The Future of Tall Buildings
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27th April 2023

The construction industry currently accounts for around 39% of the carbon dioxide emissions annually worldwide, 28% of which is operational and 11% of which is the embodied carbon of construction. The overriding question for construction as a whole is how to reduce these figures in the current climate emergency.

Tall buildings require a relatively larger amount of carbon in their construction than lower rise structures. How can we justify that? What is their future? Is it reasonable to construct tall buildings or should we consign them to construction history?

I am going to describe the factors that caused the sudden explosion in construction of tall buildings at the end of the nineteenth century. Then I will discuss the technology of tall building design. I will try to answer the essential question I have just posed, and finish with my thoughts on the future.

History

Tall buildings through history have been limited by the possibilities of the structural techniques available at the time. The pyramids in Egypt were the first man-made structures to break through the 100m height mark. The most famous were constructed during the 26th century BC, and the largest of them, the Giza pyramid, measured 146m above ground level.

More relevant to the specific theme of towers, the lighthouse of Alexandria was built in the reign of Ptolemy II between 280 and 247BC and measured around 120m.

It is not until the period of Cathedral construction in the Middle Ages, that these heights were surpassed. But even after all this time, the heights of the towers were not radically different from those built more than 1600 years before. Lincoln Cathedral spire, built in 1311, was reputedly 160 m high until it collapsed in 1548. Other spires followed around Europe, and all were around 150m high - in 1880 Cologne Cathedral was the tallest building in the world with a spire 157m high.

These structures are all built in loadbearing masonry - stone blocks piled on top of one another to create walls. These are heavy buildings, and their height is limited by three structural factors - the capacity of the stone wall to support itself, the capacity of the ground beneath the wall to support it, and the stability of the entire structure against loads acting on it.

A further factor limiting the height of buildings was the difficulty for anyone to walk to the top of them. Tall buildings were used for power or status, or as beacons, but not for economic reasons, and not many people went to the top of them.

Two technical transformations during the nineteenth century changed these limits.

In 1854 Mr Elisha Otis demonstrated a new safety hoist at the Exhibition of the Industry of All Nations in New York City. Cutting the single rope supporting the hoist that he was standing on, the platform dropped a few centimeters and then stopped, a result of the spring attached to the roof of the platform that engaged notches into the guide rails. Popular history records this incident as the beginning of elevators, but the reality is slightly more prosaic. By this period there were already many rival inventors and companies involved in means to raise people through buildings. The main point is that there was a frenzy of activity to fulfil an economic need to help people go safely up buildings.

The second major innovation was the incorporation of structural steel into the loadbearing structure of buildings.

The modern era of steel production began with the process invented by Henry Bessemer in 1855 which dropped the price of mild steel by a factor of 6 and enabled it to be produced more cheaply than wrought iron.

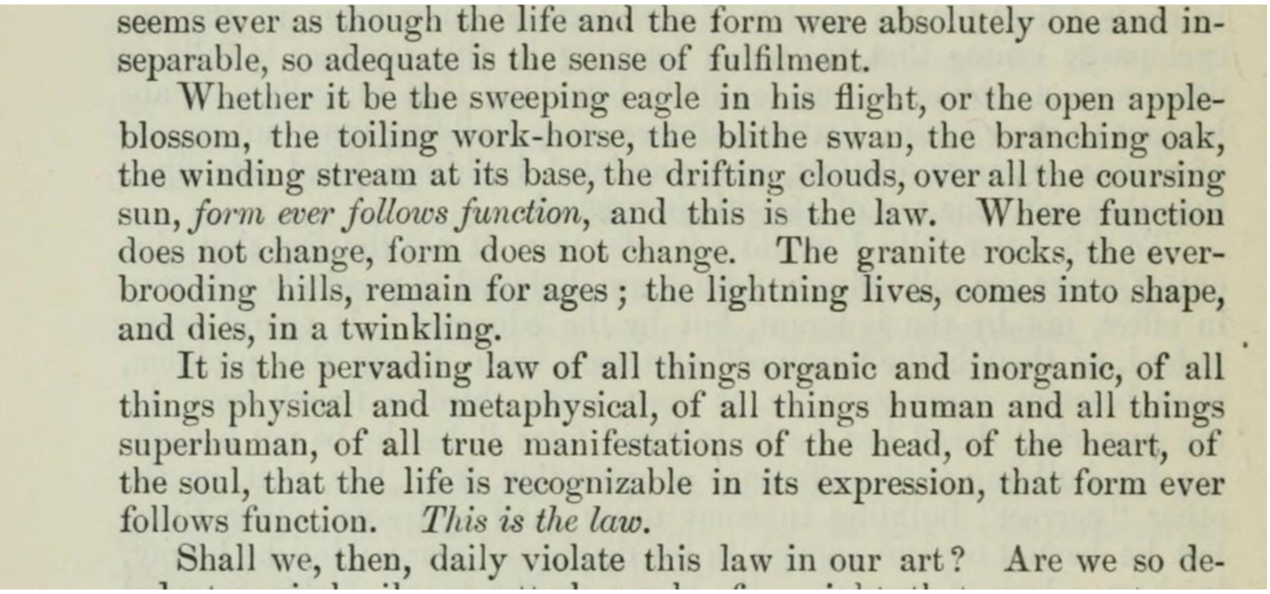
For tall buildings, the steel skeleton revolution started in Chicago and subsequently New York. Instead of buildings using loadbearing masonry walls, they started to be constructed as a steel skeleton surrounded by lighter weight walls.

