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A Database for the Stocks and Flows of Sand and Gravel

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Abstract: Increasing demand for sand and gravel globally is leading to social, environmental, and political issues that are becoming more widely recognised. Lack of data and poor accessibility of the few available data contribute to exacerbating these issues and impair evidence-based management efforts. This paper presents a database to store stocks and flows data for sand and gravel from different sources. The classification system underlying within it builds on the Universal Materials Information System (UMIS) nomenclature, which is used to construct hierarchical order in the data and in the same manner as the Yale Stocks and Flow Database (YSTAFDB), a common data format. To illustrate how the database is built and used, a case study using UK data is presented. The UK is chosen owing to relatively better access to data compared to other locations. Quantitative analyses of the data show the supply chain of these materials to be currently stable for the UK as indigenous extraction contributes 95.6% to UK sand and gravel production, with imports accounting for the rest of the inputs, of which 50% is reliant on only one nation.

Keywords: sand; gravel; material flow; database; extraction; production; use

Citation: Morley, J.D.; Myers, R.J.; Plancherel, Y.; Brito-Parada, P.R. A Database for the Stocks and Flows of Sand and Gravel. *Resources* **2022**, *11*, 72. https://doi.org/10.3390/resources11080072

Academic Editor: Damien Giurco

Received: 9 June 2022
Accepted: 28 July 2022
Published: 2 August 2022

1. Introduction

Aggregate deposits (crushed rock, sand and gravel) are the second largest resource extracted and traded globally [1]. Sand and gravel accounted for 71.9% of nonmetallic mineral extraction in 2010 [2]. Natural sand and gravel are described as loose non-cohesive granular particles of geological origin, with sand being 0.05–2 mm [3] and gravel 2–63 mm in size [4]. Sand and gravel are critical components of the construction industry used to make cement, concrete, bricks, and mortar [5]. The trade and consumption of sand have become the focus of research in recent years, unlike other aggregates such as gravel and crushed rock, due to the increased reporting of worsening issues [1]. Issues vary widely, from social concerns, such as job loss and occupational hazards, to environmental degradation and rising political tensions between nations. These issues have been allowed to perpetuate in part due to a lack of monitoring of the material stocks and flows of sand from the local to the global scale.

Improvements in data accessibility and coherency in data storage are important factors for determining the flows of sand and gravel. The assembly of data into a database constitutes an initial vital step towards the characterisation of issues surrounding these raw materials. The sand and gravel database presented in this work provides a repository to collect, store, and exchange stocks and flow data for these materials from different sources. The development of a common data structure improves ease of use; it also improves consistency in the collection of sand and gravel data, often classified using different terminology, which hinders data reconciliation. The main issues due to the consumption and trade of sand and gravel, described in Section 2, provide context for the classification system presented in Section 3. The UK is used as an example of how the database can be populated from various sources of stocks and flow data, and how it can be used as a basis for quantitative analysis in Section 4. The analysis and discussion in Section 5 focus on sand, but data on gravel have also been included in the database, given gravel data tend to be available alongside sand data.

2. Background and Wider Context

Social, environmental and political issues associated with the material stocks and flows of sand are becoming more widely recognised. A major gap in data collection exists for the material stocks and flows of sand and gravel [6] due to a chronic lack of monitoring and data reporting. The data gap hampers quantitative analyses of these material stocks and flows, allowing mismanagement issues to perpetuate. The development of a database with a common data structure able to collect and archive sand and gravel data at all magnitudes and scales is a crucial step towards characterising the issues surrounding sand and gravel. Collection and monitoring of stocks and flows data for sand and gravel across scales would allow critical issues surrounding these materials, such as sources of illegally mined sand at the local scale and the monitoring of global patterns and supply risks at the international scale, to be recognised, quantified, and dealt with appropriately. To further motivate why collecting and monitoring sand and gravel data is required, a brief outline of the current global situation around sand and gravel extraction, trade, and use is presented alongside their associated issues, followed by potential solutions.

2.1. Global Patterns

2.1.1. Increasing Demand for Sand

Demand for sand has increased rapidly to 18 kg of sand per person per day, three times greater than the level of demand 20 years ago [1]. As sand is a non-renewable resource, taking up to 200 Myr to form [7], increasing demand leads to the depletion of sand deposits. In 2009, sand and gravel accounted for 43% of global material extraction [8] of which 87% is mined from terrestrial sources, such as quarries and pits [9]. Lake Poyang in China is the largest known area of sand mining activity globally, where extraction rates were estimated, using remote sensing techniques, at 488 Mt during the period 2005–2006 [10]. Growing wealth, consumption and accelerating trade are the main drivers of this increase [11]. Buildings and infrastructure have seen the largest growth in demand with a 4.5% annual increase and now account for 75% of global sand use [2]. Since 1990, the consumption of sand in the developing Asia-Pacific region has had an average annual growth rate of 6.5%, and plateaued in Europe and North America [2]. From 2011–2013 China used more sand for concrete than the USA used during the entire 20th century [12], with the in use stock of aggregates increasing by a factor of 15 from 1978 to 2018 [13]. Modern rapid industrialisation and urbanisation are the main drivers for this increase in the Asia-Pacific region with two thirds of the predicted USD 94 trillion investment in infrastructure globally from 2015 to 2030 to be spent in emerging economies such as China and India [3]. Increasing demand for sand is predicted to continue, with India's demand for sand predicted to quadruple within the coming decades if it follows the same development trajectory as China [14]. If concerted efforts are made to reach carbon neutrality by 2100, sand usage is expected to peak at 30.8 times greater in the decade of 2090 compared to the decade of 2020, [15] as investment in large scale infrastructure such as hydropower facilities requires vast quantities of sand for concrete [3].

2.1.2. Global Sand Trade

International sand trade is predominantly regional, due to sand having a relatively low price per unit mass but relatively high transport cost [1]; selling price doubles for transportation distances greater than 50 km [7]. Many regions and nations are dependent on imports, despite sand being widely available at beaches and riverbanks globally due to the uneven distribution of particular types and grades of sand required for different industries [12]. Desert sand is not traded as it is generally considered to be too fine grained and smooth to be used in construction [5] reducing the compressive strength of concrete by up to 16% [16]. Technical advances such as sintering [16] and grinding [17] desert sand can produce concrete with no reduction in strength at low sand-cement ratios (<1.41 compared to the more commonly used higher ratios of >2) [18] not typically used in mortar and concrete.

