Materials Democracy: An action plan for realising a redistributed materials economy

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Abstract

The last 60 years has seen a profound transformation of the human relationship with the natural world. The exponential growth in human population and resource demand is now being felt at the earth system level (Steffen et al., 2015). A wholesale shift in the global economy towards a fundamentally sustainable state is now an imperative. We must transition to a circular economy where we meet our needs through production/consumption practices that operate safely within the planetary boundaries (RSA, 2014; Ellen MacArthur Foundation, 2015). The increasing interoperability between online platforms and digital fabrication technologies is catalysing a redistribution of the means of production - in so doing, enabling practices that are more socially equitable and environmentally responsible than those of 20th-century mass manufacture/consumption (Seyfang and Smith, 2007; Seravalli, 2014; Policy Connect, 2015; Kohtala, 2016; Stewart and Tooze, 2016). However, technological innovation is just one piece of the equation. As a study of 19th-century coal or 20th-century steel will illustrate, there is real material influence and consequence, risk and reward to any industrial transition (Ashton, 1963; Allen, 2010). Without a wholesale redistribution of the global materials economy - from extraction to processing, transference to recapture, aspirations for a 21st-century circular economy will stall. Through blockchain technologies, global development data, and real-time data analytics, new tools for the generation and management of materials in the global economy are now possible (Garmulewicz, 2015; Diez, 2015). To date, such tools have predominantly been developed by large corporates and are often proprietary or prohibitively expensive to access. Should this continue, we risk creating virtuous monopolies, where only large companies are able to develop circular practices --rendering small entreprises unable to thrive and compete. This paper sets out a proposal for the development of an underlying common architecture and set of protocols for the generation, aggregation and tracking of materials information in ways that are open, interoperable and incorruptible. As such, materials information is envisioned as an open web of interconnected databases. Central to such a web would be; (1) Digital signatures for raw materials so that primary material information can be carried throughout use- and life- cycles. (2) Protocols that connect layers of primary information in stacks --relaying and connecting such with secondary information about material processing and use. (3) Analytical systems that relate stacks of material information (primary and secondary) to global environmental data and sustainable targets in real-time. (4) Open APIs that leverage, visualise and translate stacks of materials information in relation to sustainability targets in machine- and human- readable formats that incentivise sustainable decision-making. Such a materials information commons could empower stakeholders at all levels to make more effective decisions. A concerted and coordinated effort across all scales and sectors must be incentivised for such an infrastructure to be operable and effective. This paper will lay out the opportunities and challenges of such an undertaking, as well as discrete projects that, if done now, could generate momentum for wider systemic development. The paper will survey existing projects including ChemHub (reference image one and two), Pattern Web (reference image three), Fab City Dashboard and the Materials Library to expand upon and characterise a recommended criteria for key material,

technological and behavioural functionalities. Lastly, the paper will pose a number of targeted research questions in order to shape next steps.

Introduction

Human activities within the industrial economy are now the main and most significant drivers of change to the Earth System. These changes, driven by both the scale of human population and the magnifying effects of human technologies, “are multiple, complex, interacting, often exponential in rate and globally significant in magnitude” (Steffen et al., 2004: 81). The years since the 1950s “have without doubt seen the most rapid transformation of the human relationship with the natural world in the history of humankind” (Steffen et al., 2004: 131). Over approximately the same period, the use of manufactured materials has increased by 4 to 15 times (Allwood et al., 2012: 7) and correlates with a rapid rise in global GDP.[i] The expansion of the global economy is directly linked to the rise in land, sea and atmospheric pollution, natural habitat loss and the extraction and consumption of resources. Creating a future free of these destructive patterns will require the abandonment of the ‘take, make and throw away’ culture, moving toward a circular economy in which human wants and needs are met by managing resources at their highest utility for the longest time within biological and technical cycles. Without a wholesale recalibration of the global materials economy to factor in both immediate and long-term implications of all material decisions, inclusive of extraction to processing and transference to recapture, aspirations for a twenty-first-century circular economy will stall.

This paper sets out a proposal for the development of an underlying common architecture and set of protocols for the generation, aggregation, and tracking of materials information in ways that are open, interoperable, and incorruptible. As such, materials information is envisioned as an open web of interconnected databases. The authors propose that such a materials information commons could empower stakeholders at all levels to make more effective decisions. For such an infrastructure to be operable and effective, a concerted and coordinated effort across all scales and sectors would need to be incentivised. This paper lays out the overarching context and need for such an undertaking and highlights both the opportunities and challenges therein. It surveys existing sources of materials information in order to expand upon and characterise recommended criteria for key material, technological, and behavioural functionalities. Lastly, this paper poses a number of areas of focus for future research.

The Current State of Materials Information

The technical, economic, ecological, and social factors of a material have a fundamental impact on the ability of a product to carry the lowest possible environmental consequences (Allwood, 2016; Downing and Warde, 2017). However, those who make things are faced with an increasingly wild ‘jungle of choices’ when it comes to selecting a material (Ball, 1997). Recent estimations put the number of distinct materials to choose from when manufacturing a product at over 160,000 (Ashby et al., 2014). And as our materials palettes and needs in every area of our lives grow more sophisticated, so too, do our material solutions become more complex (Miodownik, 2015).

