TOWARDS SUSTAINABLE AND RESILIENT (SuRe) INFRASTRUCTURE: MATERIAL DEPENDENCY AND THE ANALYSIS OF LOCAL VS. GLOBAL PROPERTIES

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ABSTRACT.
Low carbon and sustainable urban systems require reliable infrastructure systems. Our current infrastructure is deteriorating and there is a need to reduce our impacts on the environment. This will require extensive refurbishment and replacement of our infrastructure systems and unprecedented roll out of low-carbon technologies. Interventions in infrastructure technology, made on the basis that improvements in specific design variables (e.g. tensile strength, specific energy – "local" properties) risk a potential 'lock-in' to technologies that could become prohibitively expensive – or simply impossible – to commission, operate or maintain if the wider (and long-term) consequences of design decisions (i.e. the "global" properties) are not considered carefully. This paper presents a framework for assessing the relationship between low-carbon design choices (the local properties) and vulnerability of material supply risk (the global properties). Assessing these relationships is an important consideration in achieving adaptable, low carbon infrastructure for our future urban environments.

Keywords: Critical Materials, Properties, Low-carbon Transitions

1 INTRODUCTION

Sustainable and resilient urban systems require reliable infrastructure systems to support urban lifestyles. Current UK infrastructure is under sustained criticism regarding its deteriorating condition [e.g.1,2] and the historically fragmented and reactive nature of development [3,4]. The importance of infrastructure to our socio-economic systems is being increasingly acknowledged alongside the potential impacts resulting from infrastructure failure. The Government has now initiated a series of National Infrastructure Plans [3,4], proposing long-term upgrades amounting to over £250 billion of investment. It is also emphasised that the enhanced infrastructure must be designed to reduce our impacts on the environment and drive and facilitate our transition towards a low-carbon economy**.** Emissions reductions of the scale required to meet national and international targets will require rapid, systemic change including extensive refurbishment and replacement of these infrastructure systems and unprecedented roll out of low-carbon technologies.

Many technologies required to make this transition are readily available today, but often rely on critical materials and components that are at risk of supply disruption and are difficult to substitute and recycle [5]. This threatens the sustainability and resilience of future infrastructure systems. Without consideration of this criticality, the roll-out, operation and maintenance of low-carbon infrastructure will become vulnerable to disruption of the supply of materials and components. While the constraints to technological progress imposed by e.g. critical metals have received extensive academic attention [e.g. 6,7], few if any credible scenarios for implementation of widespread low-carbon technology explicitly consider criticality [8]. Engineers and policy makers faced with designing our new low-carbon infrastructure systems risk a potential lock-in to technologies that could become prohibitively expensive – or simply impossible – to commission, operate or maintain if they do not consider wider consequences of design decisions. Their access to the tools needed to adequately model and critically assess potential technology pathways may be limited. Overall, this threatens the sustainability and resilience of future infrastructure and the urban systems that rely upon its functioning.

Interventions in infrastructure technology, at elemental, material or component scale, are made on the basis that improvements in specific design variables (e.g. tensile strength, stiffness-to-weight ratio or magnetic field strength per unit volume – "local" properties) will lead to improvements to an objective property of the whole system (e.g. capital cost, running costs or carbon emissions – "global" properties). However, the relationships between local and global properties are generally poorly understood; specifically, the "unintended" consequences of changing local properties on global properties such as vulnerability to material criticality are unknown. Many materials or technologies have properties that vary considerably and treating them as elements with fixed properties overlooks the possibility that there may be optima within the local-global variable space that could be exploited to minimise vulnerability whilst maximising performance. Consideration of these relationships will improve the sustainability, adaptability and resilience of our infrastructure to potential socio-economic, political and climate change in the future.

In this paper a process for assessing and/or optimising the properties of materials, technologies and components within a system is developed. It is tested on two low-carbon technologies: rechargeable battery technologies and manufactured steel. Both of these technologies will become increasingly relevant for urban infrastructure systems i.e. communication technologies, transport, construction and energy and the proposed reduction of carbon emissions. The aim is to illustrate that a future that is reliant on technologies developed only through improvements to local design properties is a potentially short-sighted approach to delivering sustainable and resilient low-carbon infrastructure that supports our urban environments. This paper contributes to the development of a framework for analysis of infrastructure transitions that includes an enhanced 'stocks and flows' model [9] and comprehensive measures of criticality [10]. This combined framework will allow users to evaluate the material barriers to achieving adaptable, low carbon infrastructure.

1.1 Local vs. Global properties

When it comes to design decisions and technology substitutions (materials, components, structures) the relationship between the properties that determine the selection or commissioning of an alternative design of technology – *the local properties* – and the wider consequences on the system – *the global properties* – is often overlooked. Specifically, the consequences of changing local properties on global properties that aren't directly considered in the design criteria (e.g. vulnerability, embodied carbon, material criticality) can have significant implications for the sustainability and resilience of infrastructure. The evolution of permanent magnet (PM) technology during the 20th century (Fig 1) is an interesting example of local property-based design decisions.

