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Foresight Future of Cities Project: “what will cities of the future be made of?”

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Summary

The bulk materials mix in cities will not change significantly. However, increased use of ‘trace’ materials crucial for low-carbon technologies will expose cities to critical materials supply issues. Much of these materials will never physically cross city boundaries and thus cities must be considered as nodes in a wider infrastructure network. The low-carbon and resource conservation agendas will also place pressure on supply and disposal of bulk materials. Reuse of components to recover function and urban mining must be given equal prominence to traditional materials recycling.

1. Introduction

When posing the question “what will cities of the future be made of”, we need to think about two sets of materials. There are the ‘fixed’ materials that are contained in the physical artefacts that make up a city, most of which can be considered as:

- infrastructure (roads, bridges, tunnels, sewers, pipes, cables etc); or
- structures (buildings including houses, shops, factories etc).

There are also the materials contained in the products that ‘circulate’ in a city e.g. cars, clothes, consumer goods. Which of these sets of materials is ultimately most important to the functioning of a city depends very much on your definition thereof; writing from an infrastructure engineering perspective, we’ve chosen to concentrate on the fixed materials. This is not least because these make up the largest proportion of the UK’s mature infrastructural environment, and are difficult to change owing to our legacy infrastructure systems. The circulating materials, however, can and do change much more rapidly in response to market or regulatory pressures.

Nonetheless, we cannot just consider materials ‘in’ the city. Cities should be considered along with their supporting/linking infrastructure; the “city” defined by a geographical or jurisdictional boundary is the wrong functional unit. Much material supply/consumption that supports a city happens outside its boundaries, especially for low-carbon technology; it often never crosses the boundaries. For example, the rare-earth metals used in offshore wind farms are essential for supplying energy to cities, but never actually enter the city. Cities are better thought of as nodes in a complex system of systems. We need to distinguish between materials “in” the city (and thus available via urban mining or recycling/reuse) and those “feeding” the city, directly or indirectly. As cities and urban authorities can be geographically constrained in their outlook, they may not be fully aware of these issues.

2. Material "in" the city

A typical urban area contains at least 1 million tons of construction materials per square mile (equivalent to over 100 tons per person) and has done for nearly 100 years (the inflow/outflow/stock of materials in the UK is defined partly by slow turnover of housing stock in UK compared to other countries) [see Tanikawa & Hashimoto, 2009]. The bulk 'structural' materials mix for materials by mass is estimated at about:

- 33% masonry (residential buildings and heritage infrastructure);
- 28% aggregates for road and rail foundations;
- 20-25% concrete (for infrastructure);
- 4% timber (mainly in residential buildings); and
- 1 – 5% of bituminous materials (roads).

Consumption of the major construction materials in the UK amounts to around 175 million tons (Mt) per year, split between concrete and mortar (76 Mt), asphalt (53 Mt), other aggregates (32 Mt), timber products (10 Mt) and bricks (4 Mt). Thus the 'turnover' of building materials stock per capita is only a few percentage points per year, so the bulk structural materials mix in the city is unlikely to change markedly in the next 50 years.

Transport of many of these materials into and around cities is an issue; they are bulky (i.e. low value/cost per unit mass) and heavy (i.e. needed in large quantities). Thus local sourcing of materials is often of greater importance than for other, high-value materials. The local availability of such materials, especially aggregates and cement to make concrete, often varies considerably between areas and cities.

Higher value materials account for around 10% of the materials in the city. Steel (about 2% of the total and around 2.5 Mt per year for specialist structures and as reinforcement for concrete) is the most important and its use is increasing as high-rise construction becomes more prevalent. Other materials used in smaller but significant quantities include:

- plastics (around 1 Mt per year for underground pipes, insulation, stabilisation of earthworks, windows, roofing and cladding etc.) [see www.bpf.co.uk/Industry/Default.aspx];
- glass (around 1 Mt per year for glazing, facades etc.);
- aluminium (around 200,000 t per year – a very rough estimate – in specialist structural products); and
- copper (around 40,000 t per year for electrical wiring and domestic water supply, all of which is imported, the last UK copper mine closing in 1991) [see www.bgs.ac.uk].