All of a sudden, buildings were no longer limited by either the ability to walk up them, or the load capacity of either the wall material or the ground beneath them.

William Le Baron Jenney's 42m Home Insurance Building, built in Chicago in 1885, is often seen as the first skyscraper, but there is debate about this. The Home Insurance Building didn't have a complete steel skeleton. Instead it combined a steel frame with loadbearing masonry walls.

But the technology was advancing rapidly. Here are two other examples of tall buildings from the same period – each one with a steel frame surrounded by masonry or glass and steel cladding.

Of course, tall buildings needed an economic reason to drive their construction as well as the technological ability to make them. Chicago and New York were growing extraordinarily fast, and land values were increasing. In New York property values doubled between 1840 and 1870. At the same time, there was a benefit in density, in staying close to the coast, and to one another. In 1816 it cost as much to transport goods 30 miles overland as it did for those goods to cross the Atlantic.


seems ever as though the life and the form were absolutely one and inseparable, so adequate is the sense of fulfilment.

Whether it be the sweeping eagle in his flight, or the open apple-blossom, the toiling work-horse, the blithe swan, the branching oak, the winding stream at its base, the drifting clouds, over all the coursing sun, *form ever follows function*, and this is the law. Where function does not change, form does not change. The granite rocks, the ever-brooding hills, remain for ages; the lightning lives, comes into shape, and dies, in a twinkling.

It is the pervading law of all things organic and inorganic, of all things physical and metaphysical, of all things human and all things superhuman, of all true manifestations of the head, of the heart, of the soul, that the life is recognizable in its expression, that form ever follows function. *This is the law.*

Shall we, then, daily violate this law in our art? Are we so de-

As quickly as tall buildings arrived, a philosophy of their design was developed. Louis Sullivan, one of the most forward thinking architects of his generation wrote a piece called 'The Tall Building Artistically Considered 'in 1896 in which he said:

Sullivan built some fantastic early skyscrapers, disciplined and elegant. But form hasn't always followed function, and it still doesn't. The climate emergency could be an opportunity to measure the impact of departures from the most efficient structural response for a particular design. The technology of tall building construction came out of the United States, initially in Chicago and then in New York. There was a tipping point in these cities, a combination of technology and economics and political will, that drove the extraordinary expansion of highrise construction.

Technology

I want to talk now about the technology of tall building construction and show examples from our work.

At Foster + Partners, we design in integrated teams of architects and engineers, and we collaborate together on projects from the beginning of the concept stages. Our team have designed the structures for a number of tall buildings around the world.

I am going to show a selection of these to demonstrate the principles of tall building design.

These are the Lusail Towers in Doha, designed by the practice and completed in time for the FIFA World Cup

2022 in Qatar. The four towers are arranged in two pairs, 257m and 300m tall.

This is a model built by the structural team of one of the towers. We create these cardboard models to show the structure alone, to expose the skeleton of the building with the façade removed. Our aim is to design structures that are logical and efficient and elegant.

A tall building is a cantilever, fixed at the base, and subjected to both vertical and lateral loads over its height. The vertical loads are divided into the 'live loads' due primarily to the building users, and the lateral loads that are due mainly to wind and earthquakes. The building also has to support the 'dead loads', that is the self weight of the structure, the cladding, the finishes and the services.

