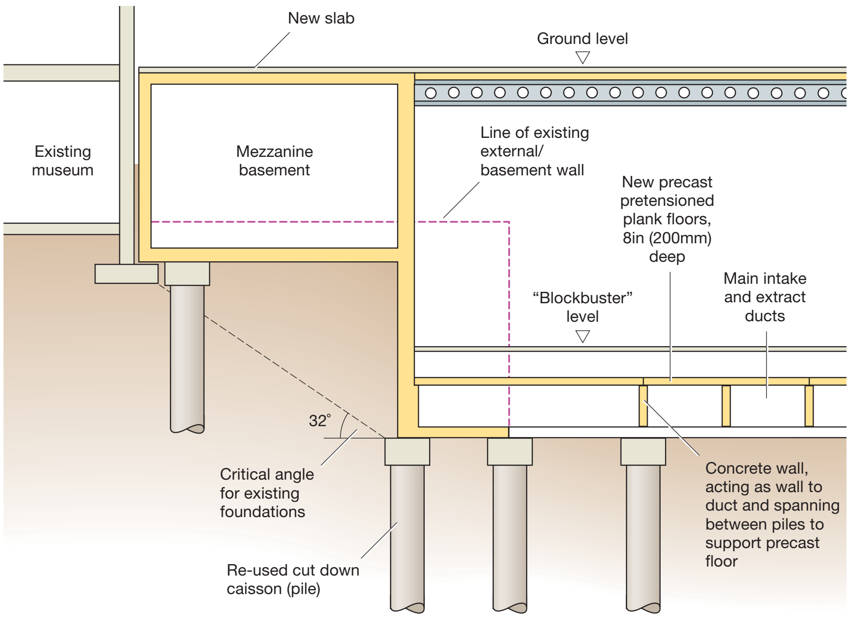
The shape and complexity of the building led to the early and natural decision, even at competition stage, to use structural steelwork. During the submission Arup was tasked with providing cost information. The structural steel component of this was significant, and was monitored extensively throughout the project.

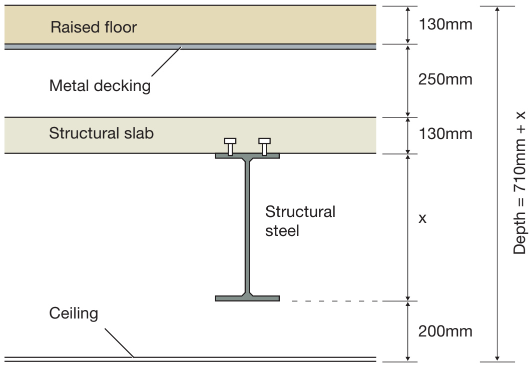
Considerable care was taken to maintain an effective and economical design at all stages. The frameworks were tailored to suit the shape and form of the building (Fig14) and to harmonise architecturally with the glazing in the cladding envelope. Fortunately, the 3-D modelling and established data transfer protocols allowed for some design experimentation to be carried out with the architect to arrive at the final chosen arrangements.

Composite steel and concrete floors complement the steel frame, and act as horizontal membranes that contribute to stabilising and maintaining the structural form. Notably, in the superstructure only a single wall is vertical; all the others generate lateral forces that act complexly on the floors. The team reviewed many load cases to ensure that the worst case structural design envelope was determined.

The building services distribution systems were incorporated into a structural raised floor (Fig 9) to give flexibility of use in the exhibition spaces. The exhibit plinth within the raised floor zone allows exhibits such as dinosaur skeletons to stand at the same level as visitors.

8. Stepped foundations adjacent to original building.





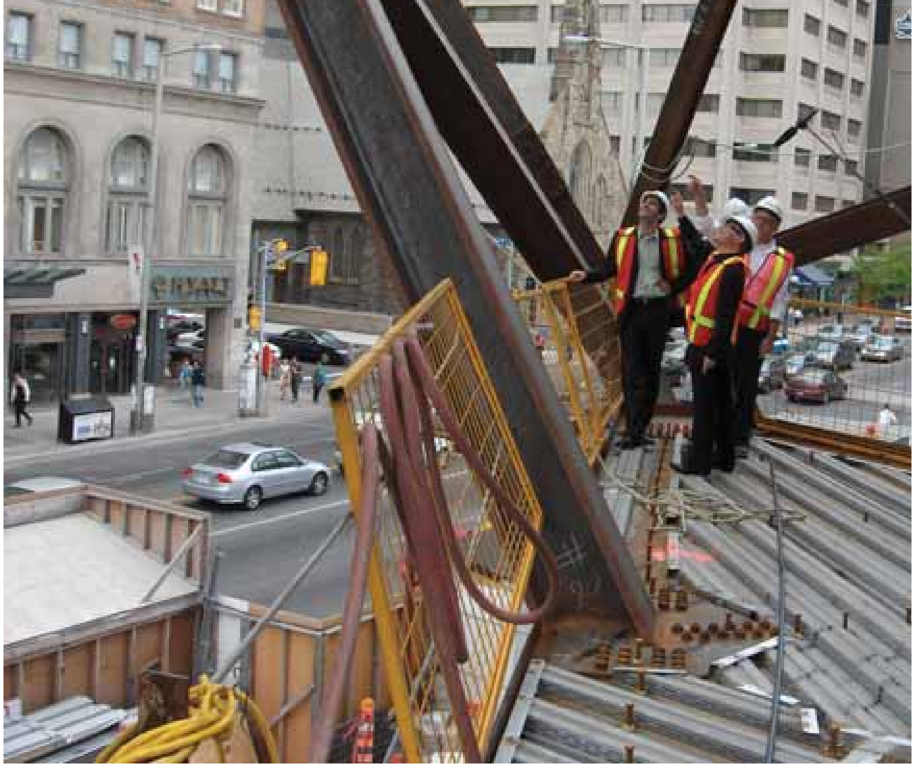
9. Structural raised floor.

Steel fabrication

The team was conscious of the need to bring a steel fabricator's advice and expertise into the final design stages, as clearly the method and sequence of construction would have potential impacts on the frame. The client was keen that local industry be supported; however, the design team needed to be sure that it was competent to carry out such an unusual and demanding project.

In the dialogue that ensued, potential contributors recognised the benefits of close collaboration. Feedback on section types came in good time for the detailed design to be finalised. For example, the specialist custom box sections initially envisaged as forming the Crystal's corners proved unsuitable for the local market and so were redesigned with wide flange beam types.

10. Crystal 5 overhanging the original building.



11. Daniel Libeskind and ROM Director and CEO William Thorsall viewing progress.

The file transfer protocol used during the concept stages was continued into the fabrication phase. The contractor drawings were rendered into actual section sizes and returned to the architects' *Form Z* drawings for compliance review. Wherever this resulted in a section change this could also be reviewed in the analysis programme. This care over fit and analysis eliminated almost all the issues that arose during fabrication and erection.

The fabrication realised some novel approaches in the workshop. The node geometry and member arrangements were complex in three dimensions, and so the steelworkers were equipped with laptop computers in the shop in order to visualise the joints. There was no conventional grid referencing system for the project and various methods of communication were used to identify components, starting with identification numbers for the five "crystals". Inevitably, however, some of the components were given figurative names such as "owl's head" and "stair of wonder" to reference their locations (Fig 10).

Erection

The erection sequence was crucial not only to suit the location and progress on site but also to ensure that the frame remained stable and within stress limits. The team was concerned that, when only partially erected, the frame would not behave as designed and modelled. Halsall's commission was extended to include construction engineering and provide works sequencing to reflect the schedule requirements.

It was important that the erected structure not be overstressed as a result of locked-in forces, and to ensure that misalignments were avoided in later erection positions, 14 models were created and reviewed with the construction managers and fabricators. This led to specific arrangements for temporary elements to maintain geometrical accuracy. This was important both in respect of adjacencies to the existing structure on three sides, and to facilitate the application of the 25% glazed and 75% aluminium external envelope. The process was a success and monitoring stations were used to chart construction progress. Satisfyingly, practice followed theory and the structure behaved as predicted by analysis.

Erection was completed with minimum site modifications and very few co-ordination issues. This success was underpinned by significant teamwork from competition concept through to fabrication and erection. Visionaries, architects, engineers, planners, and constructors worked sequentially and in parallel through close collaboration to understand and find solutions appropriate for the structural complexity of this landmark building (Fig 11).

12. New frame adjacent to original building. 13. Crystal 5 spanning the original building. 14. Frame tailored to suit cladding arrangements. 15. Frame springing from "blockbuster" basement level.

Environmental control

Design criteria

The heating and cooling requirements were based on local external design data corresponding to a 99% statistical distribution: winter -17.8°C, 100% relative humidity; summer 32°C, 24°C (wet bulb).

The internal design criteria were as follows:

"Blockbuster" gallery (basement) and Level 4 galleries in the new building

- internal summer temperature 21±2°C
- internal winter temperature 21±2°C
- relative humidity 45±3%
- outside air rate 8l/s/p.

Crystal galleries (Levels 2 and 3)

- internal summer temperature 24±2°C
- internal winter temperature 20±2°C
- relative humidity (summer) 55±5%
- Relative humidity (winter) 35±5%
- outside air rate 8l/s/p.

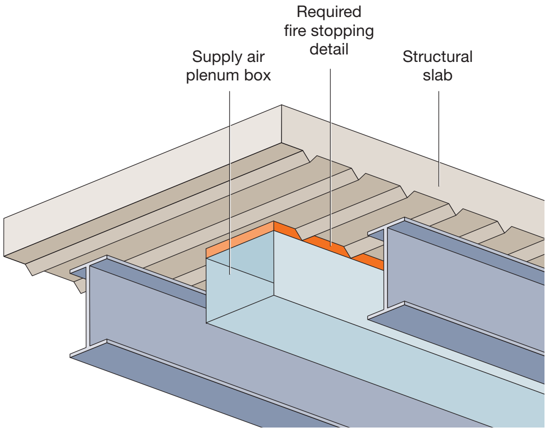
Galleries in existing buildings

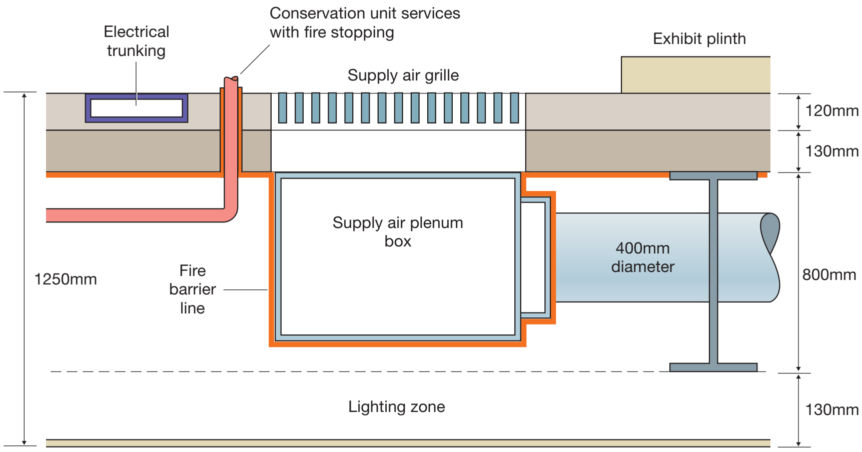
- internal summer temperature 24±2°C
- internal winter temperature 20±2°C
- relative humidity (summer) 55+4-8%
- Relative humidity (winter) 35±5%
- outside air rate: as existing.

The team developed the internal design criteria and gallery locations to optimise their performance relative both to the façades and the exhibitions they would contain. All galleries are entered via a series of buffer spaces to limit the influence of the external on the internal environment. Door air locks were carefully integrated into the entrance door arrangements and main entrance level and atrium to form a giant environmental buffer.

The "blockbuster" gallery for international travelling exhibitions requires international standard conservation criteria for temperature, humidity, and light. Its position in the new building's basement allows these factors to be closely controlled.

16. Crystal gallery floor slab.





17. Crystal gallery floor slab: section.

The Level 4 galleries are environmentally separate from the other Crystal galleries and the existing galleries, allowing close control of temperature and humidity. Their daylit environment enhances the visitor experience, and careful analysis of the windows and resulting solar exposure ensures that artefacts are protected accordingly.

The other Crystal galleries and the existing galleries are interconnected for obstruction-free visitor circulation. The design conditions were limited by the heritage status building fabric, which struggles to control vapour, infiltration, and thermal exchange. Minor repair work was undertaken to improve the fabric performance with secondary glazing and vapour barriers.

Where it is necessary for temperature, humidity, and light to be very closely controlled in any gallery, discrete closed cases are used. These are integrated into the design of the galleries with their dedicated plant housed in local plantrooms.

Energy efficiency

Maintaining energy efficiency within a curatorial environment is difficult, but by careful selection of systems, components, controls, and space links it is possible to recover energy and reduce waste. Arup included energy recovery on all the new ventilation systems using both active and passive technologies:

- condenser water-free cooling circuits integrated into the chilled water system
- passive cooling and heating (used between the intake and extract tunnels under the "blockbuster" floor by heat energy transfer through the tunnel walls)
- high efficiency motors, pumps, and fans
- underfloor air supply with free cooling condenser water circuits
- variable volume water circuits to reduce pump energy
- zoned ventilation systems to allow capacity to match demand
- design to comply with ASHRAE 90.1 Energy Code.

Crystal galleries ventilation design

The Crystal galleries have a low-level ventilation system, in which an innovative double-slab floor acts as a supply air plenum with linear grilles integrated into the floor finishes (Figs 16, 17). The floor plates are very large and the traditional approach of charging the floor void from the cores would not work. The supply air is ducted from the cores in the ceiling of the floor below and connected to the floor void above via fire-rated plenums.

The Crystal's walls are generally of dry lining fixed to the main frame. The voids between the inner and outer walls are used for MEP services risers and built-in display cases for specific items that need closer environmental control. Ventilation and cooling to these cases also pass through the voids around the steelwork. These risers are inclined within the crystal walls or attached to the lift cores. All the gallery air-handling units (AHUs) are fitted with dual cooling coils to offer significant energy savings, each AHU having equal-sized cooling coils in parallel controlled in sequence either singularly or as a pair. This operation allows dehumidification to match part loads in the museum without the huge corresponding reheating load of a single coil system.

A perimeter heating system, integrated into the façade floor trims, offsets draughts and local thermal losses at the windows.

Façade and thermal envelope

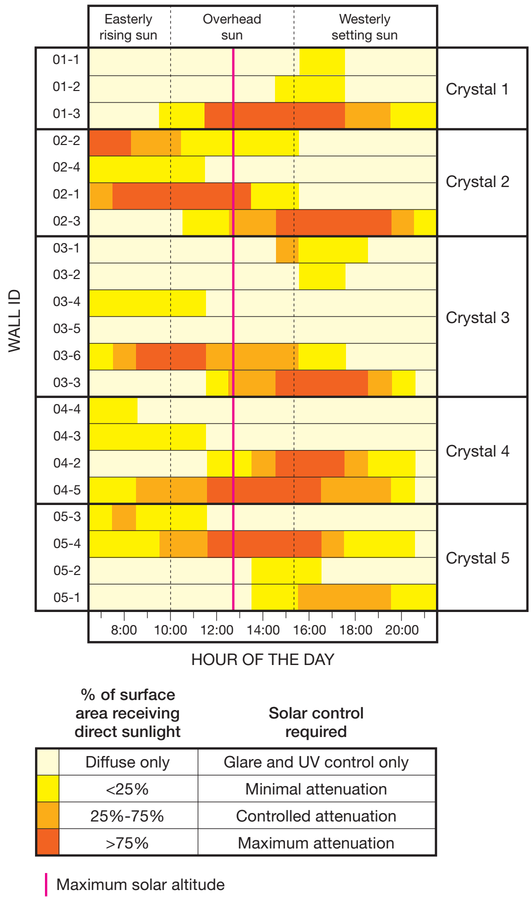
The Toronto climate is very extreme; the seasonal temperature differential exceeds 50˚C (Fig 18). This puts considerable strain on the thermal envelope, with the energy demand driven by the façade performance. The Crystal's high levels of insulation and relatively small areas of glazing give a thermally-efficient building with reduced thermal gains and losses. This high-performance envelope helps to stabilise the internal environment and thus preserve the museum artifacts. Control of solar gain is essential to limit the installed cooling capacity, reduce running costs, and maintain daylight standards and comfort. Also, the exhibits on display must be protected from direct sunlight and excessive heat gains.