3. Materials "feeding" the city

For the city to operate, it depends on a complex and interconnected hinterland, a system of systems supplying essential services located beyond its geographical and jurisdictional borders. Arguably, this system of systems is mutating much faster than the city itself. Electricity generation technology is evolving to include a significant proportion of renewables in the mix, increasing demand for new magnetic and opto-electrical materials. Electrification of inter-city rail lines has a direct effect on copper consumption for electric cables, and an indirect effect on the materials required for increased electricity supply. The move to 'smart' motorways is introducing electronic communications technologies and their associated infrastructure into our roadways, increasing demand for the materials and components associated with information technologies.

Many of the materials involved are similar to those described above – concrete, steel etc. – but a subset connected with low-carbon technologies is of particular concern (see also section 7.1 below). For example, the UK's demand for neodymium (a rare-earth metal used in high-performance permanent magnets for wind turbines and electric vehicles) is expected to climb from 20,000 tons to over 200,000 tonnes between now and 2050. By 2030, UK lithium demand for use in electric vehicle batteries could grow to somewhere between 10,000 tons and 45,000 tons from a very low base; to put this into perspective, world lithium production in 2010 was less than 30,000 tons [see Roelich et al, and Busch et al]. Ensuring that city planners are aware of these materials that circulate largely outside the city boundaries will be an essential part of future urban management.

4. Pressures on continued use: Carbon

Globally, materials manufacture accounts for around half of all CO_2 emissions. Construction materials represent at least 50% and probably more than 60% of all materials use, split roughly (in billions of tons, Gt, produced per year) between:

- 20 Gt of concrete (including plain and reinforced) accounting for 3 Gt of CO_2 emissions;
- 2 Gt of timber (1 to 5 Gt CO_2);
- 2 Gt of bricks (0.5 Gt CO_2);
- 2 Gt of asphalt (0.2 Gt CO_2); and
- 1 Gt of steel (not including rebar) (2 Gt CO_2).

(NB: These figures, deliberately expressed to only one significant figure and the subject of considerable debate and uncertainty – especially for timber – grow by several percentage points annually and the split varies widely between countries and regions.)

In other words, the manufacture of construction materials is one of the largest sources of anthropogenic CO_2 and the inevitable increase in severity of carbon mitigation regulations around the world will have a profound impact on their use. This will drive innovations in development of alternative materials, recycling and recovery, and reduced material use through better design of structures.

Significant 'overdesign' caused by conservative design codes and practices almost doubles use of materials; addressing this could reduce materials use (and hence CO_2 emissions) across the board. A recent study of 23 UK steel-framed buildings suggested that the average 'utilisation' of the steel was less than 50%; the material was carrying less than half its potential load capacity [see Moynihan & Allwood, 2014] even after all safety factors were taken into account. Similar trends can be seen in timber and concrete structures. Although we might optimise the cross-sections of generic components to minimise materials use (think of I-beams, T-beams or hollow circular tubes), we do not optimise along the length of components, but use prismatic shapes. Only the central and/or end points of the components are fully utilizing the strength and stiffness of the material. In structures such as grids or trusses made of repeated structural pieces, we use the 'worst case' piece throughout rather than performing a more sophisticated structural optimisation.

This is a modern development caused by the relative cost of materials and (design) labour changing considerably over time. Economically, the extra professional time required to design shape-optimised components is perceived to outweigh the potential savings in material costs. (This is in contrast to for example, Victorian design, where low relative labour cost drove more efficient use of materials, as can be seen in the complex structural forms of even simple wrought iron rail bridges, with multiple thicknesses of iron used throughout the length). If carbon pricing and/or materials scarcity increases the price of materials considerably, such conservative over-design will become less economically viable; increasing sophistication of computer-based design methods and risk analysis will also allow more efficient use of materials in the future.

There is a number of carbon-driven issues bespoke to the main structural materials. Most of these arise because they have a low specific cost (i.e. £ per ton) and are thus sensitive to any additional overhead such as a carbon tax.