These loads are carried by the structure down to the foundations.

The most common way to resist the lateral loads in modern buildings is by using the building's core. This is the part of the building that contains the vertical circulation - the stairs and lifts required to provide access, as well as possibly the spaces needed to house the services.

But above a certain height, anywhere from 150m to 250m, depending on the building, the core gradually ceases to be the most efficient method of providing lateral stability on its own. So we mobilise the perimeter structure to achieve greater strength and stiffness. The tallest pair of towers at Lusail incorporated trusses called outriggers which link the core to the perimeter columns at two points over the building height.

This photograph shows the four towers under construction, with the core visible above the floors. This close up shows the core, and the outriggers, and a perimeter truss at the outrigger level to spread the loads across the columns.

425

In some instances it is beneficial to the building plan to move the core to the edge of the building. An example of this is the recently completed tower at 425 Park Avenue, the result of a competition that the integrated Foster team won in 2012.

Tall buildings in Manhattan are required to fit within a tapering volume, which gets thinner over the building height, in order to allow light to penetrate between the buildings to the streets at ground level. In addition, the client wished to move the vertical circulation to the rear of the building, away from the Park Avenue entrance, in order to create whole floorplates with views of the streetscape, and Central Park to the north.

The resulting structure was conceived to be as minimal a response as possible to resist the vertical and lateral loads acting on the tower. Here is another of our card models to show the structure. A single line of columns starts at the top of the building and bifurcates at two levels as it descends. Each bifurcation creates diagonals that also connect to the core so that the columns and the core act together to provide stiffness and strength in both orientations.

The diagram on the left shows the vertical loads in the steel structure, red for compression and yellow for tension, and you can see how these compression forces gradually increase towards the base of the building. The middle diagram, beside the side view of the building, shows the overturning moment over the height of the building due to wind forces. You can see that it starts at zero at the top of the building and gradually increases towards the base. The red line shows the bending in the core and the blue line shows the total bending moment. You can see that the connections to the core, particularly the top one at around 400ft above ground level, enable the core and columns to work together and share the load between them.

The result is a structurally efficient building where the architecture and structure are completely aligned, the facade could be removed and the skeleton revealed to be completely consistent with the way the building appears from the outside.

At 388m tall, the China Merchants Bank tower will be the tallest building to date in Shenzhen. The stability for the building is provided by a combination of the reinforced concrete core, coupled with the external columns around the perimeter of the tower. The area is seismic, and the energy due to the ground movements is dissipated by a recent technology called buckling restrained braces which form part of the outrigger trusses linking the cores to the perimeter frame.

One of the areas where the technology of tall building design has advanced the most in recent years is the design of buildings for earthquakes. The principal loading due to earthquakes is a horizontal shaking of the ground beneath the building. It is now possible to model a simulated earthquake and to quantify the ability of the structure to absorb the immense amounts of energy that are imparted to it.

The building is on site and you can see here the reinforced concrete core being built, with the steel floor structure following on.

Are cities sustainable?

To come back to the original question, how does the technical capability that enables buildings such as these to be built, fit with the climate emergency and our societal need to radically reduce our production of greenhouse gases. This is a debate that is ongoing within the construction community, with understandably strongly held feelings.

Carbon dioxide equivalent is a measurement used to compare the global warming potential of the emissions from various greenhouse gases. Carbon dioxide itself does not have the largest global warming potential, but it is the gas that is most heavily emitted, and one that has a relatively long lifetime in the atmosphere. Most carbon dioxide emissions are the result of combustion of fossil fuels - through transport and through industrial processes that require high temperatures - around 1500 degree centigrade for the production of steel and cement.

The whole life carbon footprint of a building is composed of the carbon produced during its construction - the embodied carbon - and the carbon produced during its use - the operational carbon. Improvements in the insulation and power requirements of modern buildings have resulted in a substantial drop in the consumption of energy during the life of a building. As a result the embodied carbon of the construction has become relatively more important.

To consider the carbon impact of buildings, we can consider another measure which quantifies the impact of the building users. The Household Carbon Footprint measures the greenhouse gas emissions required to produce, distribute and dispose of all household consumption for one year. Here is an estimate of the household carbon footprints of residents across 31,500 zipcodes of the United States by Christopher Jones and Daniel Kammen of the University of California at Berkeley. This research uses national survey data to estimate the average household's consumption. There is a recognizable pattern. The densest areas – the city centres - show the lowest household carbon footprints – in green in the diagram. The suburbs show the highest household carbon footprints in red.