Material selection strategies that meet environmental objectives often start by identifying the phase(s) of a product’s life that proposes the greatest concern. Reconciling with and mitigating against the environmental consequences of each phase requires data not only for the obvious eco-attributes of a material,[ii] but also the physical properties of a material,[iii] the economic factors that surround that material choice,[iv] and finally impact data that pertains to specific geographical and temporal contexts (Ashby, 2009). Importantly, a holistic material selection strategy must also take into account those social and cultural factors that influence the way in which materials flow throughout everyday life. In this way, materials information plays a vital role in devising circular material selection strategies. It is, therefore, vital that actors across all scales and points of a product's lifecycle can attain materials information in a consistent, traceable, and accessible manner. Yet, whilst many recognise the need to address the ecological impacts of what they design and produce, valuable information needed to support circular practices is still missing (RSA, 2016). To demonstrate this argument, an analysis of the benefits and limitations of the most commonly found sources of materials information, for designers and producers, are explored below.

Material Safety Data Sheets

A Material Safety Data Sheet (MSDS) is a document that contains information on the potential hazards (health, fire, reactivity, and environmental) of a chemical product and how to work safely with it (COSH, 2018). It also contains information on the use, storage, handling, and emergency procedures in relation to the hazards of chemical products (COSH, 2018). The benefit of MSDSs is that they are a readily accessible, standardised source of primary information for communicating the hazards of chemical products. However, beyond this basic information, an MSDS does not carry information with enough breadth or depth for an individual to conduct circular material selection and/or decision-making processes with confidence. Furthermore, the information included within an MSDS is often hard to understand by non-specialists, lacking in detail beyond information pertaining to human health hazards, and often out of date (COSH, 2018).

Materials Libraries

Materials libraries offer curated collections of materials tailored to the needs and interests of their user-base and/or audience. Those material samples within these collections are often accompanied by useful mechanical, physical, and economic information as well as information on how they can be sourced. Within her analysis of the topic, Laughlin classifies such collections in three distinct categories: commercial ventures, professional resources, and institutional collections. Commercial ventures are those funded through membership subscription and/or sponsorship from materials manufacturers and suppliers (Laughlin, 2010: 42). This model often means that comparatively substantial sums of money are used to curate well-defined collections that attempt to address the specific material interests of their users and sponsors (Laughlin, 2010: 42).[v] Professional resources are defined as those constructed for the use of a particular profession or corporation, and which rarely looks beyond said professional remit when gathering and selecting samples (Laughlin, 2010: 49).[vi] Lastly, institutional collections are those that belong to academic institutions and primarily serve the needs of the respective student body, with the resultant collection usually being heavily affected and influenced by the nature of the institution itself (Laughlin, 2010: 57).[vii]

To date, materials libraries operate independently from one another, without any standardised way of sharing information or for assessing the validity of the information they receive from sponsors. In this regard it is important to recognise that in the absence of common protocols and standards, even the most well-informed and well-intentioned organisations will present considerably contradictory information about the materials within their collections. Furthermore, gaining access to materials libraries can prove challenging as many libraries remain inaccessible to the wider public—be that due to cost-prohibitive membership fees or closed membership models.

Material Brochures and Technical Data Sheets

Material brochures and technical data sheets supplied by material producers and agencies most often contain physical, technical, and economic information about a material, commonly alongside case studies of exemplar applications. Alongside standard MSDSs, these are often the most readily accessible sources of materials information. The availability of and ease of access to such data sheets is certainly a benefit of such information sources. However, because material producers and agencies naturally want to present their own material in the most positive light, most will quantify and qualify their material in ways that present them as the optimal choice (Allwood et al., 2012). Without viable primary source information and/or objective cross-comparison analyses, it can be very difficult to feel fully confident in the trustworthiness of materials information direct from a materials producer.

Materials Standards and Certifications

Materials standards and certifications are those voluntary, usually third party-assessed, standards designed to guide, incentivise and differentiate responsible sourcing methods, production practices, and operational management of materials or products (International Institute for Environment and Development, n.d.). Today, there are thousands of such standards and the pace of introduction has increased in the last decade.[viii] Despite the individual benefits of particular certifications, the level of inconsistency amongst the different forms limits the amount of impact any wider certification system is able to have. For example, there is a significant difference amongst the level of strictness each standard adheres to; some standards set the bar high for a sector, working with the top performers to constantly push up sustainability expectations; whilst others are more focused on the elimination of the worst practices and operate more at the entry-level in order to get a large proportion of an industry working incrementally towards better practices. Some standards can also be applied internationally whereas other standards are developed entirely with a regional or national focus. Additional inconsistencies between standards relate to the certification process and whether it is conducted by a first, second, or third party; methods for traceability and accountability; and the indexes that sustainability claims are measured against.

Life-Cycle Assessment Databases

Life-cycle assessment (LCA) is a technique for assessing the environmental impacts associated with all stages of a product's life; from raw material extraction through to materials processing, manufacture, distribution, use, repair, maintenance, disposal, and recycling (International Organisation for Standardisation, 2006). LCA information has become a leading tool for validating the cumulative environmental impact of a product or production practice. Whilst access to LCA databases has historically been limited given their proprietary and/or high-cost nature, over the past ten years there has been a proliferation of publicly accessible options.[ix] This increased access has enabled a broader range of actors to incorporate environmental stewardship into design and processing decisions.