4.1. Concrete: The manufacture of cement for concrete is responsible for at least 5% of global CO_2 emissions; when the steel-making, aggregate mining and other processes for turning this cement into reinforced concrete are taken into account, this rises to about 8%. It should be noted that this is a result of the sheer scale of concrete use – it accounts for over 50% by mass of all manufactured product output – as it is not a carbon-intensive material. The 'quick wins' for reducing the embodied carbon of concrete are to reduce the binder (i.e. cement) content of the concrete through either increased use of supplementary cementing materials such as fly-ash (from coal-burning power stations) or blast-furnace slag (from iron and steel manufacture), or by using existing concrete mix design more intelligently [see Purnell & Black, 2012]. There is much interest in the development of novel low CO_2 binders based on e.g. calcium sulphoaluminate cements or geopolymers, but this is a medium to long-term solution: such materials will take at least 5-10 years and probably longer to become certified and accepted for use in the industry and we need carbon savings now.

4.2. Steel: The relatively high CO_2 cost per unit of structural performance associated with steel [see Purnell, 2012] could potentially relegate it to increasingly specialist rather than general use if carbon pricing/taxes increase significantly over the next few years. However, of all the main structural materials, steel has the greatest potential for increased use of recycling to reduce embodied carbon. More importantly for the far future, the recovery and reuse of whole steel sections (to recover the function, not the material) at much lower energy cost than for recycling will help mitigate this (see section 8 below). The greater design flexibility afforded by the use of steel compared with reinforced concrete or timber could also lead to light-weight, high-performance structures where the carbon cost of using steel is outweighed by the carbon savings in foundation design and/or design for disassembly.

4.3. Timber: Responsibly-sourced timber and wood composites will remain the best practical, technical and carbon choice for domestic scale structural and semi-structural elements. However, the sustainability credentials of timber should be examined carefully, especially with regard to the carbon savings achievable. Timber production considered as a global process is by no means carbon-neutral; considerable energy is expended in e.g. forestry and sawmill operations, trans-continental transport, kiln drying and preservative treatment. The use of timber does not *a priori* lock-up carbon as at the system level neither the total forest stock nor built-environment stock of timber is growing. Similarly, the carbon credit purported to be associated with timber in the use phase is often based on it being used at the disposal phase to displace fossil fuels for energy generation, which can lead to double-counting of carbon. Much of the UK's timber is imported; in the future, increased transport costs driven by carbon pricing may encourage us to reinvigorate home-grown supplies, with associated employment benefits.

4.4. Masonry: The carbon efficiency of masonry (i.e. CO_2 emitted per unit of structural performance) is unclear at present (not least because much of it is used in effectively non- or semi-structural applications e.g. cladding or infill). It is likely to be lower than that of steel or timber but similar to that of concrete. However, the robustness and durability of masonry structures – witness our heritage rail infrastructure and housing stock – means that their carbon cost could be spread over a much longer lifetime. If labour resourcing issues could be overcome, structural masonry may become an attractive option for a wider range of structural applications as carbon pricing becomes more severe.

4.5. Asphalt: As with masonry, carbon efficiency figures are hard to come by, but are likely to be similar to those for concrete. Rather than experiencing carbon pricing pressures, it is more likely that asphalt and other petroleum-based materials will in future be more vulnerable to scarcity issues as oil production decreases and/or becomes prohibitively expensive for low-value applications (see below).

4.6. Others: Other materials (glass, aluminium, plastics, copper etc.) are sufficiently high-valued and specialised that the increases in carbon costs are unlikely to have a significant impact in the short- to medium-term, although pressures to make more efficient use of these materials will of course persist. Environmental legislation to restrict pollutants other than CO_2 (e.g. NO_x, SO_x, dust, noise) may also add further pressure on all materials.

5. Pressures on continued use: Resource security and scarcity.

A number of other pressures related to resource security and scarcity will also intensify over the coming decades. Some materials have or will become, locally or globally, in geologically short supply. Others may become subject to commercial supply pressures, especially where there is a high reliance on imports and/or foreign ownership of local production. A few materials may be subject to home or foreign governmental interference in supply, with export or import bans imposed in order to further geopolitical objectives. These pressures are driving recycling of construction materials (aided by restriction on landfill) but this involves significant energy input (for steel), downcycling into lower-grade products (for concrete and asphalt) or recovery of energy rather than material (for timber). In cities of the future, we might strive to prevent dissipation of value by recovering function, rather than materials. For example, this might involve carefully dismantling buildings to allow the reuse of whole steel, concrete or timber beams and columns in new structures (see section 8). As with carbon pressures, issues specific to the major materials can be identified.