The change in PM design has been stimulated by a desire to enhance the local properties of the magnets; in this example the "maximum energy product" (BH_{max}), a property that measures the stored energy of a magnet. Improvements in magnet performance in the last 40 years have been enabled by the introduction of new materials such as cobalt and neodymium into magnetic alloys. PMs can now achieve BH_{max} values 300% higher than in the 1960s. PMs are now used in a whole manner of consumer electric goods such as mobile phones, cordless tools, speakers and ipods. PMs are also now required to operate at elevated temperatures in new energy-related applications such as electric vehicles and direct-drive wind turbines [11]. This new demand has led to substitution of materials in the magnet to enhance high temperature performance. For instance, in the latest PMs, some of the lighter rare earth metal (e.g. neodymium) is replaced by heavier rare earths such as dysprosium and terbium. The substituted material can be very expensive and make up the majority of the price of a magnet despite only comprising 3-10% of its composition.

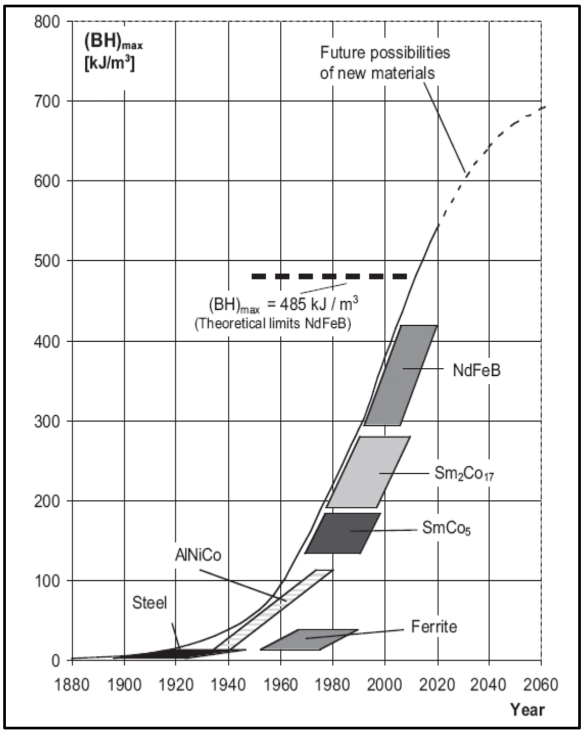

FIGURE 1. Development of permanent magnets and energy density [12]

The availability of the rare earth metals – particularly the heavier rare earth elements – is an area of increased geopolitical concern, not least as a result of China's plans for export restrictions [13]. There are also economic and environmental concerns over the extraction of these materials [14, 15]. Design choices and technology substitutions made to enhance local property performance do not generally consider the whole-system implications such as carbon cost, resilience, or risk to continued supply of material; i.e. global system properties. This major contributory aspect to the overall resilience of low-carbon infrastructure transitions is therefore unknown. Hence, our ability to adapt to future changes (i.e. socio-economic or environmental) or build sustainable urban systems could be restricted by the technology choices made at present, leading to negative 'lock-in' effect. The expansion of new technologies can be rapid – high tech applications of PMs witnessed a four-fold increase in uptake in the last five years [11] – and the resilience of systems reliant on high tech components and technologies is of real concern.

2 PROPERTIES ANALYSIS

The analysis of properties is not a new research area. However, there remain limitations to the current approach. A more detailed discussion of property assessments is presented in Purnell et al., [8]. Traditionally, the analysis of relationships between properties used for materials selection by designers is carried out using the Ashby plot [16]. This relates two local indices of interest, which may be either single properties (e.g. strength, density, energy) or combinations that allow multiple properties to be analysed on the same plot (e.g. strength-to-weight ratio). It is generally applied to compare families of materials. Although this approach is extremely useful for identifying suitable materials from a large range of choices for a given design, it is difficult to identify formal functions between properties from this approach without further analysis using other methods. It is not generally used explicitly to assess how changing local design properties can affect the behaviour or properties of the system as a whole and most applications are based at the material level.

Some investigators have attempted to relate local design properties, materials enhancements or technology choices to properties that are likely to be important at the global system level. Along with economic or technical global properties of interest, environmental factors are considered in some analysis. The global property of interest is often an eco-indicator of some kind, either a single factor (such as global warming potential, embodied CO_2 or recycled content) or composite indices derived from formal LCA studies. For example, Rydh and Sun [17] presented a series of Ashby charts of a composite "ECO'99" index vs. properties. Although an extremely useful approach they only presented the ranges of local properties and the corresponding eco-indicator rather than identifying the formal functional relationships between the two. Purnell [18] analysed the variation of embodied CO_2 (EC) per unit of structural performance for steel, reinforced concrete and timber beams and columns as a function of size and loading (local variables for structural engineering design). The relationships uncovered (Fig 2a) demonstrated clearly that any materials comparison based on simple consideration of EC per unit volume or mass is likely to be deeply flawed. Further analysis of concrete – which can vary over a wide range of compressive strength (its local property) from ~20-100 MPa – demonstrated a distinct optimum in the strength vs. EC curve [19]. The EC for 256 standard mix designs for concrete analysed varied by a factor of almost an order of magnitude (Fig 2b). In this respect, there are considerable opportunities for minimising CO_2 emissions afforded by knowledge of the local/global property relationship for structural materials.

