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Research paper

Material Stock Analysis for Implementing Circular Economic Concepts in Mongolia's Construction and Transportation Sectors

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Abstract

This study quantifies the material stock and flow in Mongolia's construction and transportation sectors. In the last few years, a rapid development in Mongolia's construction and transportation industries has led to large amounts of construction waste. Most raw materials extracted are accumulated in building infrastructure and other durable goods. This study used the bottom-up approach to estimate the material stock (MS) of Mongolia's transportation and construction industries. The analysis shows that in 2020, Mongolia accumulated about 180.7 Mt of material stock (MS) with a potential of 26.6 Mt (14.7%) of waste from the transportation and construction sectors in the future. The study also highlights materials' distribution and intensities across each sector and successfully establishes a material stock database for Mongolia's transportation and construction sectors. From the results, it can be deduced that MSFA studies will assist policymakers in forecasting future demand for materials and estimating the environmental impact, which can aid in developing relevant policies on reducing the negative environmental impacts and implementing circular economy concepts.

Keywords: Material Stock · CDW · Circular Economy · Construction Material · End-of-Life Vehicle · Mongolia

1. INTRODUCTION

Every year, a significant proportion of the global material stock is made of newly extracted materials. These new materials are added to the economy by new building construction, infrastructure development, or other durable goods like vehicles and household appliances. In contrast, outdated materials are removed from the existing stock through the demolition of buildings and disposal processes. (Union., 2018). Among these newly added stocks, the construction and transportation sectors form a significant proportion of the total materials (Tanikawa et al., 2015), (Hashimoto et al., 2007), (Tanikawa, Hashimoto, 2009). In Mongolia, the rapid development of the construction and transportation sectors resulting from rapid population growth and urbanisation (UNEP, 2017) has resulted in waste management and disposal issues. The current development trends show an increasing demand for raw materials for new construction and a high rate of construction and demolition waste (CDW) due to the ageing infrastructure and short-lived buildings being replaced by modern structures. According to a report by the Mongolian government (2017/2018), 70% of the waste originates from urban areas (Enkhbat, A., et al., 2019) and is usually sent to landfills, where CDW accounts for about 20-30% of the waste.

In the last five years, several regulations on waste reduction have been introduced by the Mongolian government, which covers waste streams, including CDW, electronic waste, medical, and household waste. The Mongolian government mainly focuses on solid municipal waste from households, commercial institutions, and non-processed industrial sources. However, waste from constructing and demolishing buildings and infrastructures has not been

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included in the waste management processes. Although Mongolia has implemented a "National Waste Management Plan (2017-2030)", one of the shortcomings of the initiative is that there were no established waste collection and disposal centres for CDW and electronic waste. The unavailability of appropriate recycling systems for the CDW and end-of-life vehicle (ELV) management in Mongolia has led to the illegal dumping of waste (Tommaso T., Somi L., 2017) before being sent to landfills. Another reason is the lack of reliable data on waste generation and management, which has created gaps between expected plans and the implementation of waste management policies (Tommaso T., Somi L., 2017*)*.

To address the issues around waste generated from the construction and transportation sectors, first, we attempt to quantify Mongolia's material flows and stock to ensure sustainable resource use and promote circular economy initiatives (Haas et al., 2015). There are several approaches to quantifying an economy's material flows and stocks. The first approach utilises the Material Stock and Flow Analysis (MSFA). The MSFA effectively implements sustainable circular economy strategies by identifying the inflow of materials and outflows within the economy, thereby enabling the reuse or recycling of materials (Mohammadiziazi, Bilec, 2022) as secondary raw materials. The quantification of materials within an economy is beneficial to provide information on the nature and intensity of the accumulated material stock, provide information on future demand for natural resources, and highlight the potential for reusing waste materials from buildings and other infrastructures (Krausmann et al., 2017a), (Tanikawa, Hashimoto, 2009), (Tanikawa et al., 2002). Japan, China, and the United States have successfully developed extensive material stock databases using different methods (Fu et al., 2022).

As Mongolia is witnessing rapid growth in material resources needed for building construction and transportation development, it is now vital to investigate the material stock within the society and estimate how much of these materials would potentially end up as Construction and Demolition Waste. The objective of this study is to establish a Material Stock (MS) database for the construction (residential and non-residential) and transportation (roads, railways, and passenger vehicles) sectors of Mongolia. In addition, the study aims to analyse the current lifespan of infrastructures and durable goods and estimate the potential CDWs and ELV waste generated in the future, focusing on circularity strategies for current waste management challenges. Table 1 presents a historical over view of the material flow and stock analyses, including brief information, purpose, methodology, and study targets.

1.1 Material Stock and Flow Analysis and Its Relevance to Circular Economy

Material Stock and Flow Analysis (MSFA) methodologies can be divided into two broad approaches: bottom-up and top-down (Müller, B., 2006), (Martinico-Perez et al., 2017). Tanikawa et al. (2015) added two more categories: demand-driven modelling and remote sensing approaches (Tanikawa et al., 2015). The top-down approach estimates material stock as an aggregate of the annual net addition to stock (NAS) over an extended period based on the differences between inflows and outflows. It uses statistical data and the average lifespan or survival functions in its estimation (Neidhardt et al., 2022). The bottom-up approach, however, categorises the stock based on their functions (residential/non-residential buildings) and material intensities (in ton/m^2). Due to data unavailability and the objective of this research, the bottom-up approach was utilised to estimate the MSFA of Mongolia.

The bottom-up approach is selected due to its suitability for policy decision-making and forecasting future demands. Similarly, from the viewpoint of circular economy, it provides information on the stock location, lifespan, and material trends used in the construction and transportation sectors and then assigns material intensities to each category (Yang et al., 2020a). The materials may vary from a single type, such as steel (Daigo et al., 2007) or composite materials (Krausmann et al., 2017) focused on specific infrastructures such as roadways (Nguyen et al., 2019) and residential buildings (B. Müller, 2006), up to the entire stock of all infrastructures (Tanikawa et al., 2015) and durable materials. As this study is the first country-scale MFSA in Mongolia, establishing an MS database will provide an opportunity to visualise how much materials are present in the economy and how they can be utilised or recycled in the future. In addition, the database would benefit material recovery and utilisation since increasing recycling efficiency can equally serve as a solution to increasing resource efficiency and reducing the intake of materials from the natural resources in Mongolia. This research offers an opportunity to introduce the significance of MSFA studies and their effectiveness in obtaining and promoting circular economy initiatives in Mongolia.

Table 1. Historical Overview Literature Review of the Studies Conducted on Material Stock

SN	Author	Area	Period	Purpose	Methodology	Target
1	Tanikawa, Hashimoto and Moriguchi, 2002	Kitakyushu, Japan	1995-2020	Quantifying existing stock, forecasting, and comparing future input and output flows	Bottom-up stock analysis via GIS	Roadway, construction stock
2	