Yet, current LCA data has a number of flaws. For one, is has been criticised for being largely incomplete, unreliable, or simply outdated. Methods for data acquisition and management at the scale required for conducting LCAs require substantial time to complete, with much of the data currently present within LCA databases having been gathered through multiple decades of research. For those products that experience rapid innovation cycles, the slow pace of data accession proves highly consequential to the validity and accuracy of one’s LCA. A second critical issue is the level of variability present between LCAs when used in cross-comparative analysis. Methods of LCA cross-comparison are often used by firms to determine better processes and/or products to use within their own organisations. However, regardless of industry standard guidelines, individual LCAs do not have a standardised analytical scope and are most often based upon locally representative samplings, oversimplified regional averages, and nationally-specified parameters.[x] The resulting high level of variability between LCA conclusions means that one’s ability to conduct a cross-comparative analysis with analytical rigor and accuracy can be extremely challenging. A third issue is the limited resolution of spatial and temporal impact the majority of LCAs provide. Most LCAs will calculate any two tonnes of a commodity as “equal”, even though within real-world contexts this is far from the case when it comes to their impact footprint. In other words, it is not enough to know that a product requires the use of 0.2 hectares of land, uses 50 litres of water, and emits 10 grams of carcinogens; it is essential to understand when and where these impacts occurred. Were biodiversity hotspots impacted? Was the water taken from a drought-prone region? Were the carcinogens released in a location where people were likely to be exposed? Answers to these types of questions are essential for data-driven impact assessment. The present lack of context-specific granular data within LCAs is highly problematic, as we do not know the finite calculation of impact across spatial and temporal scales.

Materials Information and its Impacts Across the Product Life Cycle

A simplified product life cycle from an environmental perspective includes the following basic steps: raw material extraction, raw material processing, product manufacture, use, and end-of-life (refer to Figure 1). The product design and development process phase is a critical intersecting cycle that, among its other influences, drives market demand for raw materials and determines the possibilities for reuse, remanufacturing, and recycling for products once they are disposed of (Giudice et al., 2006).

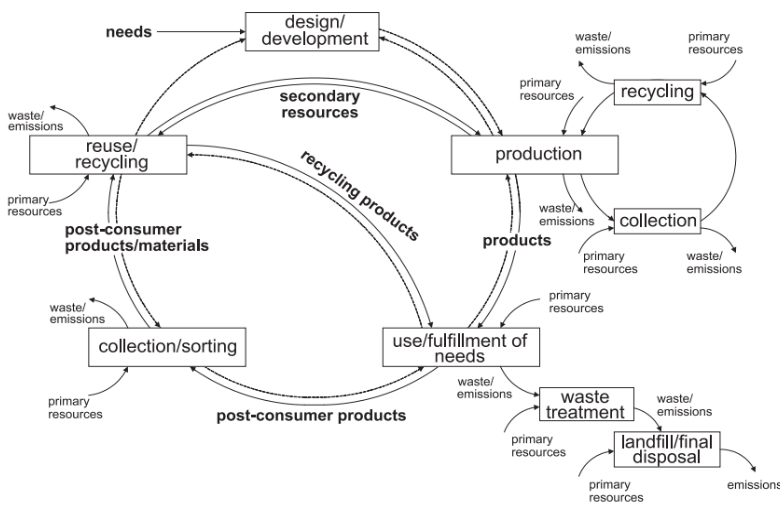

Fig. 1. Schematic representation of a generic life cycle of a product (the full arrows represent material and energy flows, while the dashed arrows represent information flows) (Rebitzer et al., 2000).

Each step of a product's life cycle generates impacts. Extracting raw materials through activities such as mining, quarrying, forestry, or agriculture inevitably requires significant amounts of resources like energy and water, while often exploiting or degrading natural lands. As a result, all materials carry an 'embodied' impact footprint of all the resources needed for their production (Kara et al., 2010). Commonly monitored embodied impacts include energy, greenhouse gas emissions, water, waste, and land use. As a material moves throughout the product life cycle, eventually becoming part of a larger product, it continues to collect embodied impact. The selection of transport modes, the efficiency of manufacturing equipment, and the practices at each facility that determine whether wastes are reused or disposed of, are just some of the determinants of the sum total of a product's embodied impact.

In addition to the impacts derived from these physical resource demands and transformations, there are many human and societal impacts resulting from activities across the product life cycle. Occupational hazards, which can range from exposure to toxic chemicals to injuries resulting from physical strain, have been estimated by the World Health Organization (WHO) to lead to approximately 40 per cent of global deaths. Many sectors are known to still have high levels of both child and slave labour (Alliance 8.7 provides annual estimates of both). The widely discussed problem of conflict minerals points to further socio-political concerns around materials sourcing. The eastern provinces of the Democratic Republic of the Congo (DRC) are rich in tin, tungsten, tantalum, and gold. The sale of these natural resources has contributed to violence and exploitation in places like the DRC, leading to international efforts to eliminate sourcing of these minerals (EU Conflict Minerals Regulation in Europe and the Dodd-Frank Act in the United States). All of these examples point to the pronounced context-dependency of material impacts. Though it is possible, and still useful, to have generic impact data for materials (which is what LCA databases currently provide), the degree of variability in the real-world scenarios in which these materials are produced is so significant and contextually impactful that generic data will rarely align with the real information for each product.