Analysis of the site sun path and shading from the surroundings allowed the team to map the glazed openings and the amount of shading across the numerous Crystal façades (Fig 19). A combination of glass performance, deep reveals, slot windows, and internal shading was deployed to satisfy this analysis.

Central plant and distribution

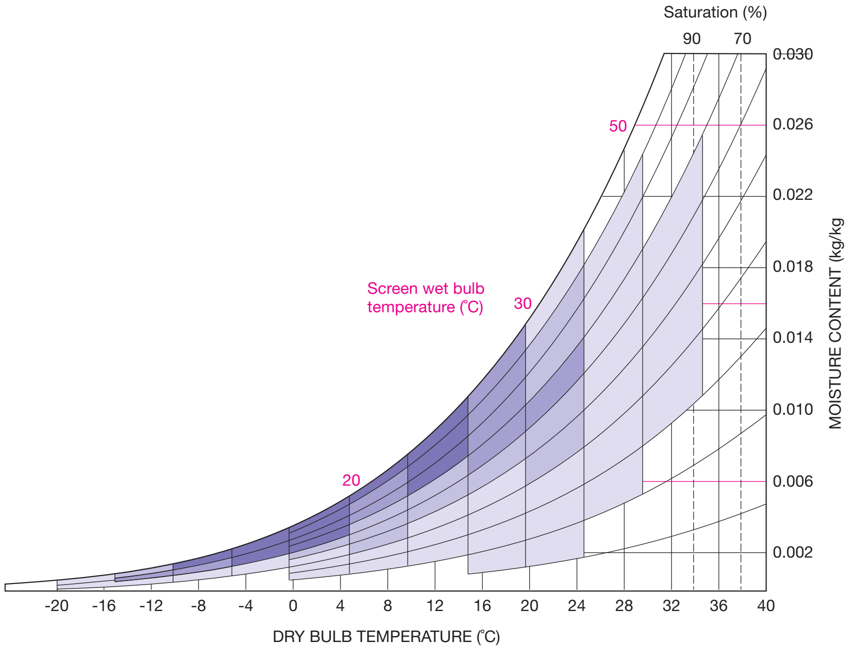
Gallery scope normally takes priority in a museum, leaving internal and basement space for primary plant. While this is acceptable for heating and cooling plant, it presents challenges for the ventilation system, which needs good access to outdoor air. The museum is connected to the city's steam heating mains and the incoming service was upgraded with new heat exchangers to match the new total demand.

Aside from the increased capacity needed to supply the new galleries, the existing chilled water plant was well past its "use-by date" and needed replacement.



19. Analysis of solar incidence on crystals,

18. Analysis of the Toronto climate and opportunities for free cooling.



As the development was within an operational museum, so the replacement also had to be done alongside and link into the existing operation. Careful phasing of the basement refurbishment allowed a new chilled water plantroom to be created.

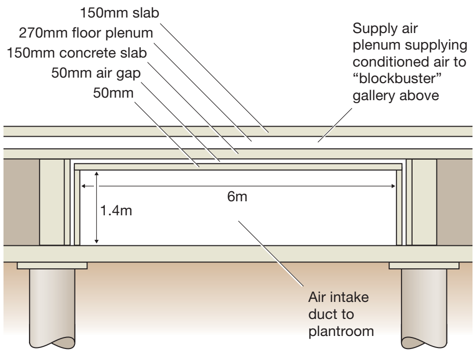
The new plant was installed and a new section of cooling tower was fitted to match the increased load and system. All this was commissioned and brought on line before the existing plant was decommissioned, the old plantroom subsequently being refurbished for storage.

The gallery compartment AHUs that were already located with each wing and level of the existing building were surveyed and maintained to increase their operating life.

The new Crystal gallery plant is in the basement of the central wing of the existing building, a location unusable for gallery functions but connecting well into the Crystal gallery construction. The team investigated ways to get outdoor and exhaust air to this location, but most of them compromised gallery space or had high construction costs. The final solution was to take the main intake and exhaust entirely under the Crystal gallery construction and integrate the louvres with the "blockbuster" gallery plantroom in the north-east corner of the site.

20. The completed Crystal 3 intersects spectacularly with the existing building.

21. Crystal galleries.



22. “Blockbuster” gallery ventilation system.

The below-slab ducts, formed by folding the basement slab downwards to create a wide channel with a lightweight cover cast above, benefit from passive thermal exchange with the earth, capturing free heating and cooling when possible (Fig 22).

The Crystal gallery ventilation ductwork was then routed through the “blockbuster” ceiling/main entrance floor construction into the central risers around the Crystal void.

Stormwater design

The design of the roof drainage system presented many challenges, with ice and snow build-up even more important than water. The complex shape also presented many obstructions to the natural flow of rain and melt water.

Each Crystal surface and intersecting valley was analysed for gradient and used as the primary water drainage route. Then the edge conditions were checked for gravity-based water runoff to identify whether it would travel inwards to a gutter or outwards off the edge. If the latter, a hidden edge gutter was fitted. Finally the windows were analysed for runoff redirection and to check that there was adequate capacity for water to go around them. If there was not, the window was bisected and a rainwater channel formed between. This process generated a very simple rainwater system, albeit with a very complex geometry.

The main valley gutters also formed the primary access route for maintenance.

Snow build-up was analysed in wind tunnel tests, and where it was shown to be excessive, snow melting tapes were installed. To avoid undue energy waste, these were only fitted where absolutely necessary to control structural loads and not just to clear the roof.

Fire protection

The entire building is sprinkler-protected, and the new galleries have a zoned smoke control system with fans built into the thick Crystal walls to extract smoke based on a fire signal.

Lighting design

Naturally daylit exhibition spaces are having a renaissance, leaving behind the black-box track-and-spotlight technique that until recently dominated US institutions. With daylight's dynamic ever-changing nature and better colour rendering than artificial light - plus the environmental bonus of energy efficiency - the benefits are clear. Despite technological advances, the human eye will always be able to perceive the subtle qualities of a light source, and daylight is impossible to simulate convincingly. So, the move to exploit ambient natural lighting and reduce reliance on artificial light has become a preferred approach in museum design nowadays.

On this project, with the geometries set by the architect, fundamental changes were rarely made, and arguably Arup's input might initially seem more peripheral, with less direct impact on the resultant form of the architecture. Yet, when dramatic spaces such as those created by Libeskind have to perform a practical role for exhibitions, it is essential that exhibition designers know where the daylight is throughout the year. Calculation of sunlight hours and annual exposure to daylight allows the exhibition designer and curator to be more informed in developing their display strategies.

The linear "strip and field" configuration adopted for the fenestration defines the crystalline geometry of the building as well as how natural light enters the façades. It was extrapolated and developed into various forms of interior lighting scheme throughout. The approach for all the gallery suites was to provide an architectural canvas of strong graphical strip lines onto which track-mounted spots can be added to suit the exhibit configurations (Fig 25).

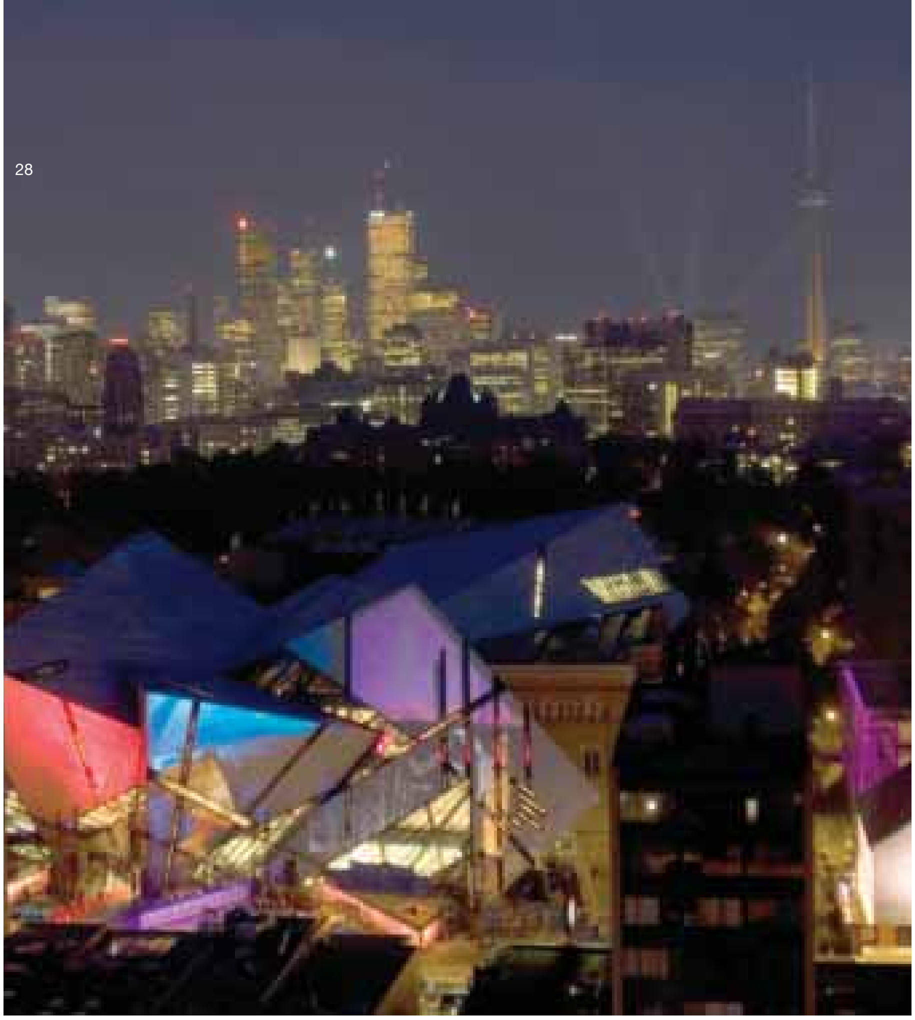
Considered to be the heart of the new project, the area that came to be known as the Spirit House on level 1 (Fig 23) is designated as a space for contemplation. Its tranquil and surreal atmosphere required discreet lighting, and the team decided that only the deck of the viewing bridge that crosses the space should be illuminated for circulation. This was achieved with continuous strips of fluorescent fixtures concealed at low level on the inner side of each bridge balustrade. The rest of the space, ie all the sloping walls, are strategically lit only if artwork is being hung there. Two-circuit tracks are integrated to the underside of the bridge to facilitate any enhanced effect required for future display configuration.

In the bar and dining areas (Fig 24), architectural lines similar to the strip windows are "cast" onto the ceiling canvas. Dual-colour fluorescent lamps (3000K/5600K) are concealed along these lines to provide ambient lighting. Separately dimmable circuits control different lamp colours, which allow the light's chromaticity as well as its intensity to be carefully balanced so as to mimic the colour quality

23. Spirit House - with chairs designed by Daniel Libeskind.

24. Dining area.

25. The galleries are lit by a combination of natural light and track-mounted spots.



The differing natural light of the seasons (Fig 26 summer; Fig 27 winter) creates a range of visual effects on the Crystal exterior, as does projected illumination during the hours after dusk (Fig 28). Toronto's other icon, the CN Tower - until recently the world's tallest freestanding structure - can be seen top right.

29. The Event Hall between the heritage building and the Crystal, with openings in the link roof allowing a sense of daylight penetration.

changes of natural light throughout the day, ie the space will primarily be lit more intimately during the evening, with warmer-toned light, compared to a brighter, cooler light around midday. Supplementary feature lighting, which is integral with the bar and restaurant furniture, is also provided.

A similar common lighting design language was also adopted for the rest of the public circulation space. Arrays of bespoke light strips, comprising fluorescent lamps above a translucent ceiling scrim, provide ambience to the general circulation area including the entrance vestibules.

An Event Hall was created by roofing over the void between the Crystal and the heritage building (Fig 29). Here, lighting emphasises the architectural and chronological differences between their façades. "Field" windows on the exterior façade are replicated in the form of display cases on the internal façade, overlooking the Event Hall, in which the lighting comprises a selection of theatre-style lighting and discreet floodlights concealed within the skylights. Projector theatre lighting was chosen for its flexibility of beam angles and availability of accessories, in addition to choice of lamp sources. Metal halide sources, compared to halogen, reduce heat dissipation into the space and energy consumption for equivalent light output. They do not allow dimming, however, so some halogen PAR (parabolic aluminised reflector) lamp sources were also installed to give half the theatre lighting dimming capability.

To help lead eyes through the glazed openings into the Crystal, distinctive light box features are incorporated in the ceilings of the staircase, main landing and elevator lobbies, where they are visible through the glazing. Vertical light boxes, each spanning across two flights of stairs, are recessed to the walls to fill the staircase with light.

Conclusion

The new Crystal extension by Daniel Libeskind has provided both the Royal Ontario Museum and Toronto with a superb iconic building that has fulfilled all the client's expectations. Its facilities give the museum a platform for the future, matching its forward thinking and enabling it to maintain its position as Canada's principal museum.

It has reinforced the ROM as a focal point for education, exhibition, and community both in and around Toronto; the restaurant in Crystal 5 is an excellent venue with superb views to the city centre.

The new building enables the curatorial staff to use exhibit display techniques not previously seen, and has raised the bar for environmental control in much of the new and original buildings. Finally it is important to recognise the generous sponsors and the leaders of the museum for their contributions needed to realise the project, together with the collaboration of the design and construction teams, vital to solving its many complex challenges.

Florence Lam is a Director of Arup and leader of the Lighting group in London. She was the principal lighting designer for the Michael Lee-Chin Crystal project.

David Lewis is a Director of Arup in the Building London group, and was Project Director for the Michael Lee-Chin Crystal project.

Julian Sutherland was formerly an Associate Director in the Building London group, and Project Manager for the Michael Lee-Chin Crystal project.

Credits

Client: Royal Ontario Museum **Architect:** Studio Daniel Libeskind **Associate architect:** Bregman+ Hamann Architects **Lead SMEP engineer and lighting designer:** Arup – Carolina Bartram, Daniel Bosia, Jenny Bousfield, Daniel Brace, Peter Brickell, Anna Burbidge, Mike Ebsworth, David George, Danny Hall, Tim Hanson, Tai Hollingsbee, Graham Humphreys, Karl Hurwood, Florence Lam, Bob Lau, Neil Leighton, David Lewis, Adam Martin, Paul Mosely, Natalie Rosenbaum, Sonia Samuel, Martin Self, Julian Sutherland, Glen Swinney, Karsten Thiem, Gareth Thyer, Hillary Williams, Jaime Wu **Associate structural engineer:** Halsall **Associate mechanical engineer:** TMP **Associate electrical engineer:** MBII **Landscape architect:** Quinn Design Associates **Heritage consultant:** ERA **Acoustic consultant:** Valcoustics **Life safety consultant:** Leber/Rubes, Inc **Contractor:** Vanbots Construction Corporation **Illustrations:** 1, 2, 21, 25-27 Studio Daniel Libeskind; 3-6 Arup; 7, 10-15 Halsall; 8, 9, 16-19, 22 Nigel Whale; 20 © Stephen Evens; 19, 23, 24, 29 © Sam Javanrouh; 28 © Royal Ontario Museum.