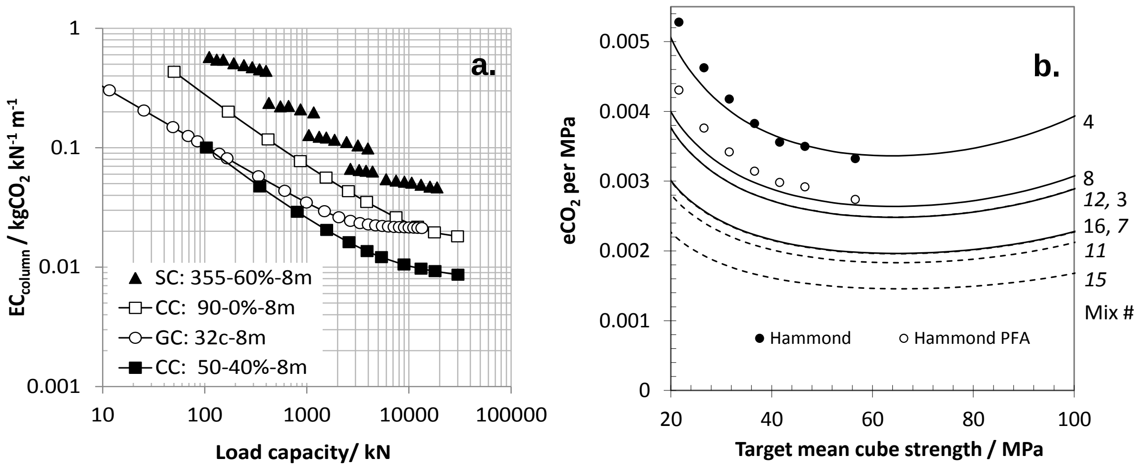

FIGURE 2: eCO_2 per unit of structural performance.
(a.) Long structural columns. SC = steel UC section; CC (open) = high-strength CEM1 reinforced concrete, (closed) = 50 MPa CEM1-PFA reinforced concrete; GC = glulam timber beams.
(b.) Unreinforced concrete. Solid lines = CEM1 mixes, dashed lines = CEM1-PFA mixes. Points = data from the ICE database (Hammond & Jones, 2008). For more details see [19] and [20].

The comparison of materials with widely varying compositions and properties (such as concrete, steel or plastics) illustrates a further analytical issue. It is common for investigations to treat such materials as effectively elemental; i.e. it is implicitly or explicitly assumed that each has a single set of local properties [8]. For example, Muller [20] assumed that the cement content of concrete has (and will) remain constant (at 11%) between 1900 and 2100; the effect of the wide variation in the local property of concrete (i.e. the compressive strength) was not examined. A similar approach was applied to the Chinese steel cycle [21], explicitly stating that analysis did not differentiate between steel, cast iron and all other iron alloys. Muller noted that changing the density of the concrete used in the analysis can affect the balance between the output of demolition waste and requirements for new construction [20]. Thus, the quality of materials, components, etc., is another interesting point of discussion. Where the variation in local properties is explicitly acknowledged, it is normally presented either as a 'data sheet' with ranges of properties (especially for plastics), rather than as an analysis of the fundamental relationship, or particular metallic alloys are presented in elemental fashion [22]. Often these simplifications are of course necessary in order that initial analysis of complex systems can be made, however, without consideration of these issues misleading conclusions can be drawn.

3 ENHANCING PROPERTY ANALYSIS

There is a need for a more robust analysis of the wider implications of local property-led design decisions; material criticality is one example of this. Studies concerned with scarcity, criticality or vulnerability do not typically include material properties although they may distinguish between substitutions of elemental choices; for example Graedel's criticality index includes both elemental substitution potential and the supply risk of the substitute element [23]. Until recently, no previous work had analysed how criticality might vary at different levels in the system e.g. materials, component, technology or infrastructure [see 8]. Purnell et al.'s preliminary analysis of permanent magnets and wind turbine technologies suggests that even where the introduction of critical materials enhances technical performance by up to an order of magnitude, the consequential increase in criticality may be two or three orders of magnitude. Furthermore, analysis at the materials and component levels produced rather different results, indicating that sustainable design decisions should be based on analysis at multiple levels [8]. This type of explicit analysis of the relationship between local and global properties is a step towards a system optimisation approach that can avoid introducing new vulnerabilities that threaten the resilience and sustainability of urban systems. Investigators often allude to this in their narrative, even if not including it in the formal analysis.

In the approach developed by Purnell et al. [8], variables that relate directly to specific design criteria (e.g. tensile strength, magnetic energy product, or mass) are defined as the **local primary properties**. Designers optimise these properties at the local level in order to effect improvements in a specific property of the whole system (e.g. capital expenditure, running costs or system capacity) defined as the **global primary property**. However, it is also recognised that changing local properties will have an effect on global properties other than those directly considered in the design (e.g. embodied carbon, or vulnerability to material criticality, defined as **global secondary properties**). Global properties will also change according to local properties that are not necessarily central to design, defined here as **local secondary properties**; importantly, these will be strong or weak functions of the local primary properties. To understand how local property changes affect the global system, **translational properties** – the subset of local properties that link local and global properties – must be identified and evaluated (see Fig 3).