Unlocking and connecting the data flows that accompany materials and products will be a vital aspect of realising circular thinking in practice (RSA, 2016). Yet, as the above analysis evidences, existing sources of materials data are most often either publicly accessible in an incomplete and inconsistent fashion, available in more comprehensive forms but at relatively high costs, or privately held within corporate and institutional silos thus inaccessible for those outside to view. Much of the issues mentioned herein are down to the fact that the aggregation and management of materials information is a highly complex, specialised and demanding task. This often results in information management systems being distributed across specialist teams or sectors - with each sector dealing in the testing, researching, and documentation of a particular set of material aspects and properties. The distribution of data, know-how and responsibility very often means that materials information becomes scattered across an innumerable and disjointed set of databases (Downing and Warde, 2017). The resulting opaque and fragmented nature of materials information often accelerates, and ultimately becomes a product of, a lack of authentication, trustworthiness, and interoperability between disparate materials datasets and stakeholders. Most often, this causes ineffective decision-making, especially when it comes to design for circularity, as decisions are based upon speculative information and individual subjective experience rather than real-time, immutable data. A key enabler of meeting the UN Sustainable Development Goals (primarily 9, 11 and 12) will be more comprehensive materials information that is widely available and new ways to manage this information. This will require new infrastructures, standards, systems, tools, cultures, and practices. In the following sections we will outline a proposal for such an infrastructure and argue how it could be leveraged as a transformative tool for realising a wholesale shift towards a circular economy.

Towards an Open Utility for Materials Information

Advancing from an understanding of the complexities and challenges to managing materials information, this section will begin to outline a concept called the *Materials Web*. The Materials Web is designed to lower the barriers to and costs associated with effective decision-making in regards to sustainable materials choices (Huber, 1990). This proposal includes 1) a set of standards and open protocols for generating, aggregating, tracking, and interpreting materials information and 2) a network of distributed, interconnected materials databases that would be readily accessible by anyone. The realisation of the Materials Web would bridge a number of information gaps that are currently standing in the way of the large-scale transition to a circular economy (Preston, 2012).

Materials Information and Critical Decision Making

The purpose of forming such a Materials Web is ultimately to provide key decision-makers along the chain with the necessary insights to realise a circular economy while simplifying the challenges of effective material selection and management. Throughout the product life cycle, decisions are made which profoundly influence the impact footprint of materials and products.[xi] Crucially, there are a couple of critical nodes in the system, where individual decisions have a dominant effect in driving change throughout the rest of the value chain: design and procurement. For example, organic Punjabi cotton has less than a half the energy footprint of conventionally-produced cotton in the United States (Cherrett et al., 2005) while polyester fibre is commonly found to have an embodied energy of at least two times that of cotton (Barber and Pellow, 2006). If product designers and procurement officers are given access to this information at the time of material selection and purchase, they can cut the energy footprint, and associated greenhouse gas emissions, of a textile product by up to 75 per cent over the worst case scenario. It is clear that with this kind of information, designers and procurement officers will be able to eliminate significant percentages of the impact associated with product manufacture. At the same time, if product designers are further equipped with the ability to communicate their design choices downstream – to users and waste processors – they can more effectively design products for extended use and multiple life cycles. The same system used for materials identification can ultimately be used to transmit information about the optimal refurbishment, disassembly, component lifetime, and residual material value of any product. With such data in hand, waste recovery facilities can begin implementing circular resource recovery models at scale.

The Materials Web: Five Pillars

To create an infrastructure capable of supporting optimised decision-making around materials, data should ideally be collected across the product life cycle, stored in an incorruptible and open format, and be easily accessible to product designers and other decision-makers. To achieve this, the authors propose to underpin the Materials Web with five pillars:

1. Data Creation: Resource Passports and Fingerprinting
2. Data Interpretation: Environmental Context Engine
3. Data Access: Open Material Databases
4. Data Interoperability: Standard Protocols
5. Data Leveraging: Open APIs

1. Data Creation: Resource Passports and Fingerprinting

The Materials Web Resource Passport would be the format used to store information about specific materials as they travel through supply chains. This data would be further complemented with generic materials data stored in open and distributed Materials Web databases. The Resource Passport would include several types of data:

- The names and geographic locations of all intermediate processes and facilities along the product's value chain, for each of the materials present in the final product.
- Embodied impact calculated across a broad range of metrics[xii] amounting to a customised Life Cycle Inventory for each material.
- A Dynamic Bill of Materials (BoM) updated to reflect the latest contents of the product (Bras 2009).[xiii]
- A clear nested breakdown of each component and material in a product, as well as how the product is assembled.

To make this possible, data collection would begin at the first phase of the product life cycle. As raw materials are extracted or harvested, they would be assigned batch numbers based on the time interval in which they were collected. The batches of material would be tagged with a physical identification system or fingerprint that is incorruptibly linked to the product through verifiable chemical and physical characteristics.