5.1. Concrete: While in a national sense materials for cement and concrete production are not scarce, planning issues restrict the expansion of most cement quarries (although most have at least 20 years of permitted reserves) but more importantly demand for aggregate outstrips local supply in many places, for example by 500% in London and the SE of England. This is providing increased commercial pressure to recycle aggregates, leading to the development of 'urban quarries' where forensic demolition of buildings allows recycling of concrete as aggregate. Further pressure to recycle construction and demolition waste comes from limited availability of landfill and associated disposal levies. In the construction of the Wembley Stadium Access Corridor, over 90% of materials obtained from demolition of major structures were recycled as aggregate and over half the aggregates used in building the new infrastructure were procured from recycled sources [see WRAP, 2007]. Aggregate shortages are also helping to drive the use of other 'secondary' aggregates, such as stent (weathered granite produced as a by-product of china clay manufacture) which was used extensively in the construction of the London 2012 Olympic Park [see Henson, 2011]. The lack of confidence in the supply chain over the availability and consistent quality of materials is the main barrier to more widespread recycling of concrete and use of secondary aggregates. Better publicity for the recycling achievements of high-profile projects such as Wembley Stadium and London 2012 would help address this.

Materials used to replace cement and thus lower the carbon footprint of concrete are also becoming scarce. Supplies of fly-ash suitable for concreting are dwindling as a result of a decreased reliance on coal (which restricts quantity) and co-burning with biomass (which restricts quality), hampering efforts to deliver low-carbon high-performance concrete [see Mann, 2014].

Removal and recycling of steel rebars from reinforced concrete is well-established. However, the Achilles heel of reinforced concrete is that one cannot normally reuse structural sections, as they are monolithically cast in-situ rather than bolted together. Future reinforced concrete design will need to adapt to allow disassembly and reuse if the material is to continue to be used, which will radically change how structures are designed (see section 8).

5.2. Steel: Indigenous supplies of steel have dwindled by almost 50% since 1993 yet imports of finished steel and raw materials are becoming expensive (doubling in price since 1997 and subject to remarkable price volatility compared to the Retail Prices Index). This is driven by a huge and growing demand from overseas construction (mainly China, which has tripled its steel demand since 2003) and other higher specific value industries (e.g. automotive) [see http://www.eef.org.uk/uksteel/About-the-industry/Steel-facts/Steel-markets-world.htm].

Thus increased recycling and reuse of steel in cities will be driven as much by economic factors as environmental factors. Current steel structural forms are also much better suited than concrete for disassembly and recovery of structural elements, making it potentially much easier to recover value from steel structures in the future (see section 8).

5.3. Timber: The UK imports (10 million m^3) considerably more timber and timber construction products than it produces (7 million m^3) and both figures are increasing [see http://www.forestry.gov.uk/]. While the UK construction industry is committed to use of responsibly sourced timber, local and global environmental regulations to combat deforestation will restrict overall supply and raise import prices. The accepted (rightly or wrongly) sustainability credentials of timber will further accelerate its use in cities and it seems sensible to furnish this demand via increased home-grown supply. Forestry Commissions figures suggest that UK timber production is increasing faster than imports, but it is not clear whether the UK has the forest or sawmill capacity to more radically increase production and reduce imports. Recovery of structural elements is possible for timber (more so than for concrete but less so than for steel) and was of course commonplace in earlier times as ship's timbers were reused to build half-timbered houses. Recovery of timber for reprocessing into timber composites (glulam, oriented strand lumber, chipboard etc.) as opposed to collection for energy recovery might well be a more sustainable use of the resource.