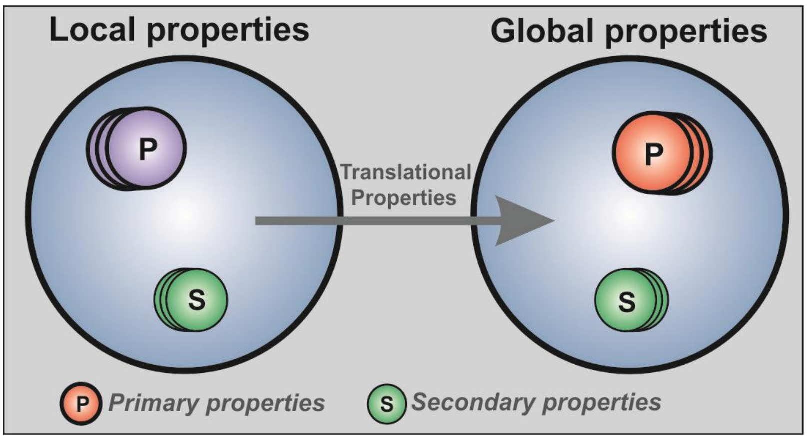

FIGURE 3. Extended properties analysis: Translational properties allow primary and secondary properties to be related to the global system properties (primary or secondary). Taken from [24].

This local-translational-global framework provides opportunities to reduce the impact and improve the performance of the system by developing an understanding of the trade-offs between properties at different levels. The analysis is not restricted to the materials level. At the component or technology level, the relationship between the local primary properties dominating the design and the global properties of the system is still of interest. For example, the engine (local) for the vehicle (global) will be chosen on the basis of the relationship between: the global primary properties of speed, acceleration and economy; local primary variables such as power output and torque curves; translational variables including mass and rotational inertia. Fuel consumption per unit power output would be both a primary and translational property. At the component or technology level, however, property relationships will not generally be continuous functions as at the materials level, but discrete values for each artefact. It follows that property relationships have to be tracked through the materials, component, structure and technology levels of the system in order that the effect on global variables of interest can be properly determined. Interventions at any level will cascade in both directions and modelling the local-global property relationships could avoid unintended consequences of 'well intended' design choices. This is illustrated in Fig 4.

4 METHODOLOGICAL APPROACH

The concept is explored using two case studies of different low-carbon technologies at two different system levels and follows the approach and methodology first presented in [8]. The first case study, at the component level, examines various rechargeable or 'secondary' battery technologies developed for use in high performance technologies such as electric vehicles (EVs) to determine the variation of material criticality (the translational property) as a function of a local primary property (the specific energy stored in each battery). The second, at the material level, examines the variation in materials criticality with design options for various grades of manufactured steel. The achievement of low-carbon responses in the automotive and construction sectors is at least partly achieved by use of high-grade steels, either to provide light-weight (and thus fuel efficiency) and/or corrosion resistance (and thus long life). These local property improvements are often achieved with the introduction of materials such as chromium or manganese. Assessing the material criticality or potential to supply chain disruption of steel grades is an important consideration in determining infrastructure system vulnerabilities (i.e. the global property).

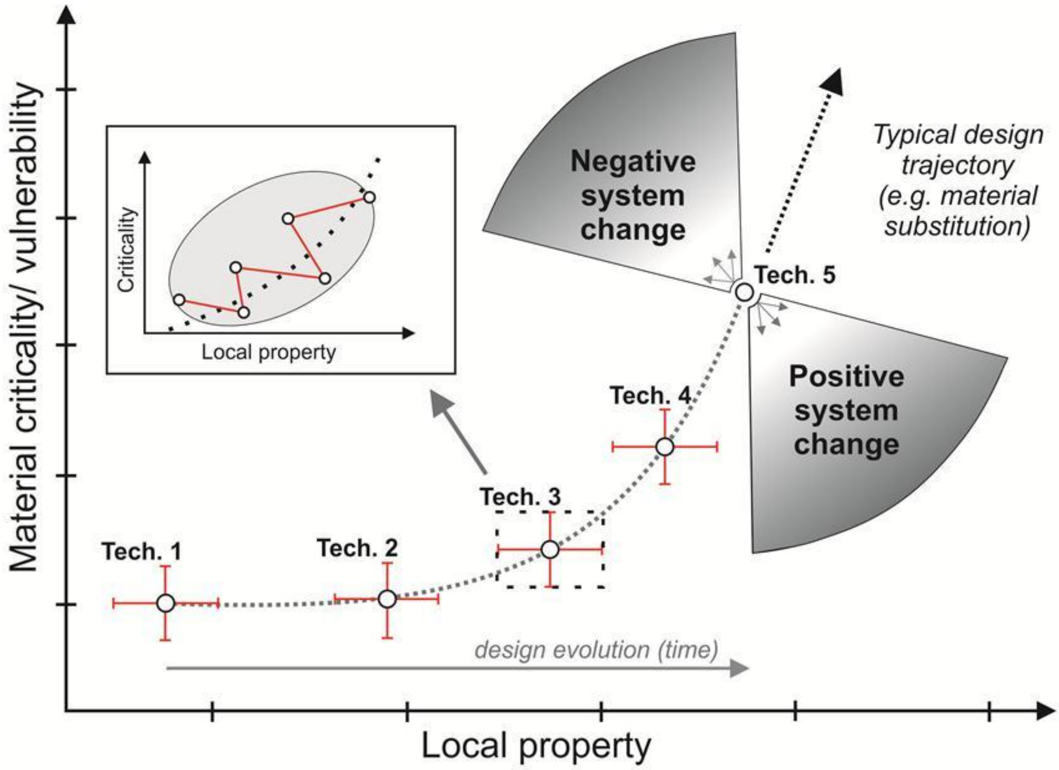

FIGURE 4. Future local property design decisions can positive or negative to the translational/global properties of the system. Local property improvements in technology (x-axis), i.e. with the addition of new materials, can be analysed & compared with the translation/global properties (e.g. material criticality) on the y-axis. Functional relationships of performance and criticality, inherent in each technology, can also be assessed (see insert).