Depletion of local sand and gravel deposits, in part due to increasing demand outstripping natural replenishment [19] and hydropower dam construction, such as along the Mekong river where sediment transport was reduced by 77% [20], has also led to longer trade routes. For example, a major trade route now exists between Belgium and China [3]. Trade in sand is dominated by a small group of nations. The top four exporters of sand are the USA, Germany, Australia and the Netherlands [5]. Between 2010 and 2014, 8 out of the top 10 exporting nations remained the same [5]. The top four importers of sand are Singapore (11% market share), Netherlands, Belgium, and Japan [5]. These nations undertake extensive land reclamation projects, which require vast quantities of sand and gravel as well as coarser aggregates such as crushed rock and armourstone.

2.2. Impacts

2.2.1. Social

The lack of adherence to safety standards during illegal sand mining increases health risks. Lower back pain and respiratory issues are common amongst illegal sand miners due to a lack of breaks and inhalation of fine particles while shovelling in small scale mines [21,22]. Local mining of black sand at Induk beach in Indonesia, taken for its superior quality in producing ornaments, has led to increased beach erosion reducing fishing capabilities, severely impacting the subsistence lifestyle of the local population [23]. The activities of so-called ‘sand mafias’ have increased due to the lack of monitoring of sand extraction. Deaths of officials, protesting locals and competing ‘sand mafia’ gang members have been reported in India; however, criminal convictions are rare [24,25]. In Morocco ‘sand mafias’ have been reported to account for 50% of sand extracted [1].

2.2.2. Environmental

Increased demand for sand has driven illegal mining, leading to increased environmental degradation such as river pollution, accelerated beach erosion and lowering of water tables [1]. Environmental impacts are varied and plentiful as Koehnken et al. [26] who categorised at least 107 impacts from a literature review of 505 international studies, discuss. Extraction rates of sand were double the discharge rate of aggregates from rivers in 2014 [14], creating a damaging imbalance within the global natural sediment system. High rates of extraction can lead to the size reduction of sand grains within rivers, which are less attractive for concrete production [20], negatively impacting natural sediment flows. Unregulated dredging of sand damages marine beds releasing nutrients from disturbed sediments that can induce eutrophication [27]. At lake Hongze in China, mining of sand has led to a 99.5% reduction in the biomass of benthic fauna, severely disrupting the local ecosystem [27]. Sand mining also negatively impacts carbon sequestration of soils near rivers. Destruction of surface soils exposes soil organics carbon at the surface, contributing to rising levels of carbon dioxide in the atmosphere. Mining of sand from the Lijiang River in China released 934 t of carbon, equivalent to 3420 t CO_2 [28].

2.2.3. Political

Many nations do not adequately monitor sand extraction or trade, as mining is illegal or involves small companies that do not report figures [2]. The sector is predominantly informal with few significant commercial supply chains, as sand is mostly mined for local use by artisanal miners [1]. At the local scale, conflicts between artisanal miners have become more common [12]. At the international scale, increased taxes and trade bans on sand to protect national assets such as beaches for tourism and storm protection, have led to increased political tensions between nations [12,29].

2.3. Potential Solutions

2.3.1. Technical Solutions

Recycling and substitution are being used to decrease the extraction of sand and its impacts by reducing sand consumption. The EU categorises recycling and substitution as risk reducing filters for material supply risk [30]. Many materials are being assessed as substitutes for sand in construction materials, such as crushed granite, barite powder and quarry dust [5]. These substitutes offer benefits over sand-based concrete: crushed granite improves chemical resistance to chlorides and sulphates [31], and crushed stone improves compressive strength by 10% [32]. Supply chain risk and manufactured product performance must be considered when choosing a material to sustainably substitute for sand and gravel in the construction industry. Recycling of the 900 Mt of Construction, Demolition and Excavation Waste (CDEW) produced annually into manufactured sand via crushing will reduce demand for primary aggregates [32]. Currently, only one-third of CDEW is recycled [33] due to the high cost and energy consumption associated with the crushing process [34], variability of supply, lack of recycling infrastructure and underdeveloped markets for recycled products [6]. Japan achieves a 95% recycling rate of these materials, but such high rates are rare [2].

2.3.2. Transition to a Circular Economy

A circular economy is an economic system where materials and manufactured products are continuously reprocessed, to extract maximum value from them [35]. Circular flows of materials can improve resource efficiency increasing sustainable material usage. Environmental impacts can vary; the recycling of glass to glass sand can increase the negative environmental impact of the material [36]. Growth in circularity of a nation's economy is typically modest; an increase from 2.7% to 5.8% for 14 key materials occurred in China from 1995 to 2015 [37].

A transition to a circular economy for natural aggregates will become more favourable as CDEW generation increases in more developed nations, due to ageing infrastructure and tougher constraints on the primary extraction of natural aggregates [6]. Circular economy ideals are becoming more widely recognised by companies throughout the construction value chain [38] and international groups within their economic policies [39,40]. Discussions between the Nordic Council of Ministers and major construction stakeholders in 2018 highlighted five main barriers to reaching a circular construction industry: lack of value chain cooperation, lack of economy of scale, lack of quality assurance, hazardous substances within CDEW and the focus on weight and not the material of CDEW [41]. Technical issues, such as recycling efficiency, and industrial planning issues, designing values chains to be circular, must be overcome for a circular aggregates industry to be realised [35].

2.3.3. Governance and Monitoring

The United Nations Environment Program (UNEP) published a report on sand and sustainability in 2019, focused on regulation, monitoring, and stronger governance as solutions to the issues surrounding the consumption and trade of sand [1]. Previous studies have used optical and Synthetic Aperture Radar (SAR) satellite images to monitor and detect illegal sand mining. A project carried out on Luzon island, the Philippines, revealed 9 illegal mining sites which contributed to measured subsidence of 5.7–15 cm/yr from 2007 to 2011 [42].