1. The Sishen Saldanha ore railway - an economic application of rail technology.

Sustainable transport infrastructure investment:

A case study for South Africa

Andrew Marsay

A South African Government commission to investigate "what is needed to bring about a sustainable increase in spending on transport infrastructure" yielded conclusions about relationships between infrastructure provision and sources of investment that have implications beyond the borders of that country.

Introduction

Q. How does one motivate increased spending on infrastructure at a time when one of the longest periods of sustained growth in recent history has come to an abrupt halt?

A. By understanding that the longevity and economic value of infrastructure greatly transcend any swings in business cycles.

While sharp business downturns can drastically reduce the time horizon of specific investment decisions, long periods of sustained economic growth may concentrate minds on the long-term role that infrastructure plays in sustaining such growth.

This article is about what Arup has been doing in one country, South Africa, to help create a more robust appreciation of the economic role of transport infrastructure and how this role can be sustained. To place this in context, however, it is worth noting how some other countries have responded to the long-term relationship between transport infrastructure and economic growth.

When economic growth recommenced in 1993 following Britain's last real recession, the instinctive response was to manage existing infrastructure better and make greater use of public transport technologies for both freight and passengers. But the scale of transport demand growth eventually led to the realisation that a major expansion in transport infrastructure could be required, leading to the publication in December 2006 of the Eddington transport study[1], the most thorough examination ever undertaken in Britain of the role of transport infrastructure in economic development.

Eddington's aim was to establish a "case for action" by determining how enhancements of transport infrastructure can offer the most economically, socially, and environmentally sustainable solutions to transport demand. The report was innovative in that it sought to widen the scope of quantitative cost/benefit appraisal by developing techniques to place monetary values on factors such as improved efficiency of urban economies, and a wide range of environmental impacts. Some of Eddington's findings are reviewed later in this article.

The USA likewise has had to revisit its understanding of the role of transport infrastructure in its economic development. As rail, road, and ports infrastructure progressively became congested, it was realised there too that more efficient management of existing facilities could not be the whole solution. Published in December 2007, "Transportation for tomorrow"[2] mapped out a strategy for responding to massive growth in transport demand.

Interestingly, the commissioners responsible were divided in their response to the situation the USA faces. Most adopted a view similar to that implemented in Britain in the late 1990s and early 2000s - broadly a demand management/multi-modal response entailing significant public intervention and funding, with strong emphasis on public transport. However, a minority report was also included representing the views of three study team members, among them Mary Peters, the Secretary of State for Transportation, which argued for investment that is more directly informed by economic appraisal and with greater private sector involvement.

South Africa also experienced unprecedented sustained economic growth in the past 12 years. The fact that these years of growth coincided, almost to the year, with the country's transition to democracy in 1994 intensified the rest of the world's surprise at this sustained period of growth. The understandable uncertainties associated with the transition meant that very few people would then have predicted a decade and more of sustained and even accelerating growth. South Africa was unused to being part of global trends and is now waking up rapidly to the huge implications for telecommunications, electricity generation, and transport demand.

Significant investment in SA's transport infrastructure started to tail off from the early/mid-1980s when sanctions began to impact and investment priorities were diverted to security. Then, in the first 10 years after 1994, priorities turned to social infrastructure investment in the health, housing, and education sectors.

Meanwhile the economy was starting to boom, and with GDP growth rates above 5%pa for the country as a whole and 7-8%pa in the commercial heart of the economy in Gauteng Province around Johannesburg, transport demand on key import/export corridors was growing in double figures. Just as harsh lessons are being learned in the country's electricity sector, with demand very close to exceeding installed generation capacity, government has realised that continued economic growth could be severely constrained if plans are not made for long-term transport infrastructure development. If, however, billions of public and private rands were to be applied to developing infrastructure, the SA Government wanted to ensure this takes place rationally and sustainably.

2. Locomotive on the Sishen Saldanha ore railway.

This is the context for the study reviewed here. In a nutshell, Government wanted to know "what is needed to bring about a sustainable increase in spending on transport infrastructure". Arup in Johannesburg was awarded the study in March 2008 and it was completed in August. The successful Arup tender had promised intelligence on relevant experiences in other countries via Arup's global practice, and duly forthcoming were reviews of the UK's rail privatisation experience and highways procurement and contracting procedures, details of Australian practice with infrastructure Public Private Partnerships (PPPs), and research on the corporatisation of the Port of Singapore.

The study was partly desk research and partly through two all-day workshops, one for roads and one for rail and ports. Past and present senior Government and private sector practitioners in infrastructure procurement, implementation, and management were brought together in Pretoria to glean lessons from the past and set best practice guidelines for the future. Arup's Australian specialist attended one event to add expertise on PPPs.

Below are captured the research findings in the report's four main sections: on statistics, on the history of procurement, on cost/benefit aspects, and on whether institutional form matters. Reviewed are:

- over 100 years of time-series comparisons of transport infrastructure investment with GDP growth data, appraising how different transport modes and GDP growth are interdependent
- the history of transport infrastructure procurement in SA and how this history and response to local and global trends has influenced the effectiveness of current approaches to procurement
- recent developments in cost/benefit appraisal methods and how their application (or non-application) influences the sustainability of transport infrastructure development
- transport infrastructure and systems, developments in other countries, and lessons potentially applicable to decisions that may need to be made with regard to some SA transport infrastructure agencies.

The final section draws together the most important recommendations made by Arup to SA's Department of Transport. Some findings of the research that may be more widely applicable are also reported.

Transport and economic development: do the statistics tell a story?

For at least 40 years economists throughout the world have studied the role of infrastructure in economic development. The critical issue has always been whether infrastructure investment brings about economic growth or economic growth leads to the capacity to invest in infrastructure. Theoretically, a broad consensus from all research is that transport infrastructure facilitates but does not create economic growth or development.

Consider a location with no resources at all, human or physical. Simply building a road or rail line to it does not conjure economic development from nothing. But where potentially valuable economic resources already exist, any major improvement in transport accessibility can result in the potential of such resources being realised.

Individual transport infrastructure projects may demonstrate this, but what of the long term? Do such impacts vary over time or with different types of transport infrastructure? These were among the questions to be answered.

Arup drew on some extraordinary statistical work at the University of the Witwatersrand in Johannesburg by Dr Peter Perkins, now a senior statistician with Statistics South Africa[3-5]. He prepared very long-term time series data sets of investment in transport, power generation, and telecommunications infrastructure in SA, sourced from early British colonial government official reports, the SA Reserve Bank, Statistics South Africa, Spoornet, The Council for Scientific and Industrial Research, Telkom, the National Traffic Information System, National Ports Authority, and other, international, sources. For SA's transport sector, rail data went back to the beginnings of the industry in 1875, ports almost to the turn of the 20th century, and paved roads to the 1920s. These were all placed alongside data for GDP growth. All the values were of course based to a common reference year for comparability.

Perkins then conducted statistical tests, first between all the infrastructure sets and GDP and then for each type of infrastructure, to see whether any statistically significant direction of causality existed. In other words does GDP growth lead infrastructure investment or is it more the other way round? The general answer was that over the very long term, infrastructure investment does lead, or force, GDP development, thus corroborating the more theoretical work that has arrived at a similar conclusion.

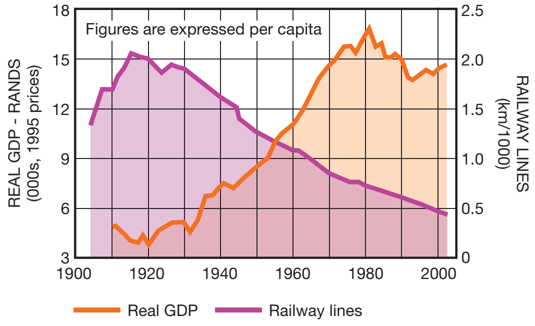
Comparison of the differing impacts of various transport modes, however, offers more interesting and perhaps controversial insights. Figs 3-5 illustrate the relationship over time between GDP growth and investment in rail and paved roads respectively in SA. All data is graphed in per capita terms as this offers a more realistic picture of wealth development over time.

Fig 3 shows that the rail network expanded significantly only until about 1930, with very little further line construction thereafter. The GDP decline from the 1980s reflects the introduction of economic sanctions from the late 1970s, with a rapid recovery from the early 1990s once political change took hold.

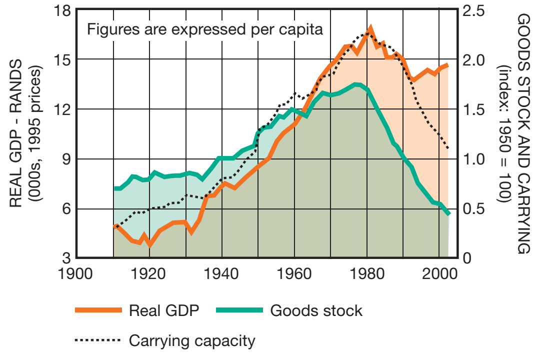
Investment in railway goods stock and carrying capacity grew in parallel with GDP up until 1980 and then fell, apparently in line with declining GDP. Despite the recovery in GDP, however, the decline in rail capacity continued dramatically (Fig 4). As will be noted in more detail below, a significant factor here was that rail transport in SA was institutionally protected from road transport competition from the 1930s through to the mid/late 1980s.

Fig 5 compares the development of SA's national and provincial paved road network with growth in real GDP over 60-70 years, and shows that:

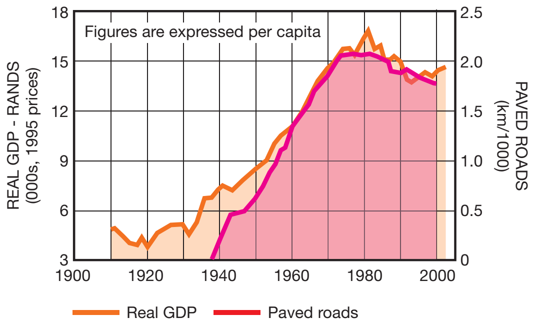
- The extent of paved roads per capita and GDP per capita align extremely closely throughout.
- Tailing-off of road construction during the sanctions period (mid-1970s to mid-1990s) precedes decline in GDP growth.
- Economic growth resumed after 1994 despite there being no further growth in the paved roads ratio.



3. Rail line route kms vs GDP, South Africa, 1900-2003[4].



4. Rail goods stock and carrying capacity vs GDP, South Africa 1900-2003[4].



5. Paved road development vs GDP development, South Africa: late 1930s-2003[4].

The team carried out statistical correlation analysis on the time/series data to investigate any direction of causality between the individual transport modes' investment and GDP patterns. The evidence suggested that while the expansion of the paved road network in South Africa seems to have had a "forcing effect" on GDP growth, with rail and ports infrastructure the evidence suggested that causality was stronger in the direction of GDP growth to the infrastructure capacity creation. This may be because the "fixedness" of rail infrastructure means that it is generally more tied to particular freight generating sources for its business. Investment is undertaken largely to capture specific trades rather than to seek to generate business speculatively.

One policy implication from this is that major investments in new network capacity should be considered only if they are linked to a secured high volume trade, where the economic benefits derive primarily from that trade and not from any wider economic impacts.

In contrast to rail investment, statistics showed the development of paved roads in SA to exhibit a long-term "forcing effect" on GDP growth, the evidence across the whole period measured being that investment in paved roads is supportive of general growth in GDP.

The fact that GDP growth resumed and accelerated following the end of sanctions and start of the democratic era does not necessarily imply that the observed correlation no longer holds. It is more likely that capacity created in the years of high growth is being taken up, with congestion the inevitable outcome. In the light of the statistically suggested relationship between roads infrastructure and GDP, the rapidly worsening highway congestion of recent years is likely to become a significant constraint on further economic growth.

This evidence that road transport infrastructure investment generates long-term economic impacts is likely to be a consequence of the essentially open access nature of road transport technology and the broad distributional flexibility that is offered once its infrastructure is in place. The policy implications are significant even though they appear contrary to much contemporary concern about road building.

Clearly statistics do indeed matter. Perkins himself nevertheless cautions against relying solely on statistically-based conclusions in making policy, and advises that investment decisions on which infrastructure to invest in should be supplemented by appropriate cost/benefit analyses. But before examining that subject, a historical question needs to be answered.

6. Demonstrators form a human barrier against cutting through Twyford Down in Hampshire, England, in 1993. The M3 motorway extension project was the "last straw" for road objectors.

7. Beyer Peacock steam locomotive on Natal Government Railway, 1884.

Approaches to procurement: does the history matter?

Arup also investigated trends in how transport infrastructure has been procured, to see if any general guidelines could be discerned that could inform the development of a more sustainable South African approach.

At the global level can be discerned cycles of private, then public, then back to private sector procurement in both road and rail infrastructure development. The research tracked these cycles and found that an underlying explanation seemed to lie in changing perceptions of who benefits from infrastructure investment, the scale of the benefits, and the timescales over which they manifest themselves. The answers to these questions typically lead to answering who should pay, and how.

Almost all rail industries around the world started with private investment. Most moved on to public ownership and investment responsibility, though the past 20 years or so has seen greater emphasis on private investment again.

In the roads sector, the cycle appears to have been the reverse. Because of the open access technology, private investors couldn't easily protect investments in roads and so very early on the requirement for a programme of publicly developed roads was established in most western countries. In the UK especially, increasingly sophisticated programmes of publicly procured highways emerged, such as those of the Road Construction Units in many county councils.

With apparently no end to the extent of new roads that appeared justified by appraisal techniques based on travel time and safety improvements, doubts began to emerge from the late 1970s onwards. In the 1980s, value for money was questioned; in the 1990s, the balance between user benefits and wider environmental disbenefits (Fig 6). The first round of opposition led to increasing pressure for private sector testing and eventually private sector procurement of roads. The second trend led eventually to road construction being virtually halted.

But with the strong economic growth that persisted until late 2008, government commissions in both the UK and the USA appeared to be saying that the scale of growth in transport demand may again require levels of investment in infrastructure that exceed the commercial appetite of the private sector.

In South Africa, these cyclic trends are not so clearly discernible, partly because in the long apartheid era the economy became increasingly isolated from international involvement. Rail indeed commenced in the private sector, with companies developing short freight and commuter lines in Durban and Cape Town from 1875 (Figs 7, 8).

8. Botha's Hill station, Durban, which saw its first train in 1879.

The advantages of the new technology to support planned urban development led to take-overs of these early private businesses by the respective colonial administrations for further expansion. Inland, in the independent Transvaal Republic, the Zuid Afrikaanse Spoorweg Maatskapye (ZASM) privately developed a line from Pretoria and Johannesburg to the Mozambique port of Delagoa Bay, near present-day Maputo.

Following Britain's 1902 military victory in the Anglo-Boer War, these three railways first fell under military jurisdiction and then were amalgamated into the single South African Railways and Harbours Company in an Act of that name in 1913. Though owned ultimately by government, the SAR&H was a commercial entity, not a government department. It was mandated to be commercially viable but also to invest in an expanded network to open up the country for mining and agricultural development. The network thus expanded to more or less its current extent by the end of the 1920s, the only significant additions since being the Richards Bay coal line and the Sishen Saldanha ore line in the 1970s and 1980s (Figs 1, 2).

In the years before significant road construction began, the SAR&H's twin mandates to support national economic development and cover its costs were fairly well aligned, although additional government investment was provided wherever no clear business case existed for opening a line to an area government thought had economic potential.

From the 1920s and 1930s onwards, road and air transport respectively began to emerge as competitors to rail. The SAR&H appealed to government that its national developmental mandate was being impeded, and succeeded in requiring all road transport operators to be issued with licences that ensured they would not compete on a rail route. The Union Airways company that was beginning to divert the mail business from the railways was taken over directly by SAR&H, eventually becoming South African Airways. Thus protected, the rail sector continued to grow its business right through until the 1980s (Fig 4), when partial transport deregulation legislation was introduced.