4.1 Relative materials criticality

In this study, a relative material criticality (*RMC*) is derived based on the material requirements of each technology based on their elemental material mix. Criticality assessments for elements have been published by various sources but in this study we shall use as a basis the 'supply risk' stated by the European Commission Raw Materials Supply Group [5]. This index varies from 0 – 5 and combines "*assessment of the political-economic stability of the producing countries, the level of concentration of production, the potential to substitute and the recycling rate*". It has been rebased in this study to vary from $C_{EC,\,n} = 0 - 1$ and assumed to approximate the probability of a disruption to supply for a given element over a standard time frame. We do not attempt a dynamic assessment at present, furthermore, as we are presenting relative criticality, the actual time frame is not important. Since each technology employs a mix of elements, RMC also takes into account the proportion by mass of each element p_n in a given technology (either in terms of relative concentrations at the materials level, or material mass per battery/vehicle at the component level). However, to reflect the fact that the availability of various elements differs enormously – obtaining an extra ton of rare earth metal is significantly more difficult than obtaining a similar increment of iron, for example – these proportions are divided by a number reflecting the relative availability of each element; in this case, we have used UK import data [25] for each element, I_n. The partial contribution from each element is then added to derive an overall figure. Finally, for the component case, the difference in the outputs of the various technologies Q (in this case battery range in kilometres) is taken into account in order that the functional unit remains correct. Mathematically, this is represented (for number of different elements n) by:

$$RMC = \frac{1}{Q}\sum_{1}^{n}\frac{C_{EC,n} \cdot p_n}{I_n} \qquad \text{eq. 1}$$

For a material level analysis, $Q = 1$ and the units of *RMC* are tons^{-1}. For a component level analysis, the summation is dimensionless and the units of *RMC* are determined by the nature of Q (km^{-1}). The limitations and assumptions of this criticality metric are detailed further in [8].

4.2 Local properties

For the component level analysis, the local primary property of the battery electric vehicle (BEV) is range in km. In vehicle applications, this is one of the primary properties of the battery along with cycle life, cost and energy output [26]. Estimates for the range of vehicle along with their net material requirements for the various batteries types were taken from Räde and Andersson's study [27] and, as such, only considers the active electrode material that takes part in the electrochemical re-actions. Note that the range of a vehicle is dependent on a number of other variables, most notably weight, and the figures used here assume a theoretical vehicle with static assumptions that allow the accurate comparison of various EV battery types [see 27]. The batteries are dimensioned for full size passenger cars and focus on BEVs (including plug-ins - PEVs) and hybrid EVs (HEVs). Two alternative data sets of the net material requirements and vehicle range are used in this study and represent potential future changes in requirements and ranges. The first is a high intensity estimate that reflects the current, or near-term, state-of-the-art for commercial batteries and the second is a low intensity estimate reflecting improved technology as assumed in [27] and [28][1]. The EV batteries considered in the study are detailed in the caption of Fig 5.

For the material level assessment, the local primary property is determined as the point at which the material (in this case steel) begins to deform plastically under strain. This point is referred to as the *yield strength* and is measured volumetrically in pascals (pa). Determined under test conditions, the behaviour of steels in these tests is closely related to the behaviour of structural-steel members under static loads [29]. As yield strength is a physical material property it is one of the key attributes used in the classification and grading of steel and a key determination of the purpose of its use i.e. via construction standards e.g., [30]. Technical information regarding the yield strength and material mixes of various grades of steel was obtained from a number of secondary sources [31 - 33]. In total, the yield strengths of 28 grades of high strength alloy, stainless and mild steel (as a reference) were assessed.

5 RESULTS

5.1 Electric vehicle batteries: component analysis

Figure 5 shows the component level analysis of battery technologies for use in BEVs, nine battery types are assessed: Lead acid (PbA), Li-polymer(V), Li-ion(Mn, Ni and Co), NaNiCl, NiMH(AB_2 and AB_5) and NiCd. Each battery has its own advantages and disadvantages, however, a full assessment of other relevant local properties (e.g. cycle life, cost) is beyond the scope of this paper at this time. In assessing the *RMC* of the battery technologies for both high-low intensities the preliminary results show a significant range of potential supply risk in orders of magnitude (not fractions) and, coupled with improvements in vehicle range, this offers an interesting narrative.

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[1] It must be noted, however, that at present not all the batteries are commercially available for EVs.