Many nations have well developed legal frameworks and policies for the industrial mining of sand, such as mining licences, but lack legal frameworks for the artisanal mining of sand [43]. In less economically developed nations these systems are mostly inefficient [44]. Vietnam, for example, has strict government policies including a Deposit of Environmental Reclamation that is paid to secure restoration after the closure of a mine [44] but fails to fulfil them due to a lack of enforcement. Taxes on the extraction and trade of sand and gravel, such as the £2/t aggregate levy in the UK [45] can promote recycling, but globally, this is difficult to implement due to the lack of monitoring of the mining and trade of sand. Strong governance regarding mining should follow core principles such as clearly defined policies, transparency, engagement with all stakeholders and strong administration to enforce the policies [44].

3. Structure and Format of the Database

3.1. Hierarchical System

As stated above and motivated by the previous section, a database for sand and gravel is required. A hierarchical system of parent and child processes in a tree-like data structure is used to classify material stocks and flows data. Each process represents an individual activity in a life cycle of a material with a stock. An example is mining, the initial stage of a material life cycle for many resources extracted from the environment for primary use. Material flows are allowed to occur between all processes. A process can either be transformative, turning an input into an output, or distributive, turning an output into an input. The data are disaggregated from the whole system into parent and child processes, each child process is more specific than its parent process. Therefore, each parent process has a non-zero even number of child processes, as every transformative process has a corresponding distributive process. UMIS [46] is implemented to provide a consistent and comprehensive way of labelling the hierarchical system. This allows for greater ease of manipulation of data within the database. Following UMIS nomenclature, each process is given an a.b.c.d.e label: 'a' is the reference material, 'b' is the root process, 'c' is the parent process, 'd' is the process type and 'e' is the child process. Semi-colons ';' are used for disaggregating parent processes, underscores '_' to represent flows between two processes, and apostrophes ''' for divergent parent process disaggregation. Figure 1 shows how this notation works. Each data value is given a process or flow label and a unique ID number to allow data values from different data sources for the same process or flow to be inserted into the database.

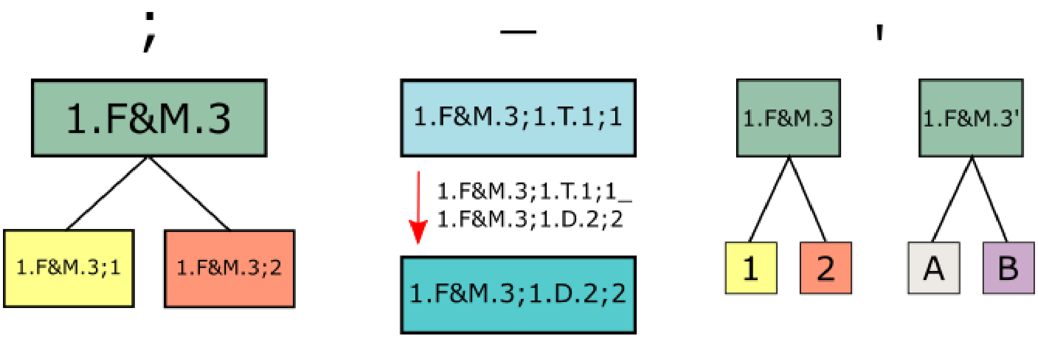

Figure 1. Graphical representation of common UMIS notation. The image on the left shows the semi-colon notation. This is used to disaggregate a parent process into a child process. The central image shows the use of the underscore notation. This is used to show a flow of material between two processes. The image on the right shows the use of the apostrophe notation, used for divergent disaggregation. Divergent disaggregation occurs when a parent process can be disaggregated in more than one way based on the different characteristics of the child processes. This shows how a parent process can be copied (' is the copied version) to allow for divergent disaggregation of parent processes. This prevents double counting of data if the data are disaggregated in more than one way (e.g., 1/2 and A/B shown in the figure).

3.2. Database Format: YSTAFDB

The YSTAFDB stores material cycle, criticality, and recycling data for 62 reference materials; individual materials, such as elements, compounds or composites for which material stocks and flows data are collected [47]. Each data entry in the YSTAFDB has a reference material, time frame and space. The YSTAFDB has 15 core tables that are softly related to each other. These tables include processes, flows, cross-boundary flows, and citations, providing a common system for storing all data and metadata collected. Each reference material has its own hierarchy table to present how the data for that reference material is disaggregated. Sand and gravel data, classified using the novel hierarchical system, are input into data tables with the same format as the YSTAFDB, allowing the sand and gravel database to be compatible with the YSTAFDB format generally.

3.3. Classification System

Figure 2 shows the classification structure of the sand and gravel data in the database, labelled using the UMIS [46] and compiled into data tables from the YSTAFDB [47]. The whole system is defined by three boundaries: the reference material, time frame, and space. The reference material is the material of interest for which data is collected. The reference time frame and space are determined by the time ranges and spatial regions corresponding to the properties of the data collected. International trade is classed as cross boundary flows between different system boundaries (here defined as nations).

Our classification system for disaggregation of sand and gravel data features elements from reports and data sets on stocks and flows for sand and gravel and commodity hierarchies made by the EU, the USA, and UN (NACE-Nomenclature des Activités Économiques dans la Communauté Européenne, NAIC-North American Industry Classification, HS-Harmonized Commodity Description and Coding Systems). The common classification system provides a comprehensive repository for sand and gravel data from different data sources to be stored, accessed and analysed .

Five root processes are often used in Material Flow Analysis (MFA) studies of material cycles: extraction, production, fabrication and manufacturing, use, and end of life. These processes, represent some of the most important processes within the material life cycle of sand and gravel concerning the social, environmental, and political issues outlined in Section 2.