One consequence of this history is that, despite the dramatic loss of business to the roads sector, rail's institutional heritage of being a custodian of national economic interest persists. This is a major factor preventing the SAR&H's successor company, Transnet, from embracing some of the private sector involvement options by which railways in other countries have sought to recover a sustainable future for themselves.

Roads procurement in SA has gone through a similar cycle to that experienced elsewhere. In the 1930s, national and provincial Roads Boards were constituted with responsibility for funding and procuring the construction of a rapidly expanding roads network. A similar pattern to the UK's RCUs was developed with sub-units operating within the larger provincial Boards.

At the time of the transition to democracy in the early 1990s, experiments were under way with private concessions to procure major road developments such as the Maputo Corridor concession. The National Roads Board led this initiative, operating increasingly commercially in its final years before the transition.

These experiences foreshadowed the establishment of a new agency structure at national level, one aim of which was to transfer the burden of national roads funding and maintenance from public to private sector. In the decade since its establishment, the South African National Roads Agency Ltd (SANRAL) has been able to progressively move away from grant funding by central government to self-funding via concessioned and direct toll projects. The current GB£1bn/ZAR15bn Gauteng Freeway Improvement Scheme is the latest stage in this evolution (Fig 10).

An important feature of this change to a more commercial status has been increasing reliance on detailed economic and social impact appraisal of schemes. SANRAL could demonstrate not only that many of its projects are intrinsically fundable but also that road investment brings substantial social and economic benefits.

Indeed, the high level of viability shown in some major schemes seems to indicate that it would be in the country's national interest if even more money than can be raised through commercial funding were invested in these schemes. In other words, the balance of public benefit against lifetime cost suggests that a sustainable increase in roads investment could be achieved by additional state funding, perhaps drawing directly on state borrowing or bond financing.

This conclusion emerging from SANRAL's practice is supported by detailed research at the University of Stellenbosch on infrastructure funding[6]. This work draws attention to an apparent anomaly: while most of the cost of SA infrastructure is met from current sources of revenue, the infrastructure is deliberately designed to add economic value through future generations. So, why are methods of procurement and funding of infrastructure not sought that reflect a better balance between cost and benefits over time?

9. Early 20th century South African national road - over Sir Lowry's Pass, Cape Town.

10. The Gauteng Freeway Improvement Scheme: adding additional central lanes while maintaining full bidirectional flow.

This implies that more long-term public sector borrowing may be warranted. Calitz and Fourie[6] carefully add the caveat that this approach should be adopted within the context of normal public financing prudence, but they note that such prudence may be excessive when the estimated benefits of infrastructure projects far exceed the costs.

SANRAL's good experience with a more commercial approach to roads procurement indicates that the PPP route to infrastructure procurement should be followed more extensively, and the DoT explicitly asked Arup to assess the pros and cons of such models as part of a more sustainable transport infrastructure funding programme.

Arup in Australia accessed a very extensive review in that country comparing PPP-procured infrastructure projects with those conventionally procured. The team drew on this extensively in arriving at the following summary of the PPP role.

The principal difference between traditional and PPP projects is that the degree of responsibility/risk borne by the public sector is typically lower, most of the project planning being done by the private party. Except for fairly small projects, both methods rely on private contractors for construction and, where relevant, operation.

Successful PPP projects typically have an early consensus on their public objectives. Both parties are thus able to be realistic with themselves and their partners about project risks, in particular the likely scale of revenues and other benefits.

Where the private benefits can be captured effectively, as in a tolled river crossing, PPPs can also take much of the funding burden away from the public sector. But the mechanism can also work efficiently even when the public sector bears most of the costs, as with the Gautrain rapid rail link between Johannesburg, Pretoria and OR Tambo Airport*. This illustrates the further fact that PPPs have the greatest benefit during project preparation, and hence are useful for implementing specialist projects where new skills not usually present in public sector institutions are being introduced. They usually lead to more accurate estimates of project costs and timing simply because the private sector's aversion to risk-taking concentrates minds better.

While PPPs are designed to engage the private sector to assist in achieving public benefits cost-effectively, they cannot be regarded as a tool for establishing the nature or scale of public benefits. And while PPPs in transport infrastructure almost invariably demonstrate efficiency of procurement and cost control, leading to "on time on budget" projects, they do not necessarily deliver national economic value for money. PPPs are thus best regarded as a special case procurement tool and not a substitute for the public sector's role.

So, does the history of procurement approaches teach us anything about how to achieve a more sustainable programme of infrastructure spending? Yes. Unsustainable approaches tend to occur when there is a misalignment between costs incurred and benefits produced. There can be misalignment of scale, when too much is spent for too little gain. This usually occurs after a new transport technology emerges and the previous one cannot offer the same benefits - substantially the reason why huge institutional realignment of the rail sector was needed over the past 20-30 years.

On the other hand, too little may be spent when the potential gains are far greater than the investments incurred. In SA this seems to be the case with the roads programme, where the procurement model only partially captures the scale of benefits estimated.

The key to sustainable transport infrastructure procurement would appear to be in designing a model that can capture the maximum proportion of benefits at minimum possible cost.

The answer probably lies in some combination of the PPP as a procurement tool and selection of projects that demonstrably yield national economic value. Because wherever procurement efficiency and economic value coincide, one has a win/win situation. So, to the next issue…

* Arup is the Independent Certifier on the new Gautrain PPP high speed rail link being built between Johannesburg, Pretoria and OR Tambo International Airport - the largest such project in Africa.

Does cost/benefit analysis matter?

In the South African context, though probably not restricted to this country, one main reason for lack of sustainability in infrastructure development is that projects with poor economic prospects are often pursued for perceived social gain while projects with potentially greater economic benefits are set aside because of perceived disbenefits to targeted groups. Explanations for this include poor appraisal methods, institutional mandates that allow agencies to judge investment priorities by non-economic criteria, or simply unwillingness to accept appraisal results if they do not appear to support prevailing policy objectives.

Although decisions may ultimately have to be made on the basis of democratic mandates, decision-makers need to be aware of the benefits and costs of their actions. When this is not so, institutionally mandated decisions may be presented publicly as economically beneficial ones, leading to ongoing distortions in infrastructure investment priorities to the detriment of society as a whole.

One such distortion emerged when the UK Commission for Integrated Transport was asked to report on the findings of the initial batch of regional multi-modal transport studies, commissioned in the late 1990s to set out long-term transport investment priorities for each region. Government had given the studies a strong steer by seeking appraisal methodologies allowing a fairer comparison of rail and other public transport investments with road options. The CfIT report[7] noted that while over 60% of all proposed investments were in rail and other public transport, benefit-to-cost ratios (BCRs) for rail solutions were typically very low and did not meet HM Treasury's benchmark BCR even with social benefits added. Most highway projects were found to score consistently much higher BCRs[8].

Simultaneously the UK rail sector was struggling to emerge from its painful privatisation exercise. A House of Commons Committee in 2003 reviewed the value for rail, seeking answers from the Rail Regulator and also the Chief Executive of the then Strategic Rail Authority (SRA) to the question, "what are we getting in return for the much higher than expected cost of running the rail network?" Both individuals referred the chair to "the social benefits", though without offering evidence equating the value of these with the costs being incurred.

The conundrum of strong public support for railways but evidence that the social benefits fell far short of the costs led Government eventually to the most thorough re-examination of the case for transport infrastructure investment ever undertaken in Britain, the Eddington Transport Study[1].

11. The first French TGV service began operating in 1981.

As well as giving a valuable historical review of how transport infrastructure facilitated economic development in Britain, Eddington also sponsored several innovative research experiments designed partly to shed light on the above conundrum. Both areas of research - "agglomeration benefits" and "monetarisation of environmental benefits" - were highly relevant to the whole system of cost/benefit analysis of transport projects.

Taking agglomeration benefits first, Eddington used the then current South and West Yorkshire multi-modal study to examine whether transport improvements add more value than just savings in travel time and costs for network users. For many years it was suspected that the benefits of improving access to urban economies were additional to savings in travel time. What about the ability to deal with more customers in one day than was possible from a remote location? What about being able to attract a wider range of skilled labour to the same location than before the transport improvement?

In France, studies of the inaugural TGV (*train à grande vitesse*) line from Paris to Lyon (Fig 11) had shown that previously Paris-only business sectors began to spring up in Lyon. The daily face-to-face contact characteristic of a capital city location now extended to the Lyon suburbs because travel was so reduced that the Parisian image could be maintained from a Lyonnais location.

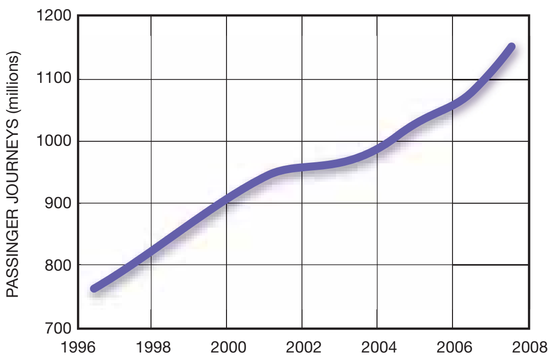
Unfortunately, no satisfactory way to objectively measure such phenomena had been achieved and so HM Treasury dismissed the anecdotal evidence as expressions of travel time and cost savings. Eddington explored this in detail and showed that urban efficiency gains or "agglomeration benefits" do indeed exist: they are additional and can contribute up to 50% extra value to conventionally calculated benefits of transport infrastructure projects.

The second major Eddington contribution to cost/benefit appraisal methodology concerned impacts on the environment. The SRA had already pioneered such a methodology in its 2003 "Sensitive lorry miles" report[9] (to which Arup contributed research). This attempted to establish how much grant should be given to firms investing in rail facilities that resulted in trucks being removed from environmentally sensitive roads. Using a combination of impact measurement and stated preference techniques ("how much of your disposable income would you forego to have less noise/pollution, etc, passing your home?"), the report arrived at a range of values for environmental impacts saved per mile for the removal of trucks from different types of road.

The "Sensitive lorry miles" data suggested that rail's environmental impact was between two and four times less per mile than that of road vehicles, depending on the category of the road being relieved by transfer of road traffic to rail.

	The monetarised evaluations (pence/mile)		
	Congested motorways	Main urban roads	Main rural roads
Road environment cost	13.9	36.2	12.1
Rail environment cost	8.8	8.8	8.8
Rail environment cost saving	5.1	27.4	3.3
Congestion cost	79.0	121.9	45.8
Rail's environmental advantage as a % of congestion cost	6%	22%	7%

12. Road and rail environmental impacts[9].



13. Passenger demand growth on the UK rail network, 1996-2007.

Eddington developed the appraisal methodologies further and arrived at rationally defendable values for a range of impacts, including global CO_2 emissions, local air pollution, noise pollution, and others.

The implication of the monetarised environmental valuations is that, while rail is indeed very much better than road, because of the dominance of congestion cost reduction in transport evaluations, rail's environmental advantage is typically not great enough to be the determinative factor in mode choice, except in dense urban contexts or in situations where rail will carry significant volumes of bulk freight (Fig 12).

Eddington then developed four appraisal stages starting with conventional costs and benefits only, and working up to inclusion of agglomeration and finally environmental. These were then applied to a package of urban and interurban transport projects including both road and rail. The overall conclusions were that benefits remain high for many of them, even after social and environmental costs and benefits have been fully accounted for. Although Eddington does not seek to engage directly in the road vs rail debate, the findings broadly confirm previous evidence that most road-based projects typically yield higher BCRs than most rail projects.

The key to effective rail projects appears to be to align them as closely as possible with urban growth so that the agglomeration benefits rather than the conventional travel time and cost benefits are the key to project viability.

The implications of these findings are highly significant for projects in the UK and South Africa. London's east/west Crossrail and the Gautrain Johannesburg/Pretoria rapid rail link have both faced sceptical responses from the respective treasuries, because their conventionally calculated economic benefit/cost ratios are low - between 2:1 and 3:1 - even allowing for social and employment creation benefits. Recognition that the Gautrain might accelerate already existing trends to urban concentration and facilitate further CBD growth was probably a factor in it getting the final go-ahead. And in London, studies of the potential agglomeration benefits associated with Crossrail have resulted in a substantially higher BCR.

In the main Eddington report this finding was couched in typically British understatement: "The benefits of transport infrastructure investments will tend to be higher where they occur in support of strongly growing urban centres and on links between points of access to an economy and those urban areas".

In its report to the South African DoT, Arup therefore recommended that transparent cost/benefit analysis methods be introduced to all transport sectors. This recommendation especially applied to Transnet, the state-owned rail freight and ports utility. At present Transnet is mandated to have a financially sound bottom line, which it is well able to achieve given its sole operator status in both sectors. But it does not apply broad-based national economic cost/benefit analysis to its major infrastructure investments, so there is no way of knowing whether these investments are really adding to national economical welfare or not.

Because South Africa's overall economic strategy is to achieve "accelerated and shared economic growth", cost/benefit analysis really does matter.

Does institutional form matter?

In the final area of investigation, the question essentially was whether public or private ownership matters as far as effective infrastructure construction and operation are concerned. To answer this, Arup sought assistance from colleagues in London and Singapore. The former contributed a discussion on how highway development and maintenance is managed in the UK, plus an excellent overview of the UK's rail privatisation experience, whilst from Singapore research assistance was provided in support of a case study of the corporatisation of Singapore Port.

The main lesson from reviewing highway procurement and management in the UK was that the key to sustainable investment programmes is flexibility in contract form. The question of public or private ownership or management appeared to be less important than seeking the most appropriate institutional mechanism for the job in hand. This entails, among other things, ensuring that implementing agencies have effective managerial as well as engineering skills. Many years of trial and error led to this point, the hard-earned lesson emerging that "horses for courses" rather than "one size fits all" is the key to a sustainable highway investment programme.

UK rail privatisation has become a paradigm for industry practitioners in other countries to either loathe or love. The comprehensive and balanced review from Arup in the UK offered very clear lessons, both positive and negative.

On the positive side it is evident that, for passenger operations, privatisation brought significant benefits to consumers. The competitive franchising model resulted in a multiplicity of operators competing not on the same tracks but within a clearly defined regulatory framework of targets and penalties. The system has been robust enough to survive several franchisee failures and being replaced or taken over by others. Passenger numbers are at their highest level in history and private investment in new rolling stock has mushroomed (Fig 13).

On the negative side, the privatisation of the rail infrastructure effectively failed, due to inadequate knowledge of the condition of the physical asset and hence massive underestimation of maintenance and renewal costs. The original privatised operator, Railtrack, focused more on share price management than technical aspects of the business, so that initially the share price rose as passenger numbers increased. While from a private business standpoint this may have been a rational approach to achieving a sound credit rating for future investment funding, the public saw neglect of a public asset for short-term private gain.

The Hatfield crash of October 17, 2000, in which four people died and dozens were injured, jolted Railtrack into awareness of its misjudgement of how extensive was the task of maintaining its infrastructure to modern safety standards. The cause was a cracked rail, and subsequent inspection of the network revealed numerous similar problems[10, 11].

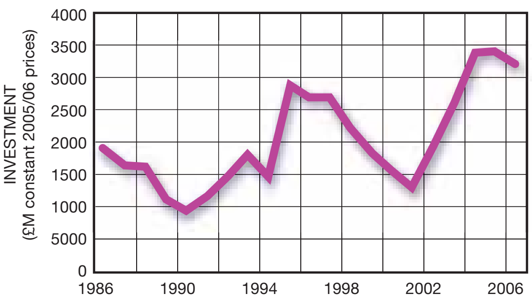
The identified costs of repairs and upgrades were way beyond the amount of investment permitted in terms of the economic regulatory regime that sought to link allowable investment to commercially earned revenue. The share price crashed and any hope of a privately funded recovery was lost.