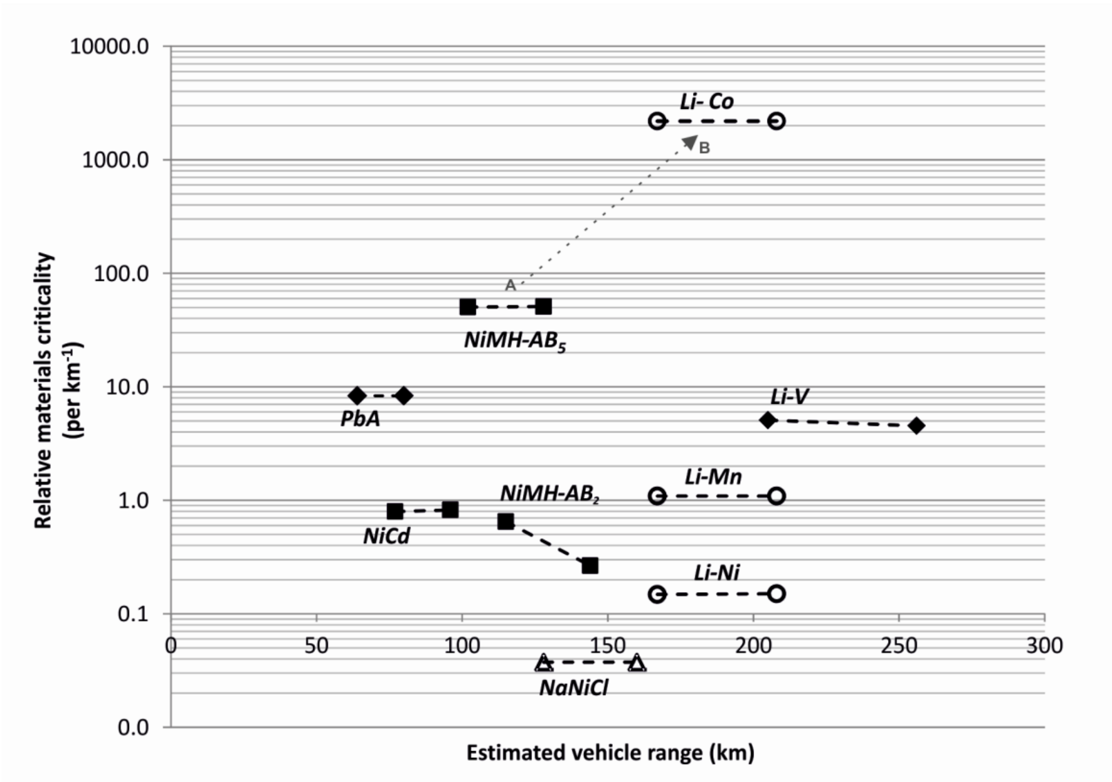

FIGURE 5. Relative material criticality (on a logarithmic scale) vs. local properties. Component level analysis of battery electric vehicles (BEVs). Nine potential batteries were assessed: Lead acid (PbA), Li-polymer (V), Li-ion (Mn, Ni and Co), NaNiCl, NiMH(AB_2 and AB_5) and NiCd using previously published data [27,28]. Hybrid electric vehicles (HEVs) are predicted to be replaced by plug-in and fully BEVs in the coming decades. A-B illustrates the potential change and its translational/global property effect.

Lead-acid (PbA) batteries are the earliest form of rechargeable battery and have been developed since this mid-19th century. The PbA battery produces the lowest range of distance achieved in this analysis (64-80 km). PbA batteries have low specific energy (~ 40 Wh/kg) and its suitability in vehicles (and other applications) is therefore restricted to starting, igniting and firing [26,34]. More recent battery technologies have increased performance whilst reducing size and weight of the unit. This has been achieved with introduction of new materials. This is demonstrated by the development of Nickel-hydroxide batteries during the last 30 years. NiCd, NiMH-AB_2, and NiMH-AB_5 make up the nickel-hydroxide group batteries in this study, which have vehicle ranges estimated between 102 – 160 km. NiMH-AB_5 batteries are most commonly used in the current generation of hybrid electric vehicles (HEVs) [35]; where A is typically a rare earth element (such as lanthanum, cerium, neodymium and praseodymium) while B is a combination of nickel, cobalt, manganese and/or aluminium [35,36].

The next generation of batteries developed were the Li-ion and Li-polymer group batteries and have been developed since the 1970s-1980s. BEVs and PHEVs require greater storage capacity and power rating than HEVs and consequently are more likely to employ li-ion batteries [37-39]. The li-ion batteries in this study (Li-Mn, Ni and Co) have significant performance improvements compared to the other battery groups analysed (167 – 208 km). Lithium is the lightest of all metals and offers the greatest electrochemical potential resulting in a high power and energy density [34,38], and subsequently in a better vehicle range performance. The final battery is a Li-polymer battery, which is a high performance technology was developed prior to the li-ion. The Li-polymer battery in this study (Li-V) contains the metal vanadium and has an estimated range of 205 – 256 km. They operate at much higher running temperatures [27] and concerns for safety issues prompted the development of li-ion technologies [34]. Recently, however, prototype EVs have now been developed using this technology [40]. The estimated future improvements in range and material requirements considered by Räde and Andersson's investigations [27,28] have a minimal effect on the results of this study and have not be considered further in this paper.