5.4. Masonry: The UK is comfortably furnished with the relevant raw materials – clays – to manufacture bricks, and brick supply is reasonably well-matched with demand at the moment, although there is very little spare production capacity and thus small changes in demand can trigger large increases in imports. More pressing supply issues are associated with lack of skilled labour rather than materials issues per se; nearly three-quarters of respondents to the Royal Institute of Charters Surveyors (RICS) UK Construction Market Survey report difficulties in sourcing bricklaying labour [see www.rics.org]. Tackling the much-heralded deficit of housing supply over demand will require an increase the supply of both bricks and bricklayers. We are culturally wedded to our brick houses and for good reason, given the proven robustness and durability of this structural form. Should masonry construction prove to be a low-carbon option for infrastructure, we may also see increased demand from this sector. The UK has a long history of local brick production, and this could be reimagined for the 22nd century (perhaps using solar or waste heat powered kilns to minimise carbon emissions, for example). We used to have a long history of local bricklayer production as well, but the fragmentation of the construction industry into multiple tiers of independent subcontractors and subsequent fragmentation of added value has removed the ability for the supply chain to absorb apprenticeship costs; addressing this skills shortage is a more pressing need for our future cities, for technical and social reasons.

5.5. Asphalt: As a composite of around 95% aggregate and 5% bitumen-based binders, general-purpose asphalt will be subject to much the same resource availability and recycling issues as concrete with regard to its main constituent. There are considerable additional pressures on certain high-performance asphalts (e.g. those used to provide skid resistance on critical road sections) because they require very specific aggregate compositions which are often only available from a limited number of quarries. In addition, increased demand on dwindling petrochemical resources from high-value industries such as plastics manufacture and vehicle fuel are likely to increase pressures on supplies of bitumen faster than those on cement supply. In-situ and ex-situ recycling of asphalts is reasonably well established but by no means universal, and it can be difficult to satisfy the various local authority and Highways Agency road surfacing specifications with recycled materials. While we can in theory increase the use of concrete road surfaces (as we have done on many of our inter-city motorways), this is problematic within the city, owing to our buried infrastructure of pipes and cables. While it is relatively easy (if ruinously disruptive) to dig up an asphalt road to repair a water main or a gas pipe, trenching and patching a concrete road is more challenging. Increased use of trenchless technology, where underground services are accessed without digging up the road above, will allow us access to a more diverse range of road surfacing options and also help minimise delays and disruptions to road transport.

5.6. Others: Little information is available on the resource security of other major urban materials. The raw materials for glass are plentiful and local, but manufacture of flat glass for construction is concentrated in only three companies. The UK aluminium industry has invested heavily in recycling facilities, but the accumulation of ‘tramp elements’ – impurities and unwanted alloying elements, especially silicon – in recycled aluminium could, in the future, cause problems for use of recycled material in structural products unless improved collection and sorting methodologies are introduced. The manufacture of plastic pipes will eventually be subject to disruption owing to pressures on petrochemical resources (as with bitumen above), but this is not on the horizon as yet.

6. Advanced construction materials for the city

Despite sporadic enthusiasm for ‘advanced’ materials in construction – composites, specialist polymers etc. – their use will be limited to specialist functions (e.g. carbon fibre composites for repair and maintenance; polymer sealants for advanced glazing; etc.) and they will not make up any more than a small fraction of a percent of the materials mix in cities. A possible exception to this would be insulating materials. One of the primary challenges facing the city is preventing heat loss in the UK’s ageing housing stock. Once all lofts have been insulated and double glazing installed etc (still a long way off incidentally; more than two-thirds of UK housing has “insufficient insulation by modern standards” - see DECC, 2013), tackling heat loss through walls is the only place to go. External and internal insulating cladding or coatings must be thin and unobtrusive and this will require more advanced materials and technologies than our current ‘air trapping’ foams and wools. Aerogels – foams with over 99% porosity made by removing the liquid phase from the pores of a gel – offer the most promising current technology and currently use silica-based materials, which are plentiful. Phase change materials, which have low melting points and high heats of fusion and can help store heat in low-mass buildings to manage thermal comfort, are generally based on easily-available organic materials such as paraffin or fatty acids. Nonetheless, policies that rely on these materials to deliver energy savings should take due regard for the associated supply chains.

7. Functional materials for city infrastructure

Technological developments in cities and infrastructure, particularly those driven by the low-carbon agenda, will introduce new 'functional' materials into cities and their essential supporting infrastructure – much of which will be physically located outside the boundary of the city (e.g. windfarms). Rather than being used for their general structural performance as most of the materials described above, functional materials are required for their specific properties, such as:

- opto-electric properties (e.g. indium used in photovoltaics, or germanium in doped glass fibres used in long-range telecommunications);
- magnetic properties (such as rare earth metals – neodymium, praseodymium among others – used in motors in high-performance wind turbines and electric vehicles); and
- electrical properties (such as copper used in power transmission and short-range telecommunications, or lithium and cobalt used in vehicle and grid storage batteries).