Government took Railtrack into administration and, against the economic evidence, recapitalised it and set it on its way again as the new, not-for-profit, but still notionally private company, Network Rail. The regulatory regime had to accommodate itself to a new funding framework in which government was committed to a medium-term programme of capital expenditure with the objective of realising a viable infrastructure company (Fig 14).

What are the lessons in terms of sustainable investment in transport infrastructure? Perhaps the most important is that if a government regards as socially desirable a service that cannot be funded fully by the private sector, then it must take very seriously its responsibility for funding such a service. With over 20 private sector train operators on the network, it became clear that without publicly supported funding certainty, they could not sustain their side of the bargain.

Taking this responsibility a step further, a government wanting a passenger rail service must ensure that mechanisms are in place to ensure good technical management of the network as well as effective business management. Ultimately, running a national rail network costs more than can be justified in any commercial business framework.

14. Government capital investment in the UK rail network, 1986-2006, throughout the privatisation process and especially since the Hatfield crash.



As already noted, the British Government also discovered that the system as a whole was costing more than could be justified within even the broadest social cost/benefit framework. Though government has committed to funding the high cost of network renewals for the medium term, the long-term future of rail in Britain will depend on continued social consensus that the cost is worth the benefit. Some doubts must remain, in view of the 2007 Rail White Paper[12] which reveals that on top of annual funding subsidies, the British rail network also carries a £25bn debt sustainable only because it carries an unconditional Government guarantee. Without this guarantee, Network Rail would not be able to fund its infrastructure programme.

Key lessons for the sustainability of transport infrastructure investment in South Africa are that every possible effort must be made to understand the true costs of running a rail network. Given the country's limitations on capital funding, it would be advisable also to identify the most cost-effective elements of the network in terms of selected service criteria, and concentrate available investment on these routes. This is what Arup advised in SA's recent national passenger rail plan. All routes are ranked in terms of a range of service criteria, leading to a set of priority rail corridors where improvement efforts will be concentrated.

The case study of Singapore Port was requested specifically by the client to discern lessons for SA's ports sector. On the surface, the structure of the ports sectors in SA and Singapore are very similar. An infrastructure owning agency also acts as a sort of in-house regulator, and a service provider runs the ports themselves. There the similarity ends, because Singapore Port is one of the most efficient in the world (Fig 15), but SA's ports perform well below international benchmarks. Productivity is relatively low, given the technical sophistication of equipment available. Tariffs are regarded by the shipping industry as far too high.

The Port of Singapore Authority was a public agency until corporatisation in 1996/97 created a separate Port of Singapore Authority (PSA) and the Maritime and Port Authority of Singapore (MPA). PSA became a commercially mandated but 100% government-owned terminal operator, with MPA providing port services such as tugboat pilotage and other port safety activities. MPA is also the port planning agency and industry regulator.

The decision to create a separate, corporatised terminal operator was made despite its previous efficiency, reputation for quality services, profitability, and timely investment in new capacity. The main rationale for the new arrangement was to allow the PSA to operate more efficiently as a commercial organisation, freeing it from the hindrances of a government body and allowing it to be commercially focused and customer-oriented.

Thus liberated, it was better placed to develop new business opportunities and respond more effectively to future challenges, and to provide customised services for individual clients. Corporatisation created many commercial incentives, which apply to private firms, and increased the separation between PSA and other government linked companies (GLCs), and the Singapore Government. This separation also ensured a level playing field so that the GLCs do not have any competitive advantages or disadvantages relative to private organisations operating under similar market risks.

Ultimately the PSA's mandate is to secure and retain Singapore's status as the world's premier container terminal. To achieve this it has entered into successful alliances with shipping companies and terminal operators all around the world as part of a strategy to retain Singapore's hub port role in the region.

The key lesson for South Africa in terms of achieving sustainable investment in its ports infrastructure is that a protected commercial status is ultimately a hobbled commercial status. Singapore was willing to allow real commercial freedom to the PSA in a manner that forced it to face up to and respond to the real demands of the international shipping industry. For this to happen in SA, Transnet's port operating business will need to be released from its ties to all other elements of the wider Transnet business and allowed to act as a freely competing private business and with the freedom to choose how and with whom it will partner in both port and inland transport operations.

15. The case study of Singapore Port was requested specifically by the client to discern lessons for South Africa's ports sector.

Conclusions

Our research suggests that roads investment is more positively correlated with economic growth in South Africa than either rail or ports investment. However, a sustainable increase in transport infrastructure spending will require all investment decisions to be informed by broad-based cost-benefit analysis. Rail investment will yield significant economic value when focused on bulk commodity projects and on urban rail projects where there are high densities and volumes, and where pre-existing trends of urban economic growth can be discerned.

Private sector participation usually brings efficiency of procurement and cost control to transport infrastructure investments, but needs to be focused on projects that are sound in national economic value terms for a sustainable increase in spend to occur. For this to happen, it is essential to know the national benefit-to-cost profiles of investments in transport infrastructure, taking account of latest developments in cost/benefit appraisal, as well as their intrinsic financial viability.

Finally, private ownership of infrastructure is not a prerequisite for a sustainable increase in infrastructure investment to occur, but this goal is more likely to be achieved in the public sector when public agencies are mandated to align their infrastructure investment decisions with demonstrated national economic value.

Andrew Marsay is Head of Transport Economics for Arup in South Africa. He led the investigation into how to achieve a sustainable increase in transport infrastructure investment on behalf of the South African Government.

Credits

Client: Department of Transport, South Africa
Economic consultant: Arup - John Davies, Nigel Halley, David Kinder, Andrew Marsay, Matshediso Seobi, Stefan Sanders, Gideon van der Westhuizen, Tan Yoong Heng
Illustrations: 1, 2, 7, 9 Transnet Freight Rail; 3-5, 12-14 Nigel Whale; 6 *The Hampshire Chronicle*; 8 Michael Jung/Dreamstime.com; 10 Keith Baker; 11 Jiri Hodecek/Dreamstime.com; 15 Nikontiger/iStockphotos.com.

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1. The west façade of the Jerry Yang and Akiko Yamazaki Environment and Energy Building.

Y2E2:

The Jerry Yang and Akiko Yamazaki Environment and Energy Building, Stanford University, California

Kurt Graffy Janette Lidstone Cole Roberts
Brandon G Sprague Jake Wayne Armin Wolski

"Y2E2 is much more than a building; it is a symbol of what is possible in our transition to sustainability. It is designed for problem-solving, designed to conserve, designed to inspire, and designed to teach."

Jeffrey Koseff, Perry L McCarty Director of the Woods Institute for the Environment.

Background

As noted elsewhere in this edition of *The Arup Journal*[1], Einstein is said to have observed that "we can't solve problems by using the same kind of thinking we used when we created them". Stanford University's Jerry Yang and Akiko Yamazaki Environment and Energy Building (Y2E2) exemplifies a new kind of thinking aimed at providing watershed solutions in the areas of environment, technology, and energy. Completed in early 2008, Y2E2 is the first element in Stanford's new Science and Engineering Quad 2 (SEQ2). Masterplanned by Boora Architects Inc, SEQ2 will deliver over 500 000ft^2 (46 450m^2) of interdisciplinary teaching and research space in four highly sustainable buildings.

Stanford believes that finding solutions responsive to today's multifaceted environmental challenges requires experts from a range of fields to work together in an interdisciplinary environment, sharing their different insights. Y2E2 therefore provides accommodation based on research focus, not academic department. These focus areas include "sustainable built systems", "climate and energy systems", "oceans and estuaries", "fresh water", "energy", and "land use and conservation".

The building accommodates researchers from biology, law, medicine, education, anthropology, and economics, as well as two departments (Civil and Environmental Engineering and Environmental Earth Systems Science), two interdisciplinary teaching programmes, and four centres and institutes including the Woods Institute for the Environment with its strategic collaborations (the Center for Ocean Solutions, the Natural Capital Project, and the Food Security and Environment Project).

Y2E2 sets a benchmark in cutting-edge university and research facilities. Representing Stanford's new interdisciplinary initiative for the integrated study of energy and natural systems made it imperative that the building itself be a model of sustainability and energy efficiency. The design team, including Arup and Boora, pursued architectural forms and building systems that would meet this sustainable goal and provide the space needed for each research focus - the connective areas allowing collaborative work, and spaces where laboratory researchers can link with the social scientists responsible for absorbing and disseminating research insights.

Stanford entered the Y2E2 design process with strong ideals that would ultimately guide subsequent work on SEQ2. These were that the university could no longer "do business as usual", and needed to:

- break down the long-standing traditions that maintain barriers between academic disciplines
- create opportunities for engineers to work alongside economists, policy makers, and biologists
- have a shared language and common vision for housing its new interdisciplinary programmes
- emphasise opportunities through organisational design
- blur traditional boundaries between disciplines
- engineer greater success in creating spaces that support people and their work.

It is fitting that an integrated team of architects, engineers, landscape designers, and contractors working on behalf of a visionary client should deliver a building dedicated to such integration.

Atria

Within the SEQ2 masterplan, Y2E2 is one of the two larger buildings, a pair of L-shapes mirroring each other across the central open space. Ranged along the centre of the horizontal element in Y2E2's L-shape are three atria, with a fourth near the top of the vertical of the L.

Measuring 81ft (24.7m) from basement to highest point, all four atria extend the full height of the building, allow the integrated disciplines to collaborate and connect, be inspired and curious, and remain transparent and open to daylight, view, and outside air (Fig 2).

The extensive use of glass at all levels, and the design's sensitivity to sightlines, reveal laboratory work, flexible seminar classes, administrative activities, and social gatherings, making all the building occupants visible to visitors and, most importantly, visible to each other (Fig 3).

The atria are not simply areas to cross, but destinations in themselves. Stairways and all interior corridors pass through them, supporting their vitality, while the spaces clustering around, including lounges, touch-down stations, kitchens, seminar rooms, wayfinding stations, social entries, and casual seating, host the interactive work of the occupants.

The atria's openness to light, sound, airflow, and temperature variation established itself early in the project as both a critical key to the project's success and as overlapping performance challenges to be solved by the fire, lighting, acoustics, and mechanical engineering teams in Arup.

Working with Boora, Arup's overall task was to create spaces that are both comfortable for the occupants and form an integral part of the building's passive ventilation and smoke release schemes.

The requirements were often contradictory, but certain priorities for successful realisation of the atria became obvious:

(1) Their upper portions needed to vent to the roof exterior so as to function properly as part of the natural ventilation scheme, with sufficient open area to provide the airflow needed.

(2) As the atria also form part of the passive smoke release design, additional surface area had be allocated in their upper portions beyond the louvre areas established for the natural ventilation system.

(3) Their tops needed to be visibly transparent to bring light into the interior, requiring a significant portion of the atrium structures above the roof to be glazed.

(4) These first three priorities effectively determined the acoustic strategies required for occupant comfort.

2. Section through atrium.

3. The glazed conference rooms give direct views to the exterior and other people working.

Laboratories

The 54 000ft² (5000m²) of laboratories in Y2E2's basement house multiple departments, each with unique research and teaching programmes. There are nine environmental labs (two environmental fluid mechanics, three environmental engineering, one structures, and three remaining labs to be used by future research recruits). Specific needs for these research programmes include:

- wet laboratory benches with fume hood workstations
- constant temperature rooms
- noisy equipment work rooms
- undergraduate teaching wet laboratory
- reverse osmosis testing facility
- fluid mechanics wave flumes with water reservoir trench system and laser-based measurement systems
- fluid mechanics teaching laboratory
- sustainable building systems research and testing facility
- sustainable building systems classroom.

The floor plan was compartmentalised into three basement control areas to allow chemical inventory flexibility. Open interchangeable wet laboratory spaces allow research programmes to expand and contract. Four large-scale flumes of different configurations (three are around 40ft/12.2m long) incorporate measurement stations using lasers.

The sustainable building systems research labs included a large-scale material baking oven and weathering simulation equipment.

4.

Multi-tasking fume hoods

A research community focused on environmental solutions must also be a solution itself, doing more with less. One of Y2E2's many innovations is the design for lab fume hoods that enables them to perform double duty. With light and ventilation systems demanding so much energy from buildings, they are often the first systems studied for reduction or optimisation opportunities.

Fume hoods are very ventilation-intensive, demanding much energy to contain and limit exposure to airborne hazards. Each may require as much volumetric air flow as a 600-700ft² (56-65m²) room. They are often grouped in a single space shared by multiple labs, which requires a great deal of air coming in and going out above and beyond that needed for ventilation

The Y2E2 design locates the fume hoods in the open lab where they serve as air returns for the ventilation system. Instead of double ventilating spaces – one system for the labs and a second for the shared fume hood rooms – the design economises with the fume hoods multi-tasking.

The lungs of the building

The atria act as the building's lungs, passively drawing air through natural buoyancy and cross-driven pressures up and out of the louvres near the apex. Evenly positioned throughout the building, they are integrated into the layout allowing direct connection and ease of natural ventilation for all the perimeter offices on every façade.

Ironically, the greatest challenges in the atria natural ventilation integration were control of the high rates of strong, buoyant airflow, and assurance of thermal comfort in the well-daylighted third floor. Both challenges are discussed later. Additional obstacles fell to Arup's fire, lighting, and acoustic teams to address.

Fire and smoke

California fire safety codes require smoke control in atria interconnecting three or more storeys. Instead of providing the usual mechanical exhaust systems, however, Arup's fire engineers and Stanford chose to capitalise on Y2E2's natural ventilation design, which would allow openings between the first floor and the basement to supply natural light and visual connection to the lowest level.

Not all atria are appropriate for naturally ventilated smoke control systems; a reasonable height limit is needed to ensure adequate buoyancy. A smoke control system may not be necessary for a short, two-storey atrium, whilst a fire may not provide enough heat and buoyancy to drive smoke out of natural ventilation openings in a tall, six-storey atrium. However, as the team worked through the early design phases, preliminary calculations showed that the Y2E2 atria were within the necessary range.

After preliminary calculations, the team gave the architect and the mechanical engineers an estimate of ventilation opening sizes, which was then used in design development. CFD modelling enabled the fire team to determine the smoke development and tenability of the space as well as the benefits of venting (Fig 5).

Analysis of numerous models, with varying sizes of ventilation opening, showed that the amount and size of these for make up air was just as significant as the amount and size of exhaust air vents. As the design was finalised, the fire engineers requested more and more make up air ventilation.

Since Boora wished to maintain a maximum amount of louvres and grills on the façade, the fire team proposed using automatically opening exterior doors under fire alarm conditions. This additional make up air opening helps the smoke evacuate the space via natural means.

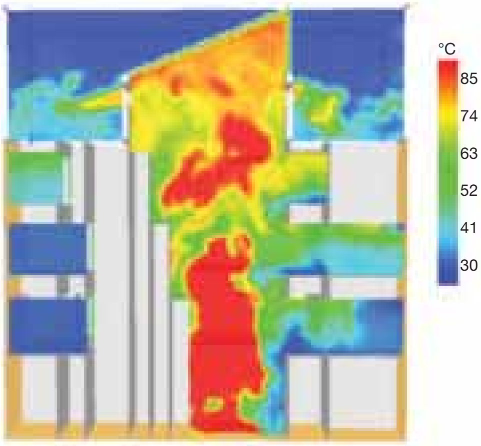
In exploring different fire scenarios, the team found that a basement fire might have insufficient buoyancy to vent its effluent out of the tops of atria of this height. The solution would normally involve more ventilation openings, but this conflicted with the Y2E2 architectural goals, so consideration was given to closing off the basement from the first floor. This achieved the goal of fire separation of the basement laboratory space from the atrium, but the faculty committee insisted on maintaining the opening.