5.2 High strength steel – material analysis

Figure 6 shows the material level analysis 28 steel grades classified into three steel groups; mild, stainless and high strength (HS) alloy and, combined, these materials contain over a dozen elements (details of which are not provided in this paper). The assessment includes 16 stainless steel grades [32], ten HS alloys [33] and two mild steel grades have been included as a reference [31]. The yield strengths investigated is this study range from ~ 200 – 750 Mpa which are representative of low – high strength steel grades. In assessing the material criticalities of the steel, the preliminary results suggest that the relationship between yield strength and criticality clearly defined. However, interesting interpretations of the results can still be made.

The mild strength steel grades assessed have relatively low-moderate yield strengths and have some of the lowest *RMC* values of the analysis owing to the predominantly iron-based composition. It should be noted that with a certain range, steel strength is engineered more by heat treatment than elemental composition, hence the wide range of yield strength for a relatively small range of *RMC*. This is also illustrated in the stainless steel analysis, for example, a cluster of low yield strength grades are observed with the highest RMC values, whilst similar RMC values can be found with grades with considerably more strength (>700 Mpa). The stainless steel analysis benefitted from the largest data set obtained and the results indicate that this material has the highest potential supply risk. The durability of the steel is utilised in appliances and structures that require high corrosion or oxidation resistant. It is classified as having a minimum of 10.5% chromium content – itself of significant economic importance [5,41] – whilst other alloying elements can be added to enhance structure properties such as formability and strength these include nickel, molybdenum, titanium and copper [32]. Grades in this study also contained manganese and niobium, the latter of which is an element the European Commission [5] have recently described as 'critical' in terms of supply risk.

Finally, the HS alloy steels in this study range from 350 – 750 Mpa (moderate to high yield strength), overlapping with the structural performance of some of the stainless steel grades. The recent interest in HS steels, particularly in offshore applications, has been prompted by the recognition of the benefit in the strength to weight ratio, the associated saving in the cost of materials and reduced construction schedules (due to welding benefits) [33]. The HS alloys assessed show a more distinct correlation between local and translational/global properties. Increases in yield strengths are observed with increases in the risk of potential supply vulnerability (*RMC* values) indicating that the chemical composition (rather than treatment) of the steel is manipulated to increase performance in this sample data set. Chromium and molybdenum are elements with relatively high *RMC* values [5] and are found in most grades of HS steel.

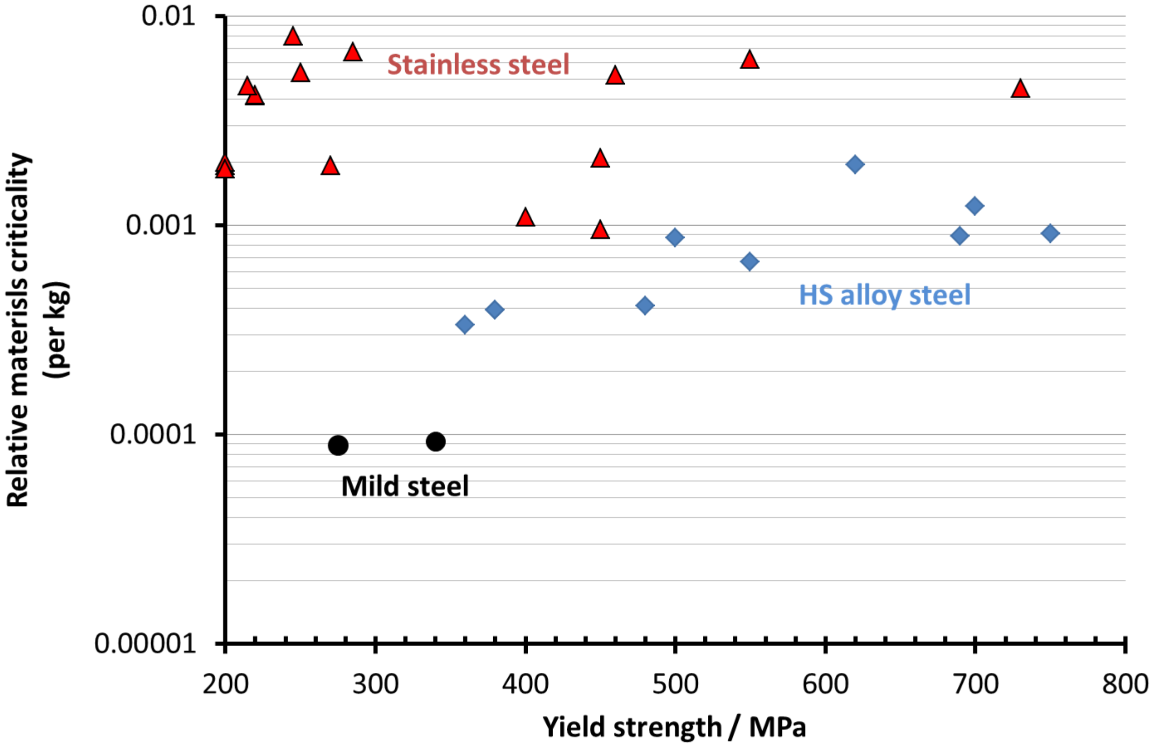

FIGURE 6. Relative material criticality (on a logarithmic scale) vs. local properties. Material level analysis of 28 steel grades, classified into mild steel, high strength (HS) alloy steel and stainless steel. Yield strengths (Mpa) and elemental compositions are taken from various published sources [31-33].