The data associated with the material identification tag would be stored on a blockchain, allowing information about the product batch in question to be securely added, removed, or modified as the material progresses through its value chain. There would be verification protocols in place for the addition and removal of data, ensuring that the information collected about the product is accurate and true. In an ideal scenario, facilities participating in Materials Web reporting would have automated data collection and recording in place, minimising the labour required for the creation of the Resource Passport. As materials travel throughout the value chain and become incorporated into products, information would be recombined and collected in an additive (or subtractive) manner.

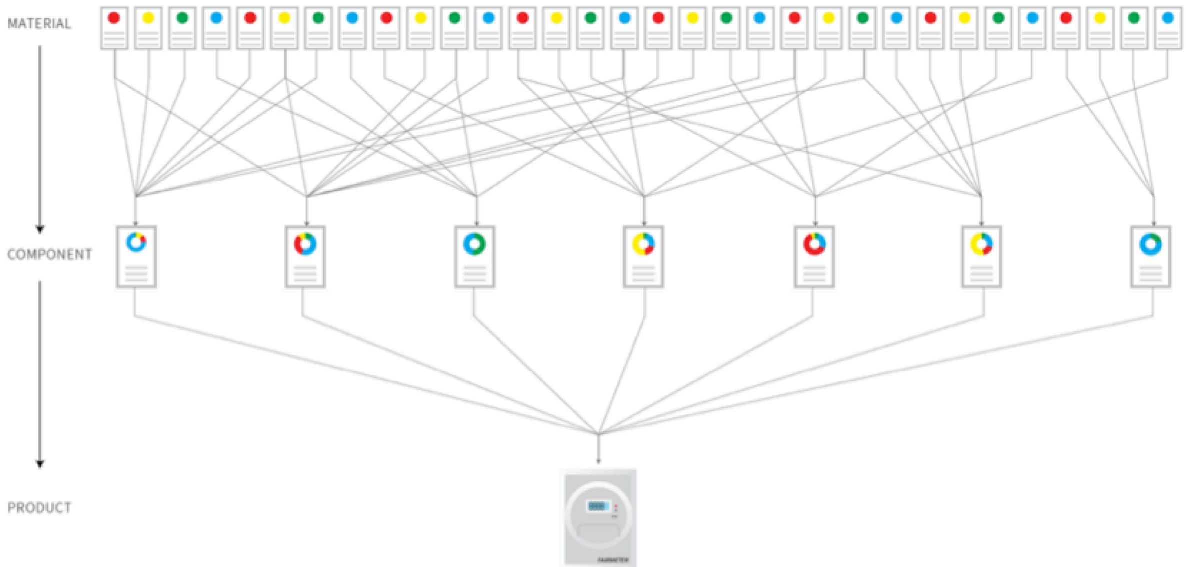

Figure 2: A schematic representation of data collection through the Resource Passport.

2. Data Linking: Environmental Context Engine
To properly interpret the impact of the resource consumption and environmental emissions recorded across the product life cycle in the Resource Passport, it will be essential to understand the context in which they occur (Ehlers, 2013). For this purpose, the second pillar of the Materials Web would be an Environmental Context Engine – a fine-grained geospatial database including, among others, data on water tables, weather patterns, biodiversity hotspots, forest cover, soil health, and population density.

This kind of information will be essential for calculating the actual impact resulting from supply chain activities and determining whether any critical impact boundaries are being transgressed on a local or regional level (Sabag-Munoz and Gladek, 2017). By geo-locating the different supply chain activities captured in a particular Resource Passport, products could be scored or 'red-flagged' on key impacts. The scores generated by the Environmental Context Engine would be automatically added to products' individual Resource Passports as the calculations occur.

3. Data Access: Open and Distributed Material Databases
One of the core assets of the Materials Web, aside from the specific data generated through the Resource Passports, would be a set of open and distributed databases containing generic information on the physical, chemical, toxicological, and cultural properties of materials. The Materials Web would define a standardised data structure, which would be updated on a regular basis, for capturing critical information about any material. Anyone would be able to contribute materials data to the open databases - for it to become 'verified,' the data would need to undergo an expert vetting procedure.[xiv] Individuals with known expertise in specific topic areas would be collectively assigned greater reputational credit as 'experts.' Once data points received a minimum threshold of verification votes from individuals with 'expert' status, the data could be marked as verified within the database.

As with the Resource Passport, the data for each material in the generic databases would be stored on a blockchain. Though some institutions may choose to locally store the databases for many individual materials, these databases would be stored on thousands of individual computers offering resilience against data loss. Similar to downloading a torrent file seeded by many individual users, any individual would be able to download the materials database for any registered material. Though the generic materials databases would be the only resource for stable material information such as chemical and physical properties, they would also be a source for averaged impact data. As information would be collected in a distributed fashion for specific materials via the Resource Passports, it would be aggregated and anonymised into average data for different material types. Regional and global impact averages for different material types could be automatically generated, providing a wealth of knowledge for designers, materials scientists, and policy makers.