Since natural lighting was important for these basement areas, a structural, fire-resistance rated glass floor was also considered. Cost ruled this out, so Arup found a third alternative - a horizontal fire shutter that would close on smoke or fire detection. By providing this between basement and first floor, the fire rating was maintained, and the challenging fire scenario in the basement eliminated. Since the shutter can be kept open during normal conditions, daylight can still reach the basement level.

This final fire engineering solution was all-important as without daylight the atria as whole entities, let alone their lowest levels, would not give an appropriate environment, or send the right message, for Stanford's sustainable, integrated research and teaching facility.

As part of the commissioning process, the authorities required live hot smoke testing, the success of which surprised even the fire marshal.

5. CFD image showing fire and smoke distribution.



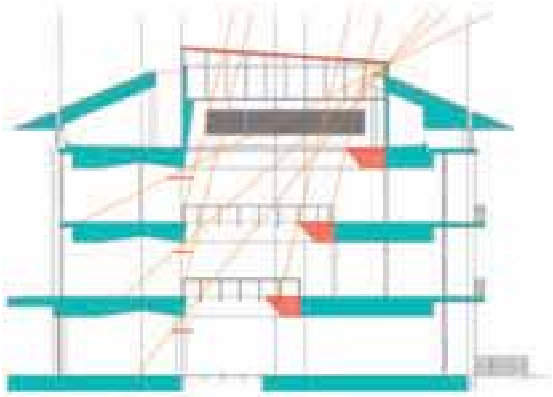
6. Light and people.

Light quality

Just as the atria serve the architectural intent by forming junction points between the building's social and intellectual activities, so they are also interfaces between the built and the natural environment. The abundance of natural light in each atrium serves as a visual clue to the building's energy story, but the light has to be controlled in a visually comfortable manner as well as utilised to the full at each level. Abundant natural light also impacts thermal comfort, and to balance these factors was imperative (Figs 6, 7).

Early in the design process, Arup's lighting engineers studied the atria shape and form in respect of the sun's path through the sky. Based on angle studies in conjunction with the architectural team, three of the atrium openings were refined to be widest near the top of the building, and narrowest at the base. This allows the floor at each level to extend a little below the opening in the floor above, with more floor space at the south sides of each atrium. These receive abundant ambient light, as direct solar light primarily lands at the north. The south sides are thus ideal locations for meeting rooms with glass walls, open to ambient light and visually connecting to the building's activities.

With the shape defined, the architectural programme for the atria was refined to include common workspaces, meeting rooms, and informal gathering spots. With so many activities needing to occur in areas with abundant sunlight, controlling glare and maintaining visual comfort were critical concerns for Arup.



7. Natural light penetration and floorplate modifications at the atria.

The atrium glazing was originally designed to incorporate etched photovoltaics (PVs), not only to generate electricity but also to mitigate the heat and glare of the direct sunlight.

In concert with the mechanical and CFD analyses, extensive modelling was used to quantify the daylight incident to the atria at different times of the year. A 3-D virtual daylight model for a typical atrium was created and used as follows:

- Daylight factors were calculated for each floor, gauging penetration into the building's core.
- Illuminance studies provided data on peak light levels where direct sun was incident.
- Luminance studies on surfaces in the atria informed contrast ratios and material finish choices.

Each played a specific role. The daylight factor analysis showed how much electric lighting in and around the atria could be dimmed or switched off to conserve energy. Together with this, the illuminance studies identified the light levels available at the different floors, under varying sky conditions. And because the space was to accommodate both social and academic informal meetings, it was essential to provide a base level of illuminance for comfort.

The integrated PV panels in the atria glazing were later value-engineered out of the project in favour of three types of roof-mounted PV technology, and the studies had to be repeated to advise on new glazing parameters. A level of frit on the glass was found necessary to mitigate the sunlight's intensity, as with meeting rooms and workspaces adjacent to the atria, direct sunlight on its vertical faces would potentially cause glare to occupants. The frit cuts light intensity, while maintaining brightness and connection to the natural environment. In turn, however, thermal comfort in the atria had to be reviewed. The level of frit was ultimately established through combined daylight and mechanical studies to optimise both visual and thermal comfort, the latter dictating a frit pattern that sufficiently mitigates incident heat from the upper levels.

Acoustic quality

Solutions were also needed to manage the way sound interacts in the open spaces. Arup's acoustic strategy had two defining boundaries: the atria would be (1) open externally, and (2) visually transparent. These established the direction for the means to achieve the acoustic targets. Being open to the outside via louvres for the mechanical system, and via motorised glazing for smoke extraction, the upper portions of the atria were vulnerable to rooftop mechanical system noise.

This meant that control of mechanical system noise from the rooftop-mounted supply and laboratory exhaust fans would have to be at the units themselves, as the atrium envelope would provide minimal sound isolation at best (louvres closed) and at worst, none (louvres open). Also, the portion of the atrium envelope not operable was primarily glazing, with minimal sound isolation value.

Acoustic modelling to map potential noise levels on the roof, using the fans and exhaust stacks as simple acoustic sources, indicated the extent of the challenge, particularly for adjacencies to the atria. Specific calculations and analysis of the mechanical systems themselves indicated the range of mitigation required.

The usual acoustic barriers were ruled out early in the analysis. Initial modelling indicated that barriers between the atria cupola louvres and the mechanical systems could impede the airflow required for natural ventilation extract or for the smoke extract system. The variables thus became location of the devices relative to the atria, selection of quieter units, or sound mitigating elements such as silencers or noise-reducing enclosures. Arup's final solutions included each of these:

- The exhaust stacks from the laboratory exhaust fans were relocated to avoid acoustic "hot-spots" on the roof from multiple stacks close to each other and to the atrium.
- The supply fans were changed from the standard single-fan air-handling units (AHUs) to a "fan-wall" unit - multiple smaller fans in a single housing supplying the same air volume as the standard fans, but with markedly reduced vibration and low-frequency fan noise.
- Intake silencers were put at the supply fan inlets, close to the atria louvres.
- Silencers were installed in the exhaust fan ductwork.
- The exhaust fans themselves were installed in sound-isolating enclosures.

On the atria interiors, room acoustic requirements were again bound by openness and transparency requirements, effectively establishing "go/no-go" zones for provision of acoustic treatment. Acoustic treatment in the atria was needed to reduce reverberation time and diminish occupancy noise and break-in noise from the building services systems.

Preliminary studies indicated that, without acoustic treatment, the room would be highly reverberant. Opportunities for treatment were, however, limited due to the lack of available wall-space and restrictions to putting acoustic banners at the tops of the atria (blocking light), along the sides of the upper atrium cupolas (blocking air flow at the louvres), or on the floor (more difficult to keep clean than hard floors).

An acoustic model was built of a "typical" atrium (all four are slightly different), and sound "sources" placed at various locations within. Arup's acoustic engineers wanted to determine, for a given source location, which surfaces in the room were acoustically "open" to that source. By analogy, if the acoustic source represented lighting, the team wanted to see which surfaces would be "illuminated" and which would remain dark. Those surfaces illuminated by a particular source location would be the first choice for placing acoustic treatment to control the direct and early reflected energy from that source. By absorbing and reducing these sound energies efficiently, control of the reverberant energy was also optimised.

Repeating this for sources at each floor level adjacent to the atria and at the atrium floor levels themselves yielded a list of surfaces that were prime locations for acoustic control of reverberation and occupant-generated noise. By vetting the effectiveness of the various room surfaces for acoustic accessibility to the direct and early sound energy from the sources, Arup could work with Boora, prioritising and focusing on a specific palette of surfaces for treatment.

8. Room acoustic requirements were again bound by openness and transparency requirements.

Process and receptacle loads

Process and receptacle loads are quickly gaining attention as the greatest energy consumers in high-performance buildings, approaching 70% in some cases. This is especially true where lighting, conditioning, and ventilation energy use is extremely low, and in buildings with intense process loads, eg science and laboratory programmes. Y2E2 was estimated to have a non-regulated end-use proportion of over 50% if no actions were taken to reduce the loads.

Historically, such loads have been considered by the energy design standards and design professions to be "non-regulated" and outside the control or influence of engineers. The USGBC's LEED® rating system for example, prior to its most recent version release, awarded all energy points only on "regulated" loads, effectively ignoring a large energy-consuming end-use in many buildings.

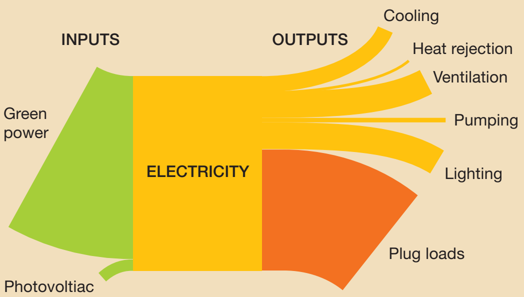
Realising the impact of these loads on Y2E2's performance, Arup argued strongly for both better understanding of the potential opportunity and the need for more informed design criteria, and the team expended significant effort identifying and characterising the equipment planned for the building. Discussions with the incoming occupants and Stanford focused on opportunities for reducing these loads, including:

- occupant habit, education, and load budgeting
- proper sizing through appropriate design margins and diversity (instead of typically excessive assumptions)
- establishment of a preferential purchasing/leasing policy where standards exist (eg EnergyStar V4, EPEAT)
- informing laboratory equipment manufacturers about a preferential purchasing intent
- consumer alliances with the University of California and other university partners
- optimising the number and location of equipment for shared use.

The benefits were identified to include:

- reduced first cost by \$1-\$2/W/ft²
- operational cost savings on a direct basis/W/hr avoided
- improved occupant comfort in naturally ventilated areas.

9. Energy flow, highlighting the potential opportunity and risk of high plug loads in Y2E2.



Natural ventilation

Stanford's temperate climate is ideal for the passive conditioning and ventilation of buildings by natural airflow (Fig 10), and over the past half-century the campus had incorporated natural ventilation in several buildings that could have otherwise have been mechanically conditioned. Not all were successful, however, and from the start of Y2E2's design the team was challenged to find a meaningful solution that incorporated lessons from the past successes and failures.

Arup studied existing buildings on the campus and gathered feedback from past and present occupants and designers.

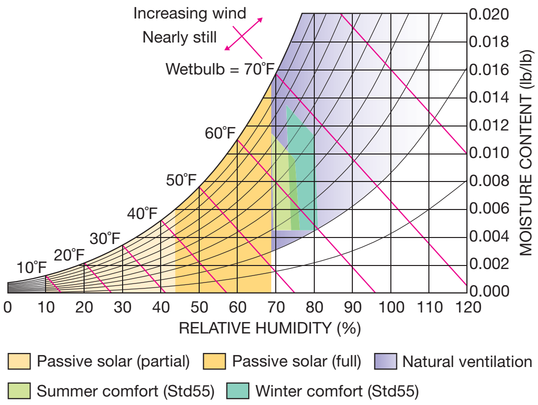
Over 30 lessons from this study were then applied to the design and operational intent of the Y2E2 natural ventilation system, including:

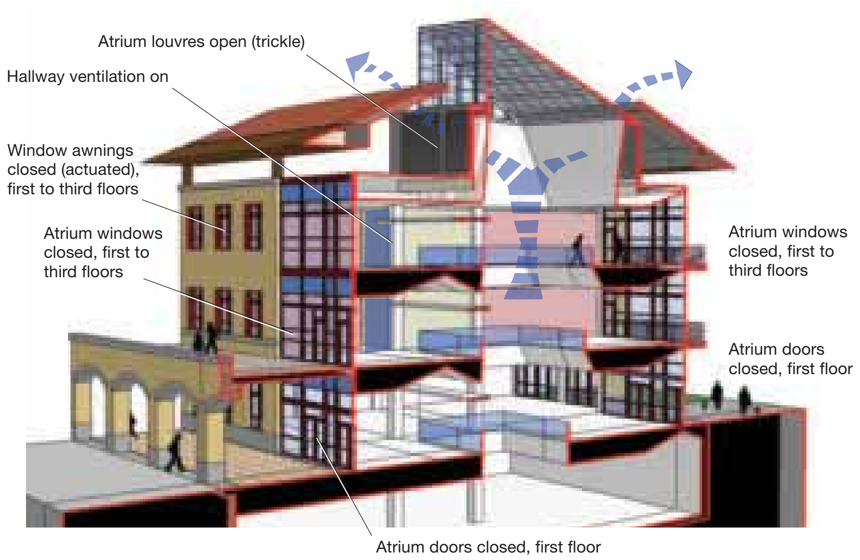
- seeking opportunities for passive redundancy (no single point of failure)
- avoiding poor quality and low-bid design/ construction practices
- ensuring maintenance and facility personnel buy-in
- clarifying occupant expectations, programme assumptions, and education
- capitalising on the reduced risk of north and east solar orientations.

Adaptive comfort and transitional zones

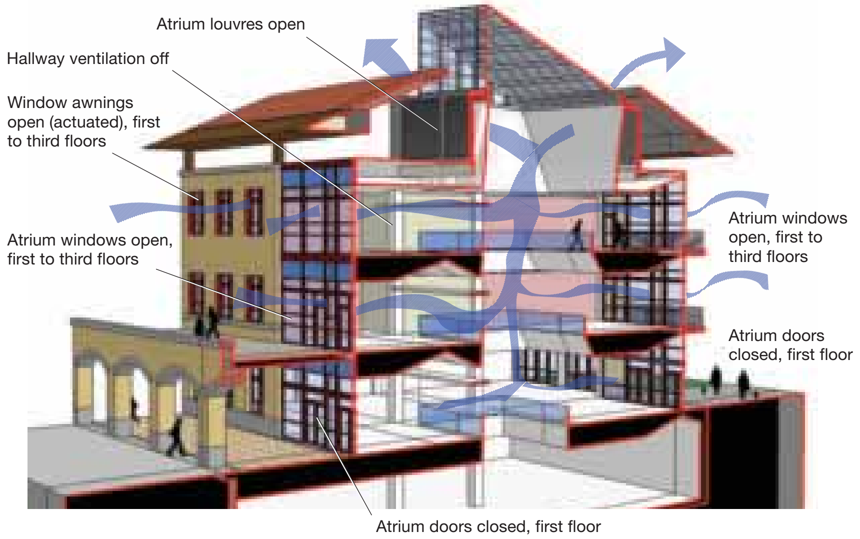
Early in masterplanning SEQ2 and the conceptual development of Y2E2, the team developed a scheme of "thermal transitioning". By providing a progressive transition from areas with the most intense temperature and sunlight and greatest occupant transience to those of least temperature variance and regular occupancy, the team could reduce energy consumption from air-conditioning but still ensure a comfortable workplace. As occupants pass from the unprotected open quadrangle, to the shaded outdoor arcade, to the naturally ventilated indoor atria, and finally into their offices and meeting areas, they move gradually toward increasing comfort, reduced thermal variation, and more regular occupancy.

10. Bioclimatic psychrometric chart, showing climate and natural ventilation comfort potential at Stanford.





11. Natural ventilation control scheme in cooling mode at temperatures above 82˚F. In this mode the building management system (BMS) closes actuator-controlled windows and initiates messages to occupants to manually close their windows.



12. Natural ventilation control scheme in night flush mode, in which the BMS opens actuator-controlled windows and initiates messages to occupants to manually open their windows.

As the occupants expressed a desire for operable windows and natural ventilation, Arup summarised for them the implications of newly-released adaptive comfort criteria based on work by Brager and deDear[2]. Occupants who could control their own environment and had a direct connection to the outdoors were shown conclusively to be more tolerant of temperature variation. Through computational analysis Arup was able to demonstrate that select offices with adequate solar protection could maintain comfortable conditions with no mechanical cooling or forced ventilation.