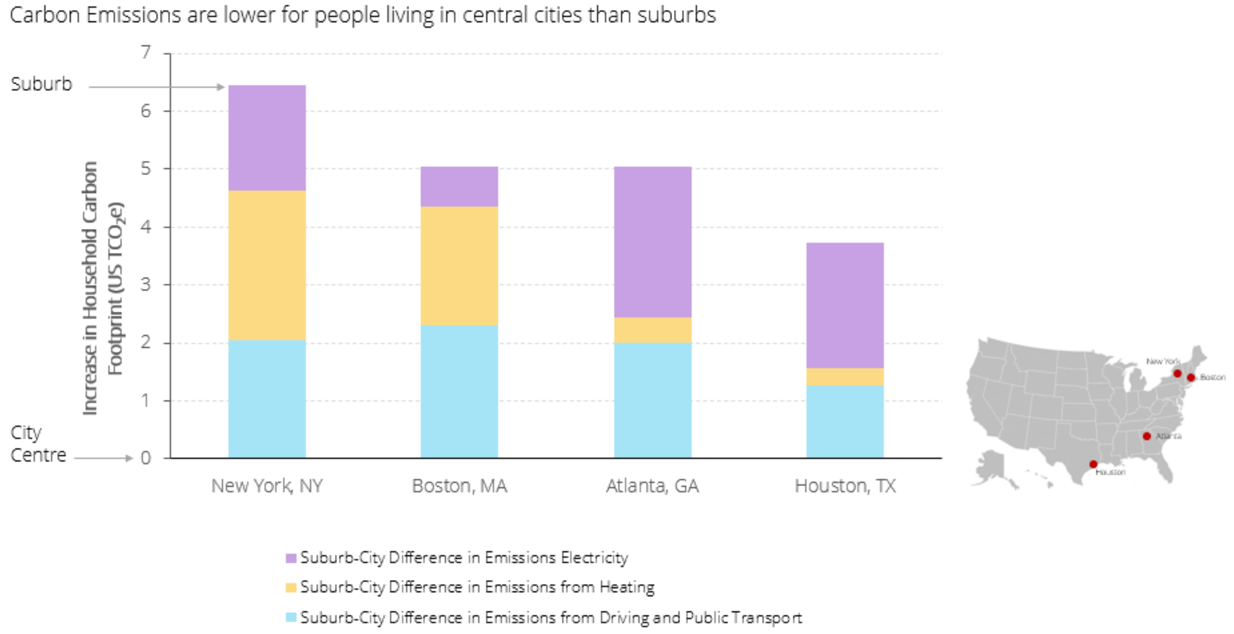
Here is a closeup of the same diagram around New York city.

The primary reason for the difference between suburb and centre is the reduction in private transport. Transportation carbon footprints are about 50% higher in large suburbs compared to large principal cities, while total carbon footprints are about 25% higher.

Here is the same information expressed graphically. Each yellow triangle is a zipcode and the horizontal axis shows population density – from low density rural areas on the left, to dense city centres on the right. The average value of household carbon footprint, shown in red, remains constant until it reaches a critical density, at which point it gradually reduces. The same effect is borne out when only the metropolitan areas are shown. New York city centre has a density of around 28,000 person/square mile, London centre, 14,500 person/square mile.

Other studies are consistent with these results. Professor Edward Glaeser of Harvard has examined metropolitan areas across the United States to see the difference in the household carbon footprint between the suburb and city centre for each area. The zero point for each bar is the household carbon for the centre of each metropolis – New York, Boston etc. The three bars are the increases in each source of carbon for the suburb of each metropolis. So the average household in a New York suburb has a household carbon footprint around 6.5T higher than a household in the centre of New York city. Households in the north use more natural gas for heating – shown in yellow, households in the south use more electricity for cooling – shown in purple.