3.3.1. Extraction

The *extraction* root process contains data on the source of sand mined. It is disaggregated into *terrestrial* and *marine and fluvial dredged* parent processes, as government data sources commonly provide data in this format. Terrestrial sand mining accounts for sand and gravel mined from the land from glacial deposits and river flood plains in open pits [48] or beaches and riverbanks in lesser developed nations. The *marine and fluvial dredged* parent process accounts for sand and gravel that is gathered from the base of a marine or fluvial environment, such as a river or continental shelf [7]. The parent process is disaggregated into four child processes, as shown in Figure 2 box A, using the same disaggregation used by the Crown Estate [49] as the four child processes account for the main marine and fluvial sources of sand and gravel. These child processes are disaggregated based on their use, either directly without landing for *beach nourishment*, *reclamation fill* or *river/miscellaneous* use such as forming levees, or landed and sorted for other use such as *primary aggregates* for construction.

3.3.2. Production

The *production* root process contains data on the types of sand, based on sorting after mining. This root process is mostly used for trade data as it accounts for the movement of sand from the time it is mined to when it is manufactured into a product. Divergent disaggregation is common as different data sources disaggregate trade data differently. The UMIS apostrophe notation is used, to prevent possible double counting of data as it is unknown whether trade data from different sources are mutually exclusive or consistent unless stated. The disaggregation of data, shown in Figure 2 box B, took inspiration from trade data sources such as Chatham House [50], Eurostat [51] and the UN HS, disaggregating the *production* root process by type, size and quality of sand and gravel. The child processes of the *production* root process, in Figure 2, are defined by Chatham House trade data [50].

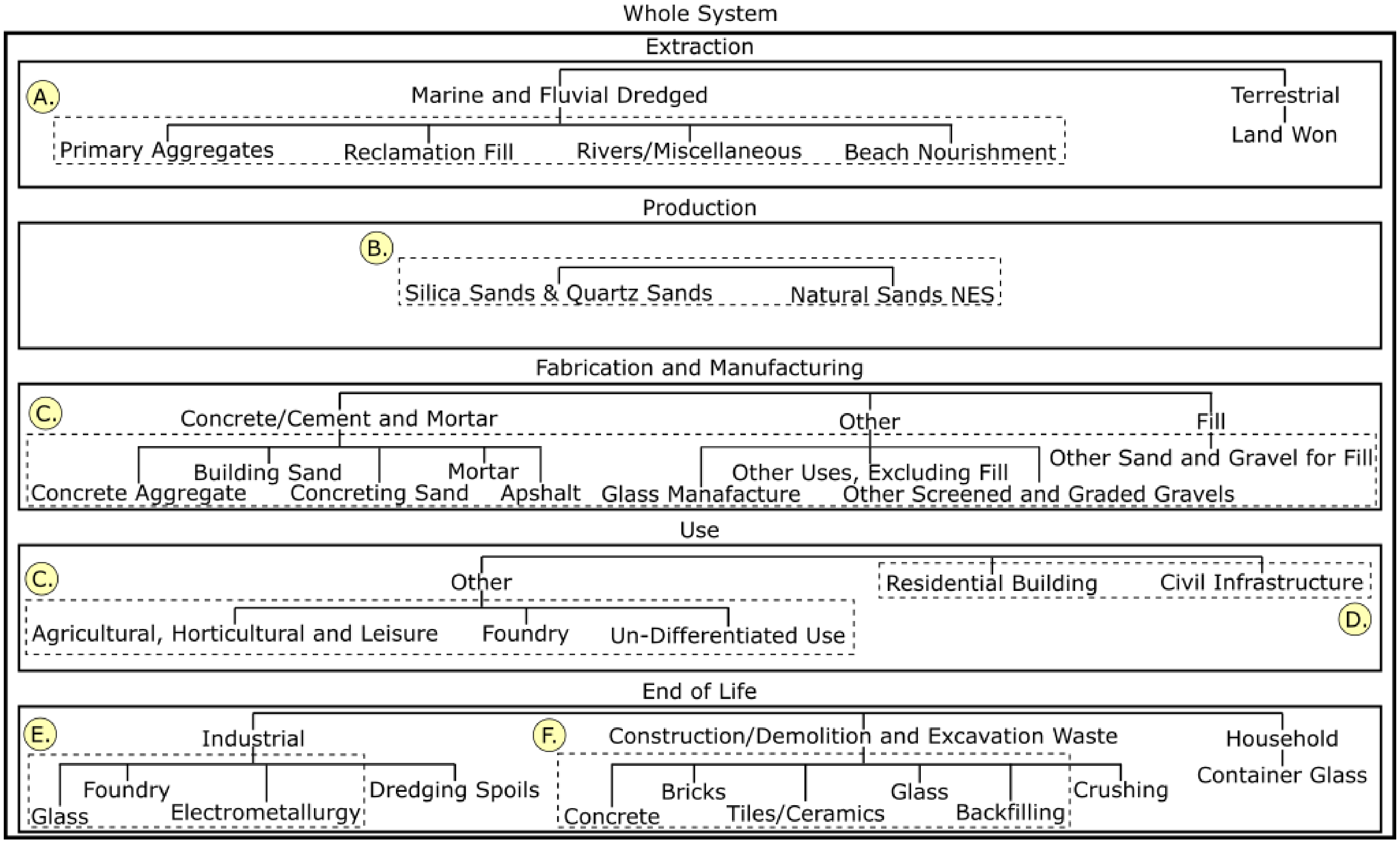

Figure 2. Classification structure of data in the sand and gravel database. The outer black outlined box represents the whole system. Each black outlined box within the whole system represents a root process of the data. Within each root process box is a tree diagram showing the disaggregation of processes within the root process. The lettered dashed boxes highlight parts of the data that use the same system of disaggregation as other reports, data sets and commodity hierarchies. NES in Natural Sands NES stands for Not Elsewhere Specified.

3.3.3. Fabrication and Manufacturing

The *fabrication and manufacturing* root process contains data on products made from sand. Fabrication and manufacturing are in the same root process as many products of sand such as mortar are produced in situ. Disaggregation of the *fabrication and manufacturing* root process is predominantly based on construction, as 75% of sand and gravel is used in concrete for construction purposes [2]. The parent process of *concrete/cement and mortar* and *fill* represent sand and gravel in the construction industry. The *concrete/cement and mortar* parent process is disaggregated into five child processes. The five child processes are based on the three main uses of sand and gravel in construction seen in the NACE, NAIC and UN HS, which are *asphalt*, *concrete*, and *mortar*. In our database sand and gravel used for concrete is separated using size and coarseness into *concreting sand*, *building sand* and *concrete aggregate*. The C boxes in Figure 2 represent where the same disaggregation as the mineral surveys from the Office for National Statistics (ONS, [52]) are used. The *other* parent process is used for processes not related to construction. An 'other' parent process is not seen in other classification systems, as the focus of other classification systems is on the product or use and not the material as in this database. Therefore, the child processes within the *other* parent process are wide ranging. These child processes contribute a very small amount to the *fabrication and manufacturing* root process compared to construction related processes.