Solar response

Recognising that effective passive conditioning and ventilation were possible with the four atria, and occupant buy-in, Arup and Boora worked to optimise the façade and space layout. The application of natural ventilation as opposed to mechanical conditioning corresponded strongly to solar orientation. After more detailed analysis, the team decided that the north and east-facing areas abutting the perimeter wall and receiving the least solar gain could be purely naturally ventilated. South and west areas would function in a mixed mode, with supplemental active chilled beams and operable windows.

The building's operable windows were designed as recessed (or "punched") windows and then treated, based on orientation, to minimise solar gain and enhance natural light penetration. North-facing windows have vertical and horizontal mullions near flush with the glass. East-facing windows have vertical mullions that extend the depth of the recess and work in concert with that recess to shade the glazing from oblique sun angles. West-facing windows have extended vertical and horizontal mullions, whilst south-facing windows have extended horizontal sunshades in place of the horizontal mullions. The south-facing sunshades protect the glass and deflect light into the room through transom windows.

Control

Given the potential strength of airflow through all the atria openings, a strategy was needed to manage the velocity while maintaining enough passive draw during warm, windless conditions to move adequate air through the building.

The result was a combination of motorised and manual operable windows combined with motorised louvres.

Through the building management system (BMS), the motorised windows open and close when interior temperatures reach a pre-set point relative to outdoor temperature, providing fresh air to all levels of the atria as well as cooling the corridors. Simultaneously, manually operable windows and ceiling fans provide and circulate fresh air to and through offices at occupant discretion. The release for all air entering the building in both ways is in the glass atria caps, which have louvres on all four sides. A rooftop wind speed and direction monitor tells the building which louvre dampers need to open and close.

In windy conditions, louvres downwind of the atrium cap open, creating negative pressure to draw air out of the building which in turn creates more draw to pull more air out. When there is no wind, all louvres open. For further control, the atria louvres can modulate their positions.

14. Rooftop motorised louvres.

Occupant control of the operable windows was a source of significant discussion and analysis during the project design. Numerous control strategies were assessed for cost and benefit, including motorised building control with occupant override, manual control with contact strip lock-outs, and visual indicators.

Due to the commitment of the occupants and lowest first cost considerations, visual indicators in the form of BMS-initiated messages to occupant computers were selected for Y2E2, along with a move-in user guide for all the occupants.

This is the first of nine major buildings under construction at Stanford, and it is important to note that successive projects have elected to incorporate manual windows with contact strip lock-outs due to differences in occupancy commitment and Arup's recommendations to minimise the potential for energy leakage in mixed mode areas.

Night flushing

With a typical day-to-night temperature swing of <25˚F, Y2E2 benefits from the ability to circulate nighttime air through the building fabric and release heat accumulated during the day. To facilitate the effectiveness of night flushing in the natural ventilation (and mechanical ventilation) sequences, thermally massive floor surfaces have been exposed in many areas. The digital control system combines readings from internal and external temperature sensors and then uses the motorised windows to allow cool air in.

Arup provided two options for night flushing control: one of sophisticated and optimal performance which, among other features, anticipates the next day's temperature based on the previous day's (or weather forecasts), and a simplified version based on instantaneous temperature readings and a single interior setpoint.

Active chilled beam technology

While relatively new in North America, active chilled beam systems are proven and popular in Europe and elsewhere. Unlike traditional "all-air" conditioning systems that provide both ventilation and cooling through a primary duct or ducts, active chilled beam systems decouple ventilation from conditioning, transferring most of the cooling and heating loads from the less efficient air distribution system (fans and ductwork) to the more efficient water distribution system (pumps and piping). The benefits are typically:

- reduced energy consumption and operating costs
- Smaller AHUs and ductwork (typically 60-80%)
- reduced floor-to-floor height (or conversely an increase in glazing head height and resulting daylight penetration)
- increased chilled water system output due to higher return water temperatures.

The building's ventilation air is supplied to the active chilled beam terminal units by the central air-handling system. This ventilation air is cooled or heated to partially handle the temperature-driven sensible loads; in the summer it is cooled/dehumidified enough to handle all the internal moisture-driven latent loads.

The ventilation air is introduced into the active chilled beam through a series of nozzles or holes - up to nine nozzles/ft (28 nozzles/m) of beam. Air passing out of the nozzles induces or "pulls" room air up into the active chilled beam and in turn through a water coil. Induced room air is

13.

cooled and/or heated by the water coil to the extent needed to control the room temperature. Induced room air is then mixed with the ventilation air and the mix discharged into the room.

In general, the central system is designed to circulate only so much air as is needed for ventilation and dehumidification; the active chilled beams provide the additional sensible cooling and/or heating required through the induced room air and water coil. The amount of primary air circulated by the central system is thus dramatically reduced, along with the size of the AHUs and ductwork.

Fan energy has been shown to be often second only to lighting in the energy consumption of typical commercial buildings in North America. Active chilled beam systems dramatically reduce the fan energy due to the relatively small amount and low pressure of the primary air circulated by the central system.

Daylighting

The campus benefits from abundant sunlight; the average direct solar insolation level of 5.4kWH/m² actually exceeds that of more southerly locales such as Houston, Texas, and is very consistent throughout the year. But although this ample sunlight is available, the team faced significant challenges:

- The masterplan dictated a building cross-section of 80ft (24.4m), ie 30-100% wider than the ideal of 40-60ft (12.2-18.3ft).
- The building's square footage, combined with the campus height limit, dictated that an entire floor would need to be below grade, forming a basement.
- The demands of faculty offices forced the partitioning of the interior with walls.
- The building's passive natural ventilation and energy efficiency goals required a high degree of solar control, especially on the west and south exposures.

The full design team worked to develop responses that included:

- skylighting the building core using the atria
- façade and room treatments to control sunlight and extend it into the interior
- seamless integration with dimmable lighting and task lighting
- basement light wells along the south exposure
- material selection to promote translucency in the interior.

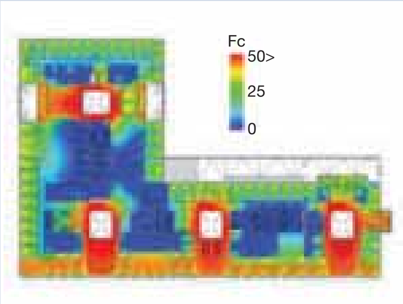
The result is a building with significant views and transparency, daylighting for approximately 60% of the occupied floorplate (including the basement level), and very little artificial lighting during the day. Indeed, during a campus-wide power outage six months after opening, many occupants failed to realise any disruption.

15. The atria deliver light to all floors including the basements.

Modelling of multiple physics

Over 60 computational models were created and run for Y2E2, reflecting 2500+ hours of computer time and ancillary analysis. This enabled the team to develop successfully many of the building's critical design elements, including the atria, naturally ventilated perimeter, daylighting systems, passive smoke evacuation, and range of energy-saving technologies. The models were also critical to cost/benefit decision-making, helping to ensure that capital investments were well informed.

16. Daylighting + illuminance model (level 2).



Daylight modelling allowed the team to better understand the effect of daylight harvesting techniques and the scope of dimming controls for the artificial lighting system. Thermal comfort modelling clarified the daylighting and ventilation requirements, to the benefit of future occupants. Acoustic modelling helped to mitigate issues of noise break-in to the atria from the rooftop mechanical systems, and examined the effect of the rooftop visual screening parapet for reflection of rooftop mechanical noise into the quadrangle below. Finally, the atrium interior acoustics were modelled to establish the locations, amount, and type of treatments needed to control background noise levels and reverberance in the atria and adjacent spaces.

Computational modelling for Y2E2 included:

- daylight (Boora, Arup) (Fig 16)
- energy (Arup)
- natural ventilation CFD (Arup)
- lab stack exhaust (Ambient Air Technologies)
- passive smoke evacuation CFD (Arup)
- Comfort CFD (Arup)
- rooftop noise mapping (Arup)
- atria acoustics (Arup).

Skylighting

By delivering light to all floors including the basement, the atria optimise the abundant daylight that penetrates the building, with the glass caps distributing natural light by reflecting it off wall surfaces. The building is designed to bring this direct sunlight down to the basement level for those using the labs, while lighting the floors above.

Side lighting

In addition to top-down light distribution, the team worked to optimise the amount and intensity of natural light entering through the perimeter. The design maximised Y2E2's length east-west, providing significant north and south façade exposure. Tailored shading and glazing strategies were used for each façade exposure. Vertical mullion caps on the east and west façades aid in shading. This, combined with high performance low-e glazing, was used to control the admittance of direct sunlight and the associated heat gains.

The north façade glazing uses high performance low-e glazing as well; however, visible light transmittance (VLT) here is highest, direct sunlight not being a concern on this face of the building. The high VLT maximises the ambient daylight available to the north- facing rooms, without compromising visual comfort. By contrast, the south façade receives significant direct sunlight throughout the year.

With Palo Alto's predominantly clear sky climate, a strategy combining external sunshades and internal light shelves optimised the distribution of daylight in the rooms on the south side, and integrated with the reduced loads needed by the building's mixed mode mechanical system.

In addition to thermal shading, the external sunshades block direct sunlight entering the windows for much of the year. In winter, when the sun is at low altitude angles, the glazing below the sunshades has a relatively low VLT, to mitigate intensity of direct sunlight. Internal light shelves help distribute daylight into the spaces by reflecting incident direct sunlight off the ceiling. The light shelves are in the same horizontal plane as the external sunshades, above which the windows extend far enough to permit the required daylight. Higher VLT glazing above the shades maximises the available direct sunlight to the top of the light shelf, enhancing the reflected light. Lower level roll-out shades have been installed on the south and east for conditions that cannot adequately be addressed by fixed shades and light shelves alone. Additionally, the light shelves continue past the edges of each window to aid in mitigating direct sunlight through the high VLT glazing.

The energy strategy

Energy provision was addressed through a step-by-step storyline that simultaneously organised, simplified, and prioritised the University's investment (Fig 17). The energy story emphasised load reduction, passive operation, and efficiency (steps 1-3); sought out energy recovery opportunities (step 4); included self-generation (step 5); and allowed for successful carbon-neutral operation (step 6).

As a result, Y2E2 is predicted to use 50% less energy* and achieve a return on investment of up to 36%, as well as be more enjoyable to visit. In response to its success, Stanford University has since mandated that this energy and sustainability performance be pursued on all subsequent buildings in SEQ2. Energy used in buildings generates an estimated 70-75% of Stanford's carbon emission, the remainder from vehicles. With the energy reduction projected for Y2E2, the design and those it inspires will greatly reduce Stanford's carbon footprint.

A complete list of strategies implemented in each step is shown on the right. Select examples have been extracted and summarised as follows:

Step 1: Reduce

Office loads: Receptacle loads directly consume electrical energy and indirectly increase the energy consumption of conditioning systems. As a result, they were a highly leveraged opportunity at Y2E2 for integrated cost savings and further energy efficiency. Repeated efforts were made during the design to rationalise receptacle load assumptions, establish budgets for future use, and allow the University to commit to a procurement policy for campus-wide performance improvement.

Reduce leakage: Spray-in insulation, typically in a thin layer into open wall, ceiling, and floor cavities, expands to about 100 times its original volume, forming an air barrier. It is then trimmed flush with the framing members before drywall is installed.

Step 2: Make passive

Mixed-mode operation: Although approximately a third of the floorplate is purely naturally ventilated (no supplemental cooling), the remaining non-lab areas of the building a mixed-mode operation that allows building occupants to open their windows during temperate conditions.

Step 3: Make efficient

Chilled beams heat and cool the conditioned non-lab areas of the building; active chilled beams utilise the more efficient water distribution system (pumps and piping) instead of the less efficient air distribution system (fans and ductwork).

Step 4: Recover

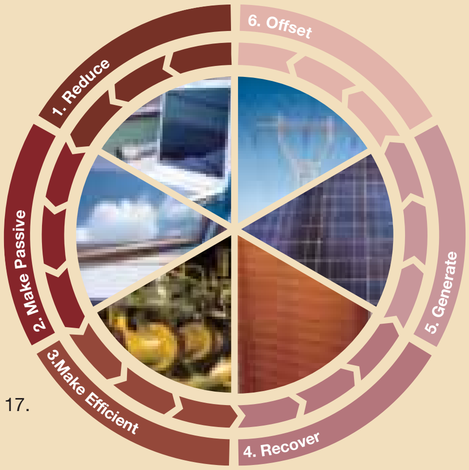
Heat pipe: Laboratory exhaust air is used to pre-condition incoming air. Using a physically separated passive solution that does not depend on moving parts avoids cross-contamination and significantly reduces maintenance.

Step 5: Generate

Monocrystalline PV: Y2E2 features a PV system with space for four arrays, of which three are installed on the south-facing roof. They produce 12.5-14.5kW at their peak and could deliver 16.5-18.5kW with the fourth system installed.

Step 6: Offset

Community reinvestment: This being a laboratory building, full site generation was not feasible. The desire to achieve carbon neutral operation has prompted the campus to seek further opportunities through purchased offsets and community reinvestment.



17.

1. Reduce
office loads
office size
education
lighting power
lab process loads
lab airflow rates
hood density
insulation
reduce leakage
shade
punch windows
thermally break
low-E glazing.

2. Make passive
incorporate atria
naturally ventilate
mixed-mode operation
expose mass
daylight
transfer boots
light shelves
open interior
translucent interior
light colours.

3 Make efficient
chilled beams
radiant floor
low pressure air
ceiling fans
daylight dimming
monitoring
cogeneration service
water-cooled computer rooms.

4. Recover
heat pipe.

5. Generate
monocrystalline PV
polycrystalline PV
amorphous thin film PV
fuel cell tie-in (future).

6. Offset
purchased offsets
community reinvestment.

Photosensors adjust the electric lighting in offices adjacent to the façades in response to the available daylight, giving appropriate levels for task lighting under any daylight condition. Translucent partition walls allow the daylight harvested in the perimeter spaces to spill into adjacent corridors, providing a visual connection to the outdoors, as well as an architectural link to the bright, daylit atria.

Complementary daylighting and task lighting

The engineered light shelves and exterior shades optimise the provision of daylight in the building, but the electric lighting must be tuned to work harmoniously with variations in natural light, creating a holistic and non-distracting system. Y2E2 does just this. A combination of task lighting and architectural lighting work seamlessly with the daylight. A combination of indirect and direct architectural lighting in the offices achieves the minimum recommended illuminance levels. Additional LED task lights or LED under-cabinet fixtures add supplemental lighting to meet users' needs. Architectural lighting power densities are very low, and the LED task lighting operates with only 6W.

The architectural lighting is controlled through a combination of photosensors and occupancy sensors, the former controlling the lighting in response to available daylight while the latter ensure that the architectural lighting turns off when occupants leave the room. Reports from staff indicate that the task lighting is the source of choice when no natural light is available, and that the architectural lighting in private offices is typically not required. The translucent partitions also allow a level of ambient light into offices from adjacent corridors.

18. Engineered light shelves and exterior shades optimise the provision of daylight in the building,

* Energy comparison uses a baseline significantly more rigorous than the national average (ASHRAE 90.1-2004). Saving predictions are 42% including process loads and 56% excluding process loads.

The water strategy

As a campus in a Mediterranean climate with frequent water shortages - and recognising that water would soon be a limiting factor in its continued development - Stanford chose to aggressively pursue both water efficiency and alternative water sources.

To address the water performance goals meaningfully, the team took a similar approach to that for energy; a step-by-step storyline that simultaneously organised, simplified, and prioritised the University's investment (Fig 19). This emphasised reduced water use in (1) landscaping and (2) the building; (3) reclaimed water use; (4) greywater capture and storage; (5) rainwater capture and storage; and (6) water use offsets.

The building is thus predicted to consume 2M gallons less water per annum and achieve 90% reduction in fixture potable water use*. Partly resulting from the Y2E2 and SEQ2 work, Stanford has invested in a reclaimed water system to serve over 2Mft^2 (186 000m^2) of development and reclaim approximately 60 000 gallons of water per day for non-potable use.