Many of these materials will only be used in tiny quantities when compared to structural materials but their function cannot be replicated by other materials without major technological change. Unfortunately, many functional materials essential to future infrastructure are defined as 'critical'; their supply in the short-term is subject to interruption owing to geopolitical, environmental or technical factors. This is recognised by the EU as a serious problem [see e.g. http://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical/index_en.htm].

7.1. Critical functional materials: Many technologies essential to low-carbon infrastructure (e.g. large wind turbines) and transport (e.g. electric vehicles) require materials that are considered to be critical as a result of potential for their supply to be disrupted in the short-term. The huge scale of the change in technology required to bring down carbon emissions from energy generation and transport to politically approved levels will cause a step-change in demand for these critical materials that cannot be met by the current supply chain for several reasons. Roelich et al (2014) set out some examples:

- Many critical materials are not mined in their own right but as co-products of major metals; it would not be immediately economically viable for production to be increased to meet demand for a minor product of mining activities;
- The mining of these materials can have significant environmental impacts and tightening environmental legislation is making it increasingly difficult to develop new mining facilities; and
- Production of critical materials can be concentrated in a small number of countries (for example over 95% of rare

earth metal mining currently occurs in China). Political instability or industrial strategy in these countries can limit the supply of critical materials. For example, rare earth metal exports from China have been subject to export taxes and in some cases export bans.

The balance between these factors varies with different critical materials and it is important that we understand the drivers of criticality when determining how best to respond, either at the policy level or by intervening in supply chains. One of the biggest contributing factors is the acceleration in demand for primary critical materials. A primary facet of any response must therefore be to reduce demand through substitution or recycling.

Substitution at the material level is extremely difficult, because the properties of critical function materials are so specific and can only be replaced by similarly critical materials. Substitution at the component or technology level – i.e. replacing one specific technology with another to deliver the same goal – shows much more promise [see Dawson et al, 2014]. To retain the ability to do this, we must encourage "technodiversity". We are familiar with biodiversity as a goal for which to strive to retain resilience in a complex ecosystem. In the city, itself a very complex system of systems, it is important to retain technodiversity to prevent lock-in to certain technologies. The temptation to strive for apparent techno-economic efficiency can lead to over-reliance on a single, supposedly optimal technology to deliver a service; putting all one's eggs in the same basket. If the availability of this technology becomes limited (not just owing to critical materials supply disruption; skills shortages in installation, construction or maintenance methods are equally relevant here) then services can be disrupted. Retaining a wide range of potential technologies to deliver a given service, even if at the expense of short-term efficiency, provides systemic resilience to the city.

Recycling of these materials can be equally problematic. Critical functional materials are used in such small quantities – typically only fractions of a percentage point by the mass of materials in an infrastructure system – and low carbon infrastructure technologies can have very long lifetimes compared to consumer goods. Because of these factors, collecting sufficient quantities to make recycling economically viable is extremely challenging. In any case, recycling methods for these materials are often only at the laboratory stage and commercial facilities are expected to take many years to develop [see e.g. http://www.colabats.eu/].

8. Urban mining and the recovery of function.

In much of the discussion above, the city has been implicitly considered largely as a sink or consumer of materials. New construction, upgrading and maintenance all consume materials, adding to the stock within the city. However, supply shortages of bulk materials (e.g. aggregate) and price increases in functional materials (e.g. copper) are already beginning to lead us to think of the city as a source of potential material; an urban quarry from which valuable materials can be extracted. For example, it is now estimated by Kohmei Halada of the National Institute for Materials Science in Japan that there is more copper above ground within our man-made society than there is easily accessible copper remaining in the ground. Thus, the city should be considered as much as a store of copper as a consumer thereof. Similar arguments could be made (at least at the local scale) for high-performance aggregates, aluminium and steel etc. Keeping track of where this material is, when it is likely to be released (via e.g. demolition) and how it can be extracted and recycled is likely to become a key function for city developers. Many of the materials suitable for urban mining are embedded within structures or assets owned by the public sector, so it is likely that any prospecting would need to have strong involvement of local authorities and government agencies.