4. Data Interoperability: Standard Protocols
The Materials Web should operate with standard protocols for information management and open data. Users must be able to understand the provenance of a dataset in order to judge whether it has sufficient quality or authority for specific purposes. This means the Materials Web must also take the necessary steps to identify and translate rights information for data that is either commissioned or derived, and also include rights information for any derivations of the data currently being published.

For data to be open, it must also be machine-readable. Making rights information machine-readable is essential for improving efficiency in the data supply chain. The Open Data Institute and the World Wide Web Consortium (W3C) are two organisations that have been bringing together best practices and open data protocols to further a set of standards for open data management (Open Data Institute, 2014).

5. Data Leveraging: Open APIs
Open Application Programming Interfaces (APIs) are important for creating the ability for others to leverage the underlying data in the Materials Web. Open APIs have proven effective at driving down the cost of connecting to and using information. For example, in looking at what factors prove most effective for building smart city data frameworks, researchers found that cities have moved to promote service development (for applications such as mapping, transportation, and infrastructure planning) using open data platforms and open APIs (Lee et al., 2014). OpenStreetMap, an alternative to Google Maps for governments and developers, is one of these open platforms. It is a project in which the product is not the map itself but the data generated. OpenStreetMap offers a series of APIs that enable commercial, non-profit, and individual users to plug directly into the datasets. These APIs help developers create complex software applications more easily and for governments to reduce costs of accessing digital services, thereby democratising information by making it easily applicable. The Materials Web should use open APIs in ways that offer new opportunities for social and commercial entrepreneurs to leverage the connected information.

<u>The Materials Web: Market Viability</u>

We propose that a Materials Web would need to fulfil four key criteria for it to become and remain a trusted and widely used source of information.

1. Open and Accessible
The Materials Web should be centrally accessible via an access portal that allows for heuristic querying. It should be open access and available for anyone to use. It should enable commercial and non-parties who create added-value applications using the information. It should be interoperable with major software and common APIs, and the granularity of the original data should be accessible if desired.

2. Non-Commercial

The underlying information should be owned or managed through a global public utility or other not-for-profit governance model, rather than by a commercial organisation. A profit motive would negatively impact collaboration and put pressure on a business model that could reduce accessibility.

3. Secure and Reliable
The characteristics of a market depend upon the ways in which actors obtain information (Galatin and Leiter, 2012). If successful, the Materials Web could be a guide for commodity markets, investment strategies, and procurement decisions. The information must therefore be secure and resistant to manipulation, requiring advanced encryption and cybersecurity.

4. Heuristic and Applicable
Users should be able to easily understand the systemic impacts of their material selection and receive suggestions for low-impact alternatives. The Materials Web will likely never provide perfect information, but the information it does provide should be actionable.

Challenges to Realising a Materials Web

The aggregation and management of materials information is a highly complex, specialised and demanding task. In 2014, the Dutch government joined two Dutch grid operators to investigate the creation of a smart energy meter that was "fair," meaning that the supply chain was free from conflict minerals derived from countries like the DRC where mineral sales fuel human rights abuses.[xv] The goal of the project was to identify which data needed to be collected from the supply chain of a smart meter (which included over 3,000 individual components) in order to evaluate whether or not the end product was fulfilling the targets of eliminating conflict minerals, lowering the material footprint, reducing toxic materials, and maximising recyclability.

The project resulted in a few important insights. One was that four types of data were needed to fulfil the product evaluation objectives:

1. Life cycle inventory (LCI) data for each component of the final product including geographical sourcing.
2. An extensive Bill of Materials (BOM) and mass breakdown.
3. Detailed end-of-life handling and processing instructions for material recovery.
4. Financial information on the value of individual components.

Unfortunately, the project also revealed numerous challenges in collecting this data. For one, there was no specific point(s) in the chain where data collection was most important or most problematic; problems were widely distributed throughout the chain. Second, the vast majority of suppliers did not collect the required information and admitted that they were unlikely to start collecting it without new legislation given the costs involved (Gladek, 2015).

Although the findings were specific to the electronics sector, the case of the Dutch Fair Meter illustrates some of the major challenges to realising a Materials Web. What follows are seven main challenges that we have identified, each followed by a potential solution pathway.

1. Data Gaps
In wealthier countries, the data revolution means thinking about smart cities and big data. But in many poorer countries, many of which are host to agriculture production and mining operations that feed global supply chains, the data revolution can mean just beginning a census or recording basic environmental data. Because of the variance of material iterations, agriculture practices, and environmental factors, data gaps can cause a mischaracterization of information. Time delays in information can also be a major bottleneck to effective

decision-making. Data takes time to collect, filter, and aggregate. The most recent year of comprehensive data is often two years old, and that is often a best-case scenario. One promising direction for solving these challenges is a combination of advanced statistics, computational analysis, and artificial intelligence techniques, with which extrapolations can be made of relevant data points using historical data, satellite photos, and other relevant information. These method would ideally be adopted more comprehensively across the current set of data aggregators, such as the World Bank, USGS, FAO, and WRI, as a Materials Web will ultimately draw upon these sources of data and aim to supplement them only where necessary.