A more complete list of strategies implemented in each step is shown on the right. Select examples have been extracted and summarised as follows:

Step 1: Reduce site use

Native and low water-consuming vegetation were incorporated, historic oak trees were saved and replanted, planted areas were minimised in favor of high benefit zones, and the little water needed for irrigation is sourced from rainwater captured in the gravity-fed Felt Lake reservoir.

Step 2: Reduce building use

Low water consumption WCs (1.28gal/flush) and urinals (0.125 gal/flush) were installed. Also, one waterless urinal was installed in each men's toilet room. Since the campus central energy facility (CEF) evaporates water in cooling towers to condition the campus buildings, savings from reduced cooling load were three to six times the savings from building fixtures.

Step 3: Reclaim water

Water for cooling in the CEF is captured, treated, and piped for laboratories and flushing. Designed under a separate project, but concurrent with Y2E2, was Stanford's on-site water treatment plant and site piping system. To help sustain itself within the natural limits of its environment, and to contribute to the conservation of potable water resources, this recycled or CEF water Is piped into Y2E2 specifically for flushing water closets and urinals (as well as potential use in laboratories if quality is deemed sufficient).

Step 4: Greywater capture

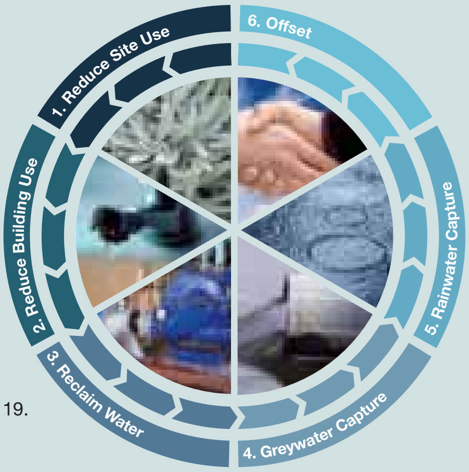
The team carried a greywater capture and treatment option for the early project phases, but once the reclaimed CEF water was confirmed, this option was eliminated.

Step 5: Rainwater capture

Although a below-grade stormwater capture, storage, and treatment system was designed in, it was deleted during early construction phases. A successor building (the Stanford Graduate School of Business) is, however, incorporating a similar rainwater capture element.

Step 6: Offset

The team recognised that some potable water would always be consumed and that better leverage could be achieved by reinvesting in other campus buildings and the surrounding community. In exploring a net zero water operation the team has considered further such opportunities.



19.

1. Reduce site use
- native and low water consuming vegetation
- historic oak trees saved and re-planted
- planted areas were minimised
- water for irrigation sourced from rainwater captured.

2. Reduce building use
- low water consumption WCs
- savings from reduced cooling load.

3. Reclaim water
- Water used for cooling is captured, treated, and piped through campus for laboratories and flushing.

4. Greywater capture
- A greywater capture and treatment option for the early project phases was undertaken. Once reclaimed water from the CEF was confirmed, greywater capture was eliminated.

5. Rainwater capture
- A future phase, below grade capture, storage and treatment system was included.

6. Offset
- Community reinvestment.

Cost

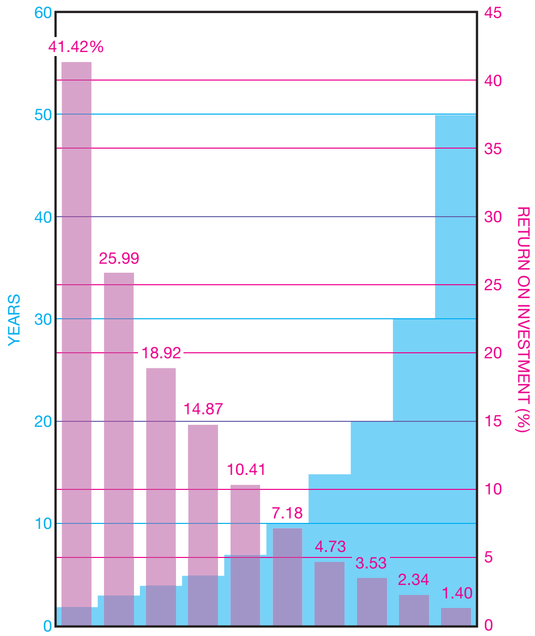
In an era of global economic development and trade, increased material demand has dramatically inflated construction costs. If demand is the first factor in the numerical rate of inflation, time is the second factor of the compounded inflation rate. Design teams are under pressure to innovate, as shorter building delivery time means reduced cost. "Faster = cheaper" is a new mandate for design/construction teams. At the same time, when the built environment is implicated in 40% of all US energy use, and energy generation, use, and conversion are in turn implicated in rising greenhouse gas emissions, building design and construction must meet increasingly high quality levels and performance targets.

The sustainability premium

During the design and construction of Y2E2, the team closely tracked and discussed the sustainability premium associated with the project. Individual design elements were broken out of the cost estimate and summed to establish a net sustainability premium (Fig 20). Its progression started from an early estimate of a 9% premium to a final estimate of a 0.9-4.6% premium. This range, agreed at the conclusion of the project in lieu of a single number, reflected the integrated design.

So much of the design served multiple functions that the assignment of a particular design element to the sustainability sum would have suggested a false accuracy. Instead, the range allowed for both liberal and conservative estimates. The resulting knowledge was more valuable than if a single % premium had been agreed.

Stanford's commitment to sustainability was demonstrated when the initial high estimate of 9% did not result in a reduction in the project goals. Instead, the team



20. Return on investment versus paybacks.

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* Calculated in comparison to the Energy Policy Act of 2005.

was encouraged to work through the ensuing phases, reducing the premium but maintaining the aspirations. Between the first and final estimates, misunderstandings of the design intent were resolved, inaccuracies in the cost estimate were addressed, the design team improved and optimised the design, the contractor suggested enhancements, and the owner made some value-based decisions.

12+% return on investment

To encourage sustainable design practices and a high return on their investment, the Stanford board of trustee's life-cycle policy mandates that any strategy that pays back in 10 years or less must be pursued. Those that will pay back in 10+ years will be considered at the discretion of the project team. Y2E2 will recover the marginal costs of measures in its design in just six years, well under the 10-year benchmark and yielding 12+% return on investment. This cost recovery will come from savings due to less energy use as well as reduced first costs in select integrated systems (Fig 21).

Integrated design/construction team

Stanford's compressed schedule reduced the time available to design and construct each building from four to two years, and so an integrated team of architects, landscape designers, engineers, university stakeholders, contractors, and subcontractors address each building comprehensively, overlapping programming, design and construction phases to deliver each project as rapidly as possible.

The involvement of construction manager/general contractor Hathaway Dinwiddie enabled real-time costing and ensured that the contractors were invested in the design from the outset. This enabled tremendously valuable constructability counsel and secured contractor buy-in during design in support of the project goals.

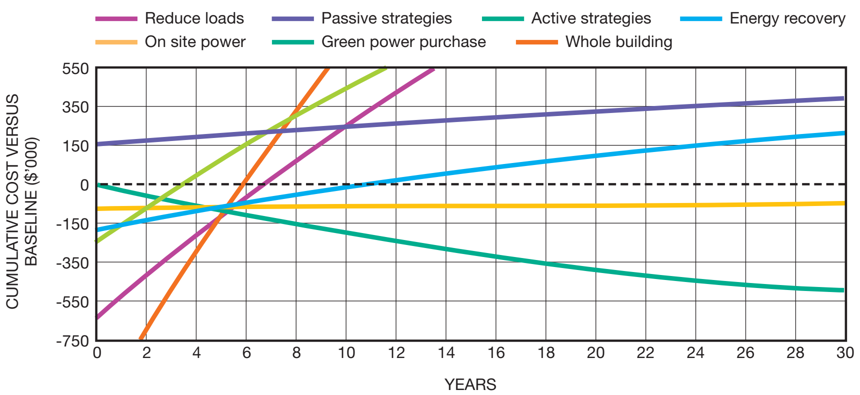
Cost savings on the precast concrete skin

The façade of limestone tiles preset in precast panels gives a consistent campus architectural expression. Importantly, it also enabled project delivery within its modest cost/ft^2 target and aggressive schedule, as it reduced construction time by over 40%.

Using these panels was significantly quicker than traditional hand-setting, installation being completed in eight weeks instead of the customary 20-24 for hand-set limestone. Much of the material cost inflation was avoided; also, fewer workers and less equipment were needed to install the panelised limestone, further reducing costs. This accelerated process imposed little critical path impact on other trades, as field crews were not on site for a long time installing panels.

The precaster further reduced costs by incorporating as many elements as possible into the panels. Window connections to them, and hardware to attach the metal window sunshades, were all installed in the plant, eliminating the need to do this on site. Additionally, because the limestone veneer and architectural detail elements were incorporated in the panels, extra steel support was not needed, further reducing overall costs for the exterior cladding.

21. Cost payback (intersection with the horizontal axis) for the six energy steps, as well as a "whole building" sum.



Conclusion

Officially dedicated on 4 March 2008, the Y2E2 building is named for Stanford Trustee Jerry Yang, co-founder of Yahoo! Inc, and his wife Akiko Yamazaki, who together pledged $75M to enhance interdisciplinary programmes at Stanford. The result is a fitting tribute to this philanthropic couple and the perfect workplace for the environmental and energy specialists who inhabit it.

Kurt Graffy is an Associate Principal of Arup in the San Francisco office, and the Americas regional skills leader for audio and audiovisual. He led the acoustics team for the Y2E2 design.

Janette Lidstone is a marketing specialist for Arup in the San Francisco office.

Cole Roberts leads the Energy and Resources business in Arup's San Francisco office. With Alisdair McGregor he led the project management/direction of Arup's Y2E2 design team, and also led the energy/sustainability assessment.

Brandon G Sprague is Communications Director at Boora Architects, Inc.

Jake Wayne is a lighting design consultant of Arup in the San Francisco office, and was a member of the lighting design team for Y2E2.

Armin Wolski is an Associate Principal of Arup in the San Francisco office, and led the fire safety design for Y2E2.

Credits

Client: Stanford University **Architect:** Boora Architects, Inc **MEP, energy/sustainability, fire/life safety, and acoustic consultant:** Arup - Key Anderson, Engin Ayaz, Peter Balint, Andrew Coles, Angus Deuchars, Joseph Digerness, Michael Dimmel, Jason Edling, Larry Encarnacion, Chris Field, Anthony Fresquez, Kurt Graffy, Gene Joves, Amit Khanna, Susan Lamont, Shaun Landman, Jun Lautan, Isabelle Lavadrine, Kathryn Lee, Dee Lindsay, Alisdair McGregor, Afaan Naqvi, Shruti Narayan, Tim Pattinson, Jason Prodoehl, Benedicte Riis-Duryea, Cole Roberts, Norman Romabiles, Geza Szakats, Larry Tedford, Jake Wayne, Matthew Williamson, Armin Wolski, James Woods, Darren Woolf **Structural engineer:** Middlebrook + Louie **Civil engineer:** BKF **Wind consultant:** Ambient Air **General contractor:** Hathaway Dinwiddie Construction Co **Landscape architect:** Hargreaves Associates **Electrical contractor:** Cupertino Electric Inc **Mechanical contractor:** ACCO **Laboratory consultant:** CAS Architects, Inc **Plumbing contractor:** Hellwig Plumbing + Greene Engineers **Controls contractor:** ICS Controls Inc **Illustrations:** 1, 3, 4, 6, 8, 14-15, 18, 22 Tim Griffith; 2 Boora Architects; 5, 7, 9, 11-12, 16-17, 19 Arup; 13 TROX®; 10, 20-21 Nigel Whale.

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About Arup

Arup is a global organisation of designers, engineers, planners, and business consultants, founded in 1946 by Sir Ove Arup (1895-1988). It has a constantly evolving skills base, and works with local and international clients around the world.

Arup is owned by Trusts established for the benefit of its staff and for charitable purposes, with no external shareholders. This ownership structure, together with the core values set down by Sir Ove Arup, are fundamental to the way the firm is organised and operates.

Independence enables Arup to:

- shape its own direction and take a long-term view, unhampered by short-term pressures from external shareholders
- distribute its profits through reinvestment in learning, research and development, to staff through a global profit-sharing scheme, and by donation to charitable organisations.

Arup's core values drive a strong culture of sharing and collaboration.

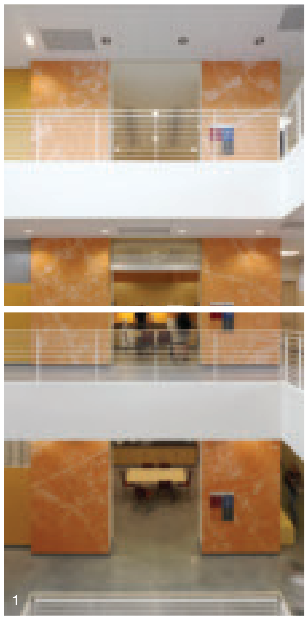
All this results in:

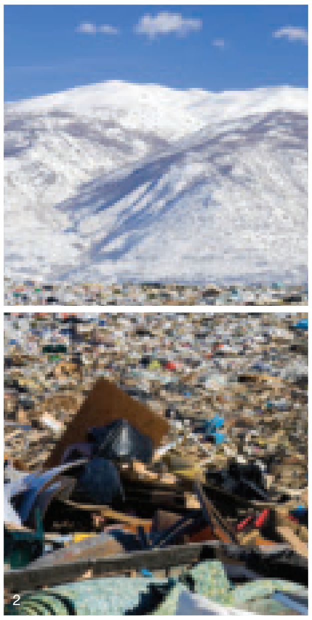
- a dynamic working environment that inspires creativity and innovation
- a commitment to the environment and the communities where we work that defines our approach to work, to clients and collaborators, and to our own members
- robust professional and personal networks that are reinforced by positive policies on equality, fairness, staff mobility, and knowledge sharing
- the ability to grow organically by attracting and retaining the best and brightest individuals from around the world - and from a broad range of cultures - who share those core values and beliefs in social usefulness, sustainable development, and excellence in the quality of our work.

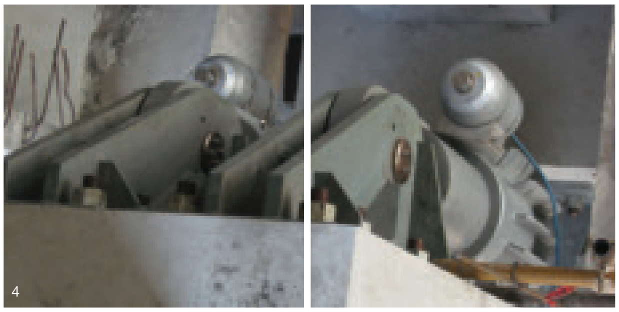
With this combination of global reach and a collaborative approach that is values-driven, Arup is uniquely positioned to fulfil its aim to shape a better world.

22. The west face of Y2E2 both suits the Stanford historical character and works with the natural environment, as window louvres, a shaded arcade, and green space improve the experience for visitors.

ARUP







Illustrations: 1. Atrium at the Jerry Yang and Akiko Yamazaki Environment and Energy Building: Tim Griffith; 2. Solutions to the problem of waste range from undesirable disposal, like this, to prevention and minimisation: Jacom Stephens/iStockphotos.com; 3. Staircase at the Crystal extension to the Royal Ontario Museum, Toronto, with strip lighting: © Sam Java; 4. Outrigger dampers at St Francis Shangri-La Place, Manila: Arup; 5. Railway bridge over Swartvlei Lake, Western Cape; infrastructure provision and investment sources have complex inter-relationships: Mda/Dreamstime.com.

Front cover: Dinosaur gallery glimpsed through the façade of the Royal Ontario Museum, Toronto: ©ROM.

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