USA | Suburb – City Difference in Emissions

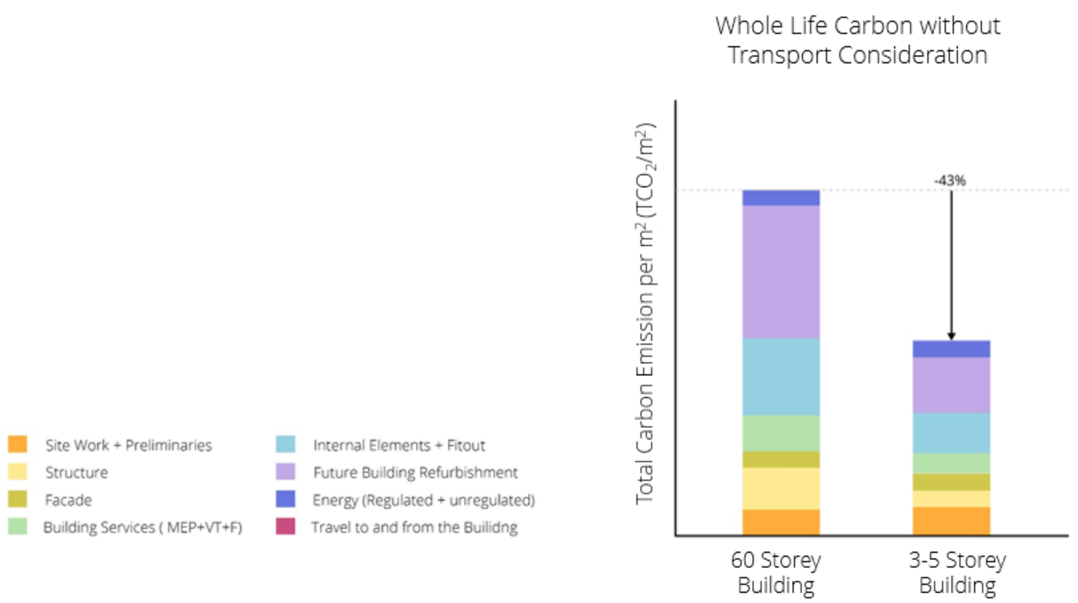


The same question was addressed by Colin Beattie and Peter Newman in Sydney Australia where the carbon footprint of 4000 living spaces over a mix of highrise, midrise, lowrise, and individual houses was compared. Once again, the study found that the higher emissions due to private transport in detached houses in low density areas was the defining factor that led to dwellings in these areas having the largest carbon footprint.

But what happens when we include the embodied carbon of construction into the calculation? Are the environmental benefits of dense city living cancelled out by the additional carbon emissions of construction of tall buildings? This is an emerging field and there are fewer studies.

Here is a comparison carried out by the Foster + Partners Sustainability team, led by Chris Trott, and published by the World Green Building Council. Chris and his team compared the whole life carbon of a tall building - around 60 storeys in a dense city with strong public transport connections to a low rise development, - around 3 to 5 storeys - in a suburban location accessed almost exclusively through private vehicle transport.

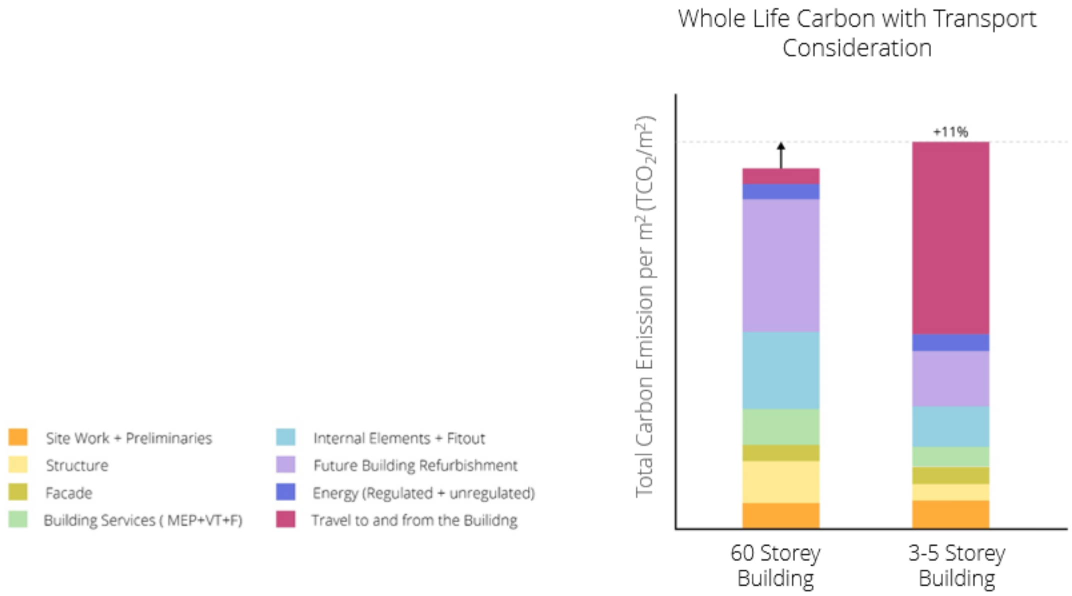
Whole Life Carbon| Tall Buildings vs Suburbs