3.3.4. Use

The *use* root process contains data on the sectors sand is used in. The parent process *residential building* and *civil infrastructure*, shown in Figure 2 box D, took inspiration from the NAIC commodity hierarchy and represent sand and gravel in the construction industry. They are included despite data allowing further disaggregation into child processes, used in the NAIC commodity hierarchy, not being directly available, as they are known to contain large amounts of sand. An 'other' parent process is included for the same reason as the *fabrication and manufacturing* root process.

3.3.5. End of Life

The *end of life* root process contains data on recycling, reuse, refurbishment, and waste [53] of sand and gravel. The *end of life* root process has been included, despite data not being directly available, as large amounts of sand and gravel are known to go to waste or be recycled. A bottom up approach [54] would be required to add waste and recycling data to the database, as waste products commonly contain crushed rock, cement, and other materials as well as sand and gravel. A bottom up approach requires estimates of the percentage of sand and gravel in recycled and waste items, which was outside the scope of this paper.

The *end of life* root process is disaggregated into three parent processes based on the source of waste for sand and gravel. The *CDEW*, *household* and *industrial* parent processes use the same classification system as used for waste by the UK government [55]. The *CDEW* parent process disaggregation, shown in Figure 2 box F, took inspiration from Mineral Products Association reports on CDEW and aggregate recycling [30,33]. An additional *crushing* process, in Figure 2, is included to account for manufactured sand and gravel from crushed CDEW that the Mineral Products Association reports did not include. The *industrial* parent process disaggregation took inspiration from a report on recycling rates in Europe by the Industrial Minerals Association (IMA) [56]. Figure 2 box E shows where the same disaggregation was used in the database as the IMA report. The IMA includes a construction and soil process, however, this has not been included since the classification system used for the database accounts for construction waste in the *CDEW* parent process. A *dredging spoils* child process is included in the *industrial* parent process. Dredging spoils is a waste product from the extraction of sand and gravel via marine dredging. This was not included in the IMA report as the IMA report focused on the recycling of silica from products and not from waste.

4. Populating and Using the Database: An Example for the UK

Data were collected and analysed for the UK to show how the database can be built and utilised (database provided in Supplementary Material). UK data on sand extraction, trade and use was used as it is relatively accessible, comprehensive, and reliable. Monitoring of sand extraction, trade and use is made simple due to only a small number of companies accounting for 80% of sand extraction in the UK and reliable due to strict enforcement of annual data reporting by the UK government [1]. Collection of data is challenging due to variable definitions used in the literature, constant amendments and updates of the data sources, contradicting values, and lack of information about data uncertainty.

4.1. UK System

The database for material stocks and flows data for sand and gravel, provided in the Supplementary Material, contains data for the UK from 1955 to 2021 and extraction and trade data for all nations from 2000 to 2019. The majority of extraction and use data came are provided by the UK government and Office for National Statistics (ONS, [52]). Trade and extraction data for other nations came from EuroStat [51], Chatham House [50] and the European Aggregate Association (UEPG, [57]). References for all data sources are provided in the Supplementary Materials. Data for marine and fluvial dredged aggregates were sourced from the Crown Estate [49]; a UK government owned company.

Recycling and waste data for sand and gravel in the UK could not be found. Recycling and waste data for sand and gravel are rarely reported as they are bound constituents within products, such as concrete and glass, whose amounts of sand and gravel can vary considerably due to different desired characteristics of final products and variable manufacturer specifications. Data for the amount of recycled aggregates used in construction is available. In 2018, 25% of aggregates used in construction were from recycled CDEW [30]. A report by the Waste and Resources Action Program in 2008 stated that 43.5 Mt of recycled CDEW was used as aggregates [58]. A bottom up approach would be required to estimate the amount of sand and gravel in recycled aggregates, which is beyond the scope of this paper. The main analysis of the UK data, therefore, focused on the security of supply and not on identifying potential illicit activity, as it was not possible to differentiate between illicit activity and lack of data at this point, such as missing waste and recycling data.

4.2. UK Extraction

Figure 3 shows a time series of sand and gravel extraction in the UK. Figure 3 shows sand and gravel extraction dropping substantially, by 29.7%, between the years 2007–2010, due to the global financial crisis of 2007–2008 which led to a decrease in construction, reducing demand and extraction for sand and gravel. Since 2012 sand and gravel extraction has steadily increased but remains below extraction rates from the 1990s and early 2000s. This type of analysis can be used to determine future trends of extraction, which is important if the UK wants to mitigate potential future supply chain issues for sand and gravel. Guaranteeing supplies of sand and gravel is crucial for future and ongoing large scale critical infrastructure projects in the UK. The High Speed 2 railway line, vital for transportation within the UK, requires 6,768,600 tonnes of concrete, an equivalent of 2,100,000 tonnes of sand and 3,150,000 tonnes of gravel assuming a 31% weight percentage of sand and 46.5% weight percentage of gravel in concrete [34], for its second phase [59]. Continual annual decreases in the extraction of sand could make the UK more reliant on imports of sand and gravel over the long term, leading to increasing supply chain risks leading to possible delays in large scale infrastructure projects. A wide range of strategies and technologies could be employed to mitigate these risks. Strategies could include increasing the annual extraction of sand by dredging [60], as only 8.27% of licensed seabed in the UK is currently dredged [61], increasing the recycling rate of sand and gravel excavation waste [62] from its current value of 57% (recycling rate of CDEW is currently high at 90%) [33], or using new technologies outlined in Section 2.3.1. A holistic approach, considering social and environmental impacts, must be used when reviewing these and other strategies to prevent new issues arising linked to the stocks and flows of sand and gravel in the UK [63].