6 DISCUSSION

At the component level, it has been shown that changing from the older technology lead-acid (PbA) to a newer technology such as Li-ion (Mn, Ni), NaNiCl, $NiMH_{AB}^{2}$ or NiCd can reduce the systems vulnerability to supply risk whilst increasing system performance. In is not always that straight forward and the analysis of the Li-ion batteries, which now contribute to 60% of the secondary battery market [34], shows interesting results. On one level, the Li-Ni battery provides performance improvements with the second lowest *RMC* values; with less risk and more power than the NiMH powered alternatives the transition to 'Li-ion' would seem justifiable. Li-Co powered Li-ion batteries, however, illustrates a significant increase in supply risk with no performance improvements from the cobalt free Li-ion batteries. Analysis that treats Li-ion batteries as 'elemental' would miss this point, thus it requires further consideration and investigation before any robust conclusions can be made however. The material mix of the components in NiMH powered vehicles shows similar patterns, and the introduction of rare earth metals in NiMH-AB_5 seems unjustified as a reduction in performance is observed with a substantial increase in criticality. Interestingly, Li-ion is becoming the preferred choice for BEVs, HEVs that commonly use NiMH batteries (see A-B, Fig 5) are predicted to be replaced by PHEVs and BEVs during the next two decades [42]. Based on this preliminary analysis, this transition will result in a significant increase in risk for the future supply of materials for BEVs. Finally, it is not yet known if a move to Li-Polymer batteries is suitable for mass manufacturing of BEVs or whether it is publically safe. Although it does not have the least potential for supply risk, it would seem a justified step from Li-Co powered BEVs as improvements in the local/translational property relationship are seen.

The material level analysis indicates that the local properties of steel grades and the effect on potential supply risk can vary significantly (Fig 6). In terms of *RMC*, the use of mild steel is associated with the lowest risk of supply constraints, whilst the use of stainless steel can be associated with the highest *RMC* values. The potential for supply chain disruption between these materials is a significant order of magnitude higher and substitution of mild steel for stainless steel would not be justified on this basis (and other properties not assessed). HS steels have a relatively high critically, in comparison to mild steel, and the results suggest that strength based design improvements (local properties) have a negative effect on vulnerability and supply risk (global/translational). The results also indicated subtle differences between two types of structural performance improvements that can be made to steel. The heat treatment of steel grades can produce significant strength improvements with little or no change to *RMC*. On the other hand, changing the chemical composition of steel to improve structural strength can result in trends similar to those shown in the HS alloy analysis with increased material criticality. Further work is needed to consider a full spectrum of steel grades that are representative for low-carbon infrastructures, and also analyse the functionality of different elemental compositions within each grade to determine the key critical composition element.

If the implications of utilising critical or rare earth metals in electrical applications and low carbon infrastructures were known 60 years ago, would designers have developed technologies that risked such complicated supply constraints? In our search for energy efficiency and sustainability, i.e. lighter, stronger and higher performance materials and technologies, long-term foresight can easily be ignored as choices are determined by the desire for local property improvements. The scale and pace of the proposed infrastructure upgrades will certainly place pressure on traditional bulk material resources such as metals, aggregates and cement. The planning of sustainable urban environments which include battery operated vehicles (i.e. buses, trams, passenger cars) and the use of low-carbon materials (such as HS steel) must consider the risk posed by criticality that could result from a step-change in the roll-out of these technologies and the implications this has for system adaptability and resilience. If urban systems are to be built on technology rich infrastructure (e.g. ICT, transport, energy, etc.), there is a need to balance to the improvements in performance vs. long term global property implications (i.e. adaptability and resilience). Choosing the latest technology substitutions without considering their effect on the global system property is not a sustainable approach to urban system design.

7 CONCLUSION

This paper has presented an approach moving towards the development of an analytical framework that can assess the effects of local property led design choices and material/component substitutions on the probability of supply risks and system vulnerability – translational/global properties. The framework was applied to a component level case study of electric vehicles and a material level case study using structural steel, both of which are important components of a future low-carbon infrastructure. These preliminary results clearly show that previous design improvements can increase potential supply risks by an order of magnitude or more. It also showed that improvements can also be made without affecting material supply risk. An increased risk of supply may contribute to potential ‘lock-in’ effects and a reduction in the resilience and adaptability of the system to change (e.g. social, economic, political, climate). A question that remains is: on what basis will future design choices for our urban infrastructure systems be made?. Urban environments that are to be designed with the latest technologies must consider the long-term implications of these system improvements and adequately assess the potential vulnerability of major infrastructure design choices. The approach taken should be treated as preliminary as further work is needed to develop adequate confidence in the results achievable. This paper contributes to the development of a framework for analysis for infrastructure transitions that includes; an enhanced 'stocks and flows' model [9]; comprehensive measures of criticality [10]; and a process for assessing and/or optimising the properties of materials, technologies and components within the system. The combined overall framework will allow users to evaluate the material barriers to achieving adaptable, low carbon infrastructure.

ACKNOWLEDGEMENTS

The support of the Engineering and Physical Sciences Research Council (grant number EP/J005576/1) is gratefully acknowledged.

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