Source : Transitioning to an integrated whole life approach to sustainability in the built environment
World Green Building Council/Chris Trott, Foster + Partners

These graphs show the embodied carbon and the operational carbon for the two developments. The embodied carbon of the structure is greater for the tall building than for the low rise. However, it is interesting to note that the greatest source of embodied carbon is due to the interior fitouts of the buildings, stripping out and changing the internal finishes, envisaged to be carried out at 10 year intervals over the 60 year projected building lifespan. These graphs include for the future electrification of transport, as well as the reducing carbon content of the materials due to projected reductions in fossil fuel use.

Whole Life Carbon | Tall Buildings vs Suburbs



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World Green Building Council/Chris Trott, Foster + Partners

But the situation reverses when the embodied carbon of travel to and from the development is taken into account. The embodied carbon of private transport for the low rise development exceeds the reductions due to the structure and fitout of the low rise construction.

Tall buildings enable urban density at which point public transport becomes economically viable, and local travel distances become shorter, permitting walking and cycling. The decrease in carbon emissions from shared heating and cooling, and above all the reduction in private transport, overrides the increase in carbon emissions from building tall.

And the benefits of density, of people living and working in close proximity, are substantial for the economy of a country. In the United States, workers who live in big cities earn around 30% more than workers who do not. Americans who live in metropolitan areas with more than one million residents are more than 50% more productive on average that Americans who live in smaller metropolitan areas, even when we account for different levels of education, experience and type of industry. This gap is the same in other countries, both rich, and developing economies.

It is worth bearing in mind that there is no absolute reason for it to cost more to live in a city than a suburb. It is the result of policy decisions such as the supply of new development allowed in cities, and the relatively low cost of private transport compared to public transport due to the subsidy of road construction.

It is also worth considering that countries are at different points of their urbanization, and every city started life as a field.

The Future

Regardless of this, we should in any case aim to make tall buildings as carbon efficient as possible.

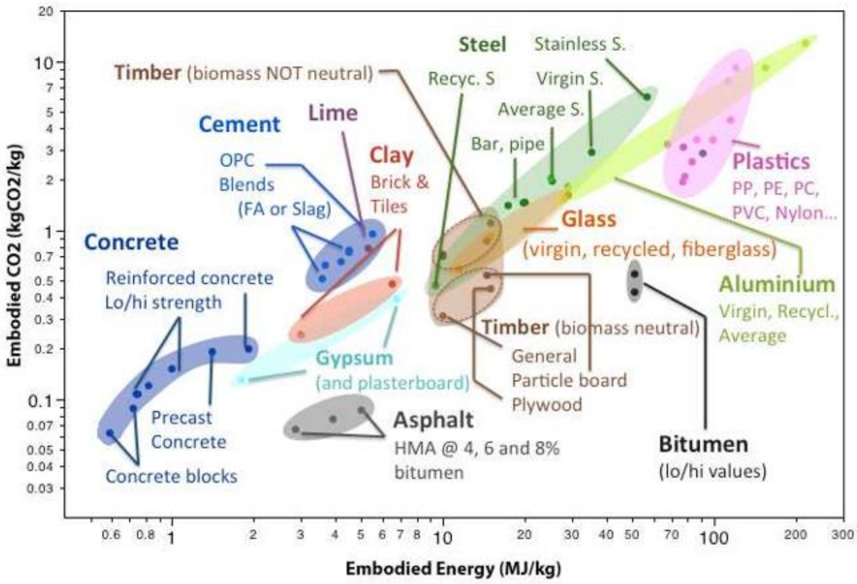
Wherever possible, we should consider reusing existing structures in order to avoid incurring the embodied carbon of new construction. When this is not practical, we should recycle the materials from the buildings that we remove.