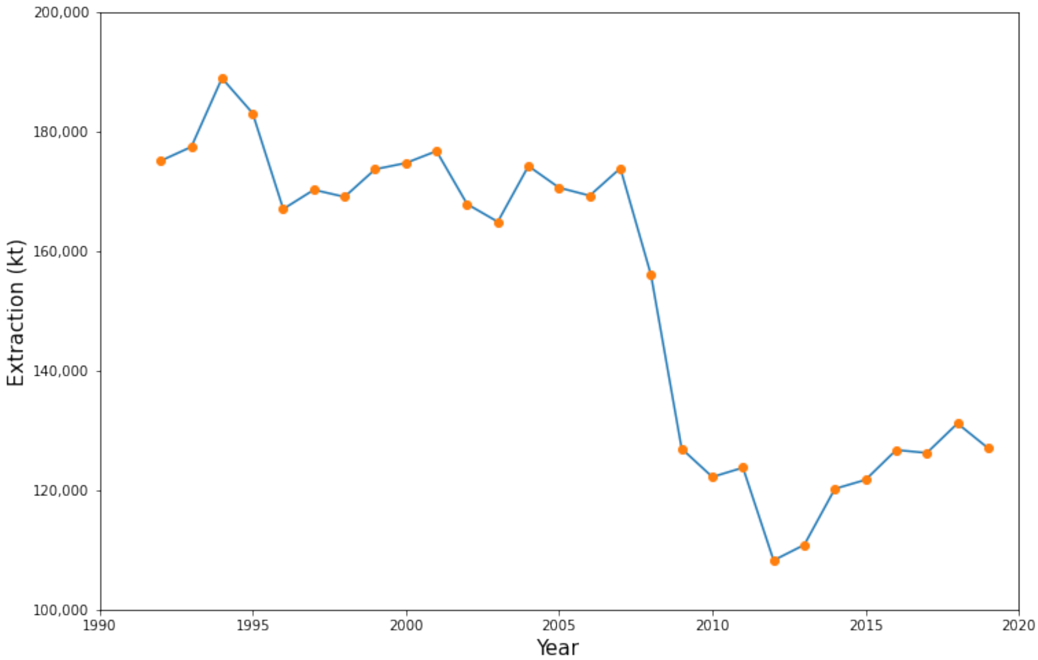

Figure 3. Time series of the mass of sand and gravel extracted from the UK from 1992 to 2019.

4.3. Input-Output Analysis for 2014 UK Data

Inputs and outputs for sand and gravel data collected for the UK in 2014 are shown in Figure 4, as a Sankey diagram. The year 2014 was chosen despite many of the processes in Figure 2 not being represented in Figure 4 as it had the most comprehensive set of data for any of the years data was collected.

Figure 4 displays a mass imbalance: the outputs are 52.7% less than the inputs for the UK [54]. The mass deficit observed in Figure 4 could be due to the absence of stocks and changes in stocks data in the analysis, as mass can be conserved if the deficit between all inputs and outputs is equal to the change in stock of the whole system, or other missing data. One should note that the data set built here remains incomplete as some uses of sand are still not quantified and the magnitude of recycling stocks and flows still needs to be estimated. In the UK, the difference observed in Figure 4 is unlikely to stem from illegal mining, given the operating and sustainability standards in the UK aggregate industry [1,64].

The mass balance deficit of 52.7% is considerably larger than the 30% recycling rate of aggregates in the UK [64], therefore, the mass balance deficit cannot be fully accounted for by end of life recycling flows of aggregates. The difference between the mass balance deficit and recycling rate of aggregates is likely to be larger than noted as recycled aggregates contain materials other than sand and gravel, and sand and gravel have additional uses other than as aggregates for construction.

Uncertainties in the data have not been accounted for but these uncertainties are likely to be at least within the order of 500 tonnes, inferring from the fact that certain reports round data values to the nearest 1000 tonnes. The UK exports sand to 99 nations while only importing sand from 54 nations. Assuming a maximum absolute uncertainty of 500 tonnes per nation per flow, the absolute maximum uncertainty for trade is 76.5 kt, which accounts for only 0.12% of the mass deficit between the input and outputs. Thus, the mass balance deficit is likely predominantly due to the data set being incomplete as data regarding all the stocks, flows and changes in stock of sand and gravel are seemingly not reported (and are therefore still missing from the database).

Figure 4 shows imports being relatively small compared to indigenous extraction for the UK. Only 4.6% of the inputs are accounted for by imports. This shows the UK as secure in its supply of sand and gravel as the UK does not rely on large quantities of imports from other nations for its sand and gravel supply. The data available suggest that if there were future trade restrictions (e.g., COVID-19 or Brexit), the UK would be able to domestically extract enough sand and gravel, as well as other aggregates, for construction purposes.

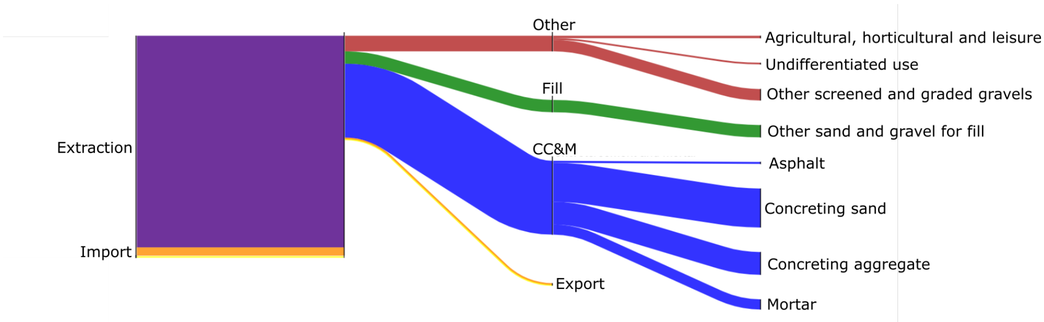

Figure 4. Sankey diagram showing the inputs and outputs of sand and gravel for the UK in 2014. Orange and yellow flows are trade data from Chatham House: orange corresponds to silica sands & quartz sands, and yellow to natural sands NES (not elsewhere specified). The acronym CC&M stands for concrete/cement and mortar. The year 2014 was chosen as it had the most complete data set. The software Floweaver [65] was used to generate the figure.