2. Deriving Information

Existing databases offer differing datasets on the same observed phenomena. Merging different data sets to arrive at new composite information can be critical for cleanly incorporating different information or units of measurement regarding the same material, environmental impacts, or even weather patterns (Vallero, 2017). In a Materials Web, information from a broad range of sources about a material and its contextual factors will need to be combined into one new data point, or at the very least certain data sources need to supersede or be given more credibility than others.

Managing information requires transparency of both the history and the methods behind that manipulation and management. *Openactive.io* is one interesting example, as it merges community-provided datasets to create an overall picture of various health and wellness statistics. Another solution may be to further such methods by using blockchain technology to ensure there are records of the compositing of data and that those records are open.

3. Data Collection Incentives

As illustrated in the case of the Dutch Fair Meter, an order of 16-million units was too small to create leverage within the electronics chain, even among some of the most progressive suppliers. Supply chain actors had minimal incentive to act without the presence of legislation that mandated improved data collection and reporting.

New regulation at the national, EU, and international level would support the collection and reporting of this information, but other incentives beyond legal should be able to be leveraged. Supply chain actors may respond to incentives such as ease of collecting and providing data, new business models for exploiting that data, increased access to markets and sales channels, and other consumer and CSR pressures from large enough groups downstream.

4. Data Verification and Trustworthiness

The effectiveness of a data-driven initiative like the Materials Web is partially dependent on the reliability of the data it uses. If a Materials Web becomes an information utility that is used by an increasing number of actors to inform an increasing amount of decisions, the incentive to provide false information also increases.[xvi] It will be imperative that the Materials Web find a method to improve the trustworthiness of its information, or at minimum find a way to explicitly factor the level of untrustworthiness into how it composites and presents information.

Audits, implemented through a network of global and local actors, are already used to verify claims for the purposes of certifications. Certifications have become widely used for the most commonly traded commodities.[xvii] We propose that certifications could become more advanced and decentralized by incorporating blockchain technology, verified local actors, smartphones, and affordable satellite imagery in order verify claims at a reduced cost.

5. Proprietary Information

Organisations, particularly businesses, view their information as proprietary and important to protect. This includes competitive operational information, such as the origin of materials and which quantities are flowing through production processes. It also includes intellectual property information, such as the detailed specialisations of a new-patented material. These tensions in Big Data between transparent governance and intellectual property rights involve complex considerations relating to innovation economics, ownership, and licensing (Minssen and Pierce, 2009).

MIT's *Trust: Data* project is working to solve some of these underlying challenges. One of their connected initiatives, the OPAL project aims to make a broad array of data available for inspection and analysis without violating personal data privacy with the following three interventions (Hardjono, 2016):

1. *<u>Move the algorithm to the data</u>: Performing algorithm-execution on data at the location of the data repository means that raw data never leaves its repository, and access to it is controlled by the repository owner. Only aggregate answers or "Safe Answers" are returned.*
2. *<u>Algorithms must be open</u>: Algorithms must be openly published, studied, and vetted by experts to be 'safe' from violating privacy requirements and other needs stemming from the context of their use.*
3. *<u>Data is always in an encrypted state</u>: Data must be in an encrypted state while being transmitted and during computation.*

6. Tracking Technology

Radio-frequency identification (RFID) has become a widespread technology. Cost reductions in tags and readers, as well as the governance behind the technology, has led to its widespread use. Recent developments have led to its further integration into a global Internet of things (Farris et al., 2017). But as the Fair Meter project demonstrated, tracking materials as they move through the supply chain can be a significant barrier when you consider the earlier stages from extraction to processing. In the supply chain of metals and electronics, for example, the chain is broken when minerals are either mixed from multiple sources or undergo physical transformation when smelted. In a related issue, some materials enter a production process in fractions and are difficult to count, such as an amount of sand or concrete in a mixture.

Tracking of materials requires a physical chain along the life cycle. This is likely a challenge of information management, not technology; for non-metallic inputs of materials, chemical fingerprinting is already used to track the origin of some materials like wood, but this information must still be transfer as the material moves throughout the supply chain. Processing facilities would ideally have a new materials accounting layer on top of their current production systems that could interface with other facilities. This accounting layer would need a way to attribute percentages of certain batches of material information to each component or product that is made.

7. Information Accessibility

As of 2015, 4.2 billion people around the world remained disconnected from the Internet, meaning that over half of the world lacked Internet access, with usage growing only nine per cent per year (Internet Live Stats, 2015). That means even if all the other barriers to achieving a Materials Web could be overcome tomorrow, over half the population could lack access to an important global information utility. This is not a problem unique to the Materials Web, but as we envision global information utilities, we should also consider how to improve access to those utilities for people who lack Internet connectivity or personal electronic devices.

Beyond the existing initiatives that aim to increase Internet connectivity by improving ground telecommunications or implementing low-orbit satellites, a more human-centred approach could also increase access. Growing networks of fabrication labs, makerspaces, and hackerspaces have created a more decentralised set of resources that can facilitate fabrication, entrepreneurship, and craftsmanship.[xviii] This growing movement could be accelerated to serve as nodes for accessing materials information.