Similarly, great saving in both carbon and cash could be made if more careful consideration was given to recovering the function of materials, rather than recycling the materials themselves. For example, production of recycled steel from construction and demolition waste involves multiple sorting, grading, melting and re-casting processes that consume up to 10 GJ per tonne of steel – equivalent to nearly 300 kWh or the monthly electricity consumption of a medium-sized house. Recovering a complete steel beam for reuse in a new building requires negligible processing and energy consumption by comparison. Thinking more carefully about how we put materials into our cities, by designing for easy end-of-life dismantling and reuse of components, could make a huge contribution to reducing carbon emissions and increasing resource security for the UK. Such thinking will involve transformation of both design and demolition processes; the former to aid end-of-life disassembly (cf. the EU's automotive End of Life Vehicles Directive) and the latter to encourage forensic, rather than explosive, demolition. Reuse of structural elements will require advances in asset management based on an extension of the 'Building Information Modelling' (BIM) concept such that the initial and residual properties of individual structural elements can be catalogued and archived, allowing easy reassignment to new structures. It may also require changes in ownership patterns, perhaps where the capacity of a structural element is leased by the building owner for the life of the building, in the same way as the Rolls Royce business model now sells 'flight time' services to customers rather than aeroplane engines.

This also applies to functional materials as well as structural materials. For example, there is already investigation being made into designing the batteries for electric vehicles, such that they can be recovered at end-of-life for reuse in energy storage for localised renewable energy generation.

Promotion of recycling, recovery and reuse of materials and/or components requires social, economic and cultural innovation as well as technical advances. For bulk materials, inventory systems that know where and when recyclable arisings are likely to occur and regulatory pressure to exploit them is at least as important as having the technical ability to recover the material. For specialist materials, ensuring that markets exist for recovered materials is essential. For recovery of function – i.e. reuse of components – cultural attitudes amongst designers towards modular design, and the social acceptability of reused or refurbished components, will be as big a barrier to implementation as any technical issue.

9. Concluding remarks.

The slow turnover of building stock in the UK means that the mix of materials that make up our cities will not change much over the coming decades, but cities still consume many tons of material per person per year. Increasing pressure from the need to reduce carbon emissions and secure supplies will drive us towards more widespread use of recycled and recovered resources; changes in infrastructure and building design will be required to make this easier. Cities themselves are huge repositories of valuable materials, and city planners will also need to help make sure that materials and components recovered from the city during 'urban mining' are in the right place at the right time.

We will also begin to rely on a relatively small but crucially important fraction of 'functional' materials that will be used in the infrastructure of the future, particularly for energy generation and transport. Some of these materials are critical; they are prone to supply restrictions that can put roll-out plans for this new infrastructure at risk. As many of these materials will never cross city boundaries, we need to make sure urban planners are aware of such materials and how their supply can affect the city.

The use of advanced materials in the city will be limited in general, but with one key exception: insulation materials. Finding materials than can prevent heat loss through domestic walls without compromising the appearance or functionality of people's houses is one of the major materials challenges facing the city.

10. Gaps in the evidence or research

There are too many areas requiring further research and funding to list them all, but from our perspective they might include:

- Developing a framework for assessing and mitigating criticality: allowing planners to assess the risk that policy decisions requiring implementation of a given technology open up vulnerability to critical materials supply;
- 'Bottom up' embodied CO_2 assessments for design purposes: current 'top down' post-facto Life Cycle Assessment analyses offer little guidance to designers of low-carbon infrastructure when selecting materials;
- Design rules, inventory and recovery protocols to encourage disassembly and reuse of components to recover function (cf. End of Vehicle Life Directive for the automotive industry);
- Investigation of interacting technical, social, cultural and regulatory barriers to recycling, including critical examination of policies based on collection rates;
- Design rules to encourage material-efficient design and prevent over-design caused by conservatism and high design:materials cost ratios; and
- High-performance retrofit insulation materials and systems.

11. Key pieces of existing research and data sources

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