4.4. UK Trade

Figure 5 shows the main nations the UK trades sand with. Analysis of trade data is important, despite imports only accounting for 4.6% of the inputs of sand into the UK. As shown in Figure 4, import flows of sand and gravel to the UK (5.85 Mt) are comparable in magnitude to the annual use of sand and gravel for asphalt (1.17 Mt) and mortar (5.79 Mt) critical for construction in the UK.

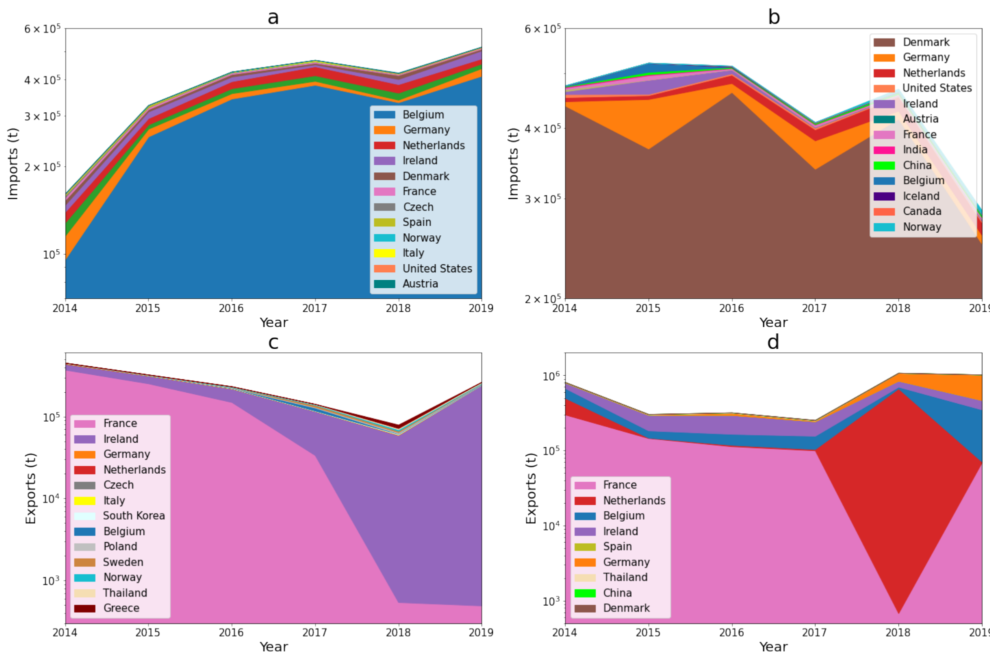

Figure 5. Composite line graphs to show the imports and exports of the two types of sand for the UK. Data provided are from Chatham House [50]. (**a**) imports of silica sands & quartz sands; (**b**) imports of natural sands NES (not elsewhere specified); (**c**) exports of silica sands & quartz sands; (**d**) exports of natural sands NES. Only nations where the import or export was greater than 1 kt have been shown.

All four graphs in Figure 5 show UK sand trade as being highly regional as most trade occurs with nearby European nations including Belgium, Denmark, Germany, France and the Netherlands. There are only small trade flows with the United States, Canada, Australia, India, China, South Korea, and Thailand. Dips in trade have occurred, such as during 2019 in Figure 5b and during 2018 in Figure 5c followed by a rebound in 2019, illustrating relative volatility in the sand trade in the UK. The UK mainly imports and exports sand with 10 nations or less. In 2019, 99.5% of trade in both sand types occurred with only 10 nations. The UK is likely over-reliant on some nations for sand. The dominance of individual nations can be seen in Figure 5, as over 50% of trade in both sand types for the UK occurred with one nation during 2019, with Ireland accounting for 91.2% of all silica sands and quartz sands exports. Exports to France show sudden drops for silica sands & quartz sands in 2017 (77.5%) and natural sands NES (not elsewhere specified) in 2018 (99.3%) followed by an increase in total exports in either the same or following year, from nearby European nations. This shows that the UK may be able to mitigate the risks of sudden changes in export patterns, by exporting more to other nations.

5. Discussion

5.1. Consequences for the UK

Analysis of data for the UK shows how the database and its data structure presented here can be used to compile data for the stocks and flows of sand and gravel from different sources with variable classification systems. Data collected for the UK provide insights into the volatility and sensitivity of sand and gravel supply in the UK despite the data sets being incomplete. These insights can be used to consider the impact of certain scenarios on the UK supply chain of sand and gravel, including regional disruptions, such as sudden changes in trade patterns with nearby Western European neighbours due to Brexit, or global disruptions, such as the COVID-19 pandemic or the global banking crisis of 2007–2008.

The data show the UK to be currently self-reliant in its supply of sand and gravel as only 4.6% of sand and gravel does not come from indigenous sources. Sudden changes in the trade of sand and gravel for the UK would not lead to national shortages. To guarantee long term supply chain security for sand and gravel the UK must mitigate current potential issues. Replenishment rates of sand and gravel deposits in the UK were only 63% from the year 2009 to 2018, therefore, for every 100 t of sand and gravel mined in the UK, only 63 t were replaced by new planning permissions for mines [66]. Sales of sand and gravel for Great Britain increased by 7.57% from 2020 to 2021 [67] mostly due to increased demand in construction after stagnation in the industry during 2020 due to the COVID-19 pandemic. Decreasing replenishment rates and increasing sales of sand and gravel coupled with continually low indigenous extraction rates since 2007, as seen in Figure 3, could lead to greater possible reliance on imports of sand and gravel for the UK in the future. In terms of magnitude, current trade data show that if sand and gravel imports from Belgium and Denmark (the top two sources of imports for the UK, Figure 5) were halved, the UK could have a deficit in the supply of sand and gravel equal in magnitude to the annual use of asphalt. The UK government should investigate these trends and employ national mitigation strategies and new technologies to reduce primary resource demand to prevent any potential future risks in the supply chain of sand and gravel.