Conclusion

This paper has laid out a number of limitations associated with the current state of materials information; why a new system such as the Materials Web is needed for facilitating the transition to a circular economy that includes all scales of enterprise; how that system might function; and what criteria it should adhere to. We have also outlined a set of seven challenges we see that need to be overcome in the realisation of an open utility for materials information. These challenges stem from the experiences of the authors as well as additional research, but they are far from comprehensive. The challenges of achieving an open Materials Web deserve the further attention of engineers, social scientists, designers, and data scientists. The solutions suggested offer a potential direction and also need further research to identify their feasibility and attractiveness compared to alternative strategies.

Outlined below are four key research areas the authors suggest should be tackled to both determine the feasibility of and the benefits to such an ambitious proposal.

1. Open protocols and standards for the specification of web searchable materials datasheets. This would need to take into account how accurate and specific information is collected at the initial extraction or harvesting point, as well as how that data is then added to and made openly accessible by all actors as those resources become materials, components, and products. This would also explore how datasheets could integrate into search tools and supplier databases; how the granting of rights and permissions relating to proprietary information would be managed; and how datasheets could collectively function as a distributed open access materials library.
2. Impacts, requirements, and value of such a system to actors across the supply chain. This would explore how each actor, as well the connections between actors could be affected, to what extent and what consequence.
3. Opportunities for new and existing tools, services, applications, and business models to contribute to, integrate with, and/or leverage such a common data infrastructure.
4. Management and regulation of such a system to ensure data is comprehensive, accurate and trustworthy. This includes the overall operational model of such a global scale initiative as well as how policies and regulations at regional and national levels could enable or stall part or all of this vision.

The authors believe that this work is both timely and imperative. If materials information as a global body of knowledge remains incomplete, scattered across multiple documents and databases, and does not offer a comprehensive picture of all options and their consequences, those making materials decisions will do so in an impoverished state. Without such an intervention, which should be designed to be intuitive and available at zero or marginal cost, the transition to a truly circular economy will be stifled.

[i] Gross domestic product (GDP).
[ii] For example, energy, emissions, toxicity, recyclability, etc.
[iii] For example, the mechanical, thermal, electrical and chemical properties, etc.
[iv] For example, the price volatility, availability, tariffs, and import and export tax, etc.
[v] Examples include Material Connexion https://www.materialconnexion.com/; Granta https://www.grantadesign.com/products/ces/.
[vi] Examples include the Materials Resource Centre at the Institute of Materials, Minerals and Mining http://www.iom3.org/news/2007/apr/23/materials-resource-centre-opens; Google's Portico https://healthybuilding.net/news/2016/10/05/portico-press-release.
[vii] Examples include the Institute of Making's Materials Library at University College London http://www.instituteofmaking.org.uk/materials-library; the Materials and Products Collection at Central Saint Martins http://blogs.arts.ac.uk/csm-short-courses/2017/12/11/csm-library-materials-product-collection/.
[viii] Examples include the C2C Certified Registry http://www.c2ccertified.org/products/registry; the Ecolabel Index http://www.ecolabelindex.com/.
[ix] Examples include EcoInvent (https://www.ecoinvent.org/); GaBi (http://www.gabi-software.com/uk-ireland/index/).
[x] Consider the in-depth analyses of 13 LCAs of wood and paper products conducted by the National Council for Air and Stream Improvement in 2004 (National Council for Air and Stream Improvement Inc. 2004). The Council found the methodological frameworks, datasets and assumptions used across the 13 LCAs to be significantly lacking in consistency. This inconsistency led to a highly variable, and at times contradictory, set of conclusions.
[xi] For example, manufacturers can choose to install solar panels and emissions scrubbers on their production facilities. Logistics companies can implement advanced telematics to improve vehicle safety and driver efficiency. Waste collectors and processors can choose to refurbish, recycle, incinerate, or landfill the resources they collect. Ultimately the decisions of all of these stakeholders across the chain will need to align along circular principles if we aim to achieve an inherently low-impact, efficient, and circular economic model.
[xii] Metrics would include, but not be limited to: energy, greenhouse gas emissions, water, waste, land use, etc.,
[xiii] The Resource Passport would include a format for an advanced BoM, standardising it across all products and processed materials. The format needs to protect intellectual property and proprietary information while enabling designers, procurement officers and waste management organisations sufficient information to avoid toxicity risks and maximise resource recovery (Jensen 2015).
[xiv] There are several working examples for crowdsourced vetting that could become the mechanisms for verifying data in the Materials Web.
[xv] Metabolic, a company founded by two of the authors of this paper, completed this analysis for a consortium that included the Dutch Ministry of Infrastructure and the Environment and Dutch grid network providers Alliander and Stedin.
[xvi] e.g. for the purposes of influencing investments, certifying products, or protecting national industries
[xvii] The path of forest certifications is emblematic of the prevalence of certifications in the chain; as of 2007 PEFC certified forests stood at 194.4 million hectares and by 2017 this had risen to 313.5 million. Over the same period the number of chain of custody certificates issued rose from 3,545 to 11,484 (PEFC 2017).
[xviii] According to FabLabs.io there are over 1,200 so-called Fab Labs across 30 countries with more makerspaces and hackerspaces springing up as viable sources of skill training and economic mobility as they become part of libraries, schools, and community centers (Kemp et al. 2016).

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