And we need to make buildings that last. A city street can last for 500 or 1000 years, while a building might be pulled down after 20 years. Our philosophy needs to change - we need to think of buildings as vertical streets, whose functions can change, but whose structure remains.

We are constantly striving to lower the carbon content of our buildings through efficient design, and performance based analysis, and I gave some examples of this earlier in my presentation. But in the future we need to focus also on the materials that we use, and wherever possible to minimize the carbon in these materials.

As this graph shows, material embodied carbon is correlated with the embodied energy of their production.

Correlation Between Embodied Carbon and Embodied Energy



This is a reflection of the fact that fossil fuels constitute the majority of the energy used in material production.

So one of the most efficient methods to reduce the embodied carbon of materials is to minimize the use of fossil fuels in their production, to use renewable energy sources to achieve the high temperatures needed to produce the materials.

Rather than cover all materials in this presentation, I would like to focus on the material that is by far the most heavily used. Concrete.

Concrete is strong, durable, fire resistant, and cost effective, It is also the most used man-made material in the world, and behind only water as the world’s most used resource. And its use is increasing exponentially.

90% of the carbon emissions in concrete are due to the cement that, when mixed with water, binds the course aggregate, and fine aggregate - sand - together. These emissions are from two sources - the energy required to heat the limestone up to 1500 degrees in order to create lime, and in addition the carbon dioxide released when the limestone - Calcium Carbonate - is transformed to lime - Calcium Oxide. The huge worldwide production of cement means that its production accounts for around 8% of the world’s total annual carbon dioxide emissions.

It is astonishing to consider that this universal material has changed very little since it was patented, as Ordinary Portland Cement, by Joseph Aspdin in 1827, and subsequently adjusted by his son William Aspdin in the 1840s. The principal national concrete codes in the UK, Europe and the United States are based on this material.

There are two commonly used additional cementious materials that can be added in order to reduce the amount of the ordinary Portland cement content in concrete - both are waste products from other industries. Pulverized Fly Ash is the waste product from coal combustion, and ground granulated blast furnace slag is obtained from iron and steel production. We should use these wherever possible. But both are limited and dwindling resources, and fully utilized. So they are not on their own going to substantially reduce the carbon emissions of cement.

An emerging alternative is to mix ground limestone and calcined clay with the Ordinary Portland Cement. These are abundant resources, available all over the world, although further study is needed to assess their quality in each location. Their use is only just becoming codified, but they have the capacity to reduce the carbon content of concrete by over 40%.

And we need to design and build lean buildings, that reflect the forces acting on them and the constraints of their locations. Our design philosophy needs to reflect resource scarcity, any departure from efficient design needs to be justifiable through the benefits to those who use the building or its vicinity.

Here is a final example of a tall building, in a dense city, designed as efficiently as possible for the constraints of its location.

In 2017 we entered a competition for the new headquarters of JP Morgan at 270 Park Avenue. The brief called for a building around 1400 ft high in total, on a narrow site - 140ft wide, and, crucially, over the underground railway lines that lead into Grand Central Station further south on Park Avenue.

During the competition, the teams were informed that they would all be obliged to adopt the same column structure down into the basement in order to avoid the trains underneath. But we found another approach, where we defined a grid that gathered the columns into fan structures and brought loads down on each facade at just 3 points. Inside the building, we brought the loads down on double columns at a further three points.

These diagrams show the loads in the structure – red for compression and yellow for tension. The structural solution is driven by the constraints of the site. You can see that the external bracing on the east and west facade provides stiffness and strength to the building over and above that provided by the core and outriggers. Here is a view of the bracing and fan columns at ground level. And here is the same view of the structure on site.

The building will be 100 percent powered by renewable energy sourced from a New York State hydroelectric plant, and recycled, reused or upcycled 97% of the building materials from the demolition. The building doubles the density of the previous building on the site.

Tall buildings came about through a combination of technological innovation and societal need. A tipping point occurred around the second half of the nineteenth century, and a period of rapid growth followed.

We are at a tipping point now, with regards to our climate. We need to build efficiently, reuse and recycle wherever possible, and minimize the carbon in the construction. But we cannot consider buildings in isolation from their environment or society - increased density results in lower overall carbon emissions, and creates cities for people to live and thrive in.