5.2. Data Availability and Collection

The depth of analysis that can be completed using the database is a function of the breadth and quality of the data available. If data could be collected for the entire material life cycle of sand and gravel, for a particular nation or region, a comprehensive MFA and/or Life Cycle Assessment (LCA) study could be complete, adding further insight to the analyses of the data collected. Unfortunately, even in the relatively well-documented case of the UK, data could only be found for 68% of child processes, with the end-of-life root process devoid of any data at all. The dominance of cross boundary flows (trade data) accounting for 98.5% of all data values collected and the lack of data for key parts of the sand and gravel material life cycle imposes serious limits on the types of analyses that can be currently pursued, but the data gaps are now at least known.

Measures of uncertainty are also generally lacking. Only ONS and UK government sources provided limited measures of uncertainty with data values being stated as being rounded to the nearest one thousand tonnes. Absence of quantified uncertainties limits the reliability of the analyses made from available data. Contradictory data values were common across the various data sources considered for the UK case study. In some cases, differences up to 250% exist between reported values that aim to characterise the same quantities. Large contradictions in data values reported, differences in definitions and routine revisions and updates of data sources can all introduce strong biases in interpretation. The database presented here can help mitigate these data collection problems, as the proposed classification system removes the ambiguity in definitions, and can be updated easily.

5.3. Future Opportunities

The sand and gravel database presented here provides a common classification system for sand and gravel data to be collected from multiple data sources for further analysis. Building on this, data processing techniques such as Bayesian inference [68] or bottom up MFA procedures could be used to fill in the data gaps where data are missing and account for uncertainties in a consistent manner. Construction and assembly of consistent databases, such as the sand and gravel database presented, can aid the effective implementation of governmental policies and framework, such as circular economy ideals, to increase sustainability within the material life cycle of sand and grave. The ability of the database and its data structure to be utilised to inform and guide policymakers is not limited by data availability unlike its ability to model material flows of sand and gravel for a given region. Nations with sparse and inconsistent data for the extraction, trade and use of sand and gravel, due to the informality of the sector or lower levels of monitoring due to lesser technology penetration or lesser enforced policies or frameworks, are still able to benefit from the data structure. The data structure can highlight data gaps for a nation, allowing more targeted policies to be effectively implemented and enforced to collect more and better quality data.

Suitable sand and gravel data could be used to detect and monitor illegal sand mining and its subsequent trade between nations where it is reported or suspected to exist. Discrepancies in the reporting of trade data from different nations and irreconcilable gaps in the material life cycle could be used to identify areas of possible illicit activity. Singapore is an example of a nation in which illegal trade in sand is allegedly conducted [29,69]. Over the last 20 years, Singapore has imported 517 Mt of sand from neighbouring nations such as Indonesia and Cambodia for land reclamation projects to increase its land area by 23% [1]. Since March 2009, companies importing sand to Singapore have not been required to provide environmental assessments or export permits, allowing illegally mined sand from neighbouring nations to be imported into Singapore [69]. This has led to environmental degradation in source nations, with evidence suggesting that 24 Indonesian islands have been lost due to illegal sand mining from 2005 to 2014 [14]. The sand and gravel database presented here provides a broad understanding of the mining and trade of sand for a nation, such as that given above for Singapore. Systematic collection of data, analyses of these data and possibly additional checks using Earth observations can be made to better constrain the role of illicit activities or missing data in the material life cycle of sand and gravel for a given region.

6. Conclusions

A database for the stocks and flows of sand and gravel was created, using the UMIS to develop the hierarchical system and the YSTAFDB to define the data tables. The database uses a common classification system for all stocks and flows of these materials, that can readily accommodate additional data as they become available. The common classification system facilitates greater convergence in the available data for sand and gravel, allowing more succinct analyses to be made, assisting policymakers in making more informed decisions on the sustainable extraction, trade and use of sand and gravel. Improved reporting of material stocks and flows data for sand and gravel in the future should become a priority, and become systematic, as this will greatly enhance the value of the database presented and improve informed management of sand and gravel sourcing and use.

A case study is presented for the UK. Analysis of UK data identifies informative trends, despite the data not being comprehensive. Current data shows the UK as self-reliant in its sourcing of sand and gravel. Continual low indigenous extraction rates since 2007, low resource replenishment rates and increasing sales of sand and gravel could lead to long term risks in the supply chain of sand and gravel for the UK, such as an increased reliance on imports. Employment of new national strategies and technologies to decrease primary resource demand could be used to mitigate these potential issues.

Incomplete data such as data for the use of sand in residential buildings and civil infrastructure and recycling and waste of sand constitutes the main source of uncertainty in the database currently. Further analysis using bottom up MFA procedures can be used to fill in these gaps within material cycles for sand and gravel. MFA models could then be used to monitor supply chains in nations where illegal sand mining is a major concern, and lead to a more complete understanding of circular economy ideals for sand and gravel.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/resources11080072/s1, Spreadsheets S1–S10. Spreadsheet S1: citations. Spreadsheet S2: cross_boundary_flows. Spreadsheet S3: cross_boundary_flow_citations. Spreadsheet S4: flows. Spreadsheet S5: flows_citations. Spreadsheet S6: hierarchy_table. Spreadsheet S7: processes. Spreadsheet S8: processes_citations. Spreadsheet S9: publications. Spreadsheet S10: trade_codes.

Author Contributions: Conceptualization, J.D.M., R.J.M., Y.P. and P.R.B.-P.; methodology, J.D.M., R.J.M. and P.R.B.-P.; formal analysis, J.D.M.; investigation, J.D.M.; data curation, J.D.M.; writing–original draft preparation, J.D.M.; writing–review and editing, J.D.M., R.J.M., Y.P. and P.R.B.-P.; visualization, J.D.M.; supervision, R.J.M., Y.P. and P.R.B.-P.; project administration, P.R.B.-P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used in this article can be found in the Supplementary Materials.

Acknowledgments: We are grateful to Zhenxia Shen for their help checking the database and Ugo Legendre for their valuable comments.

Conflicts of Interest: The authors declare no conflict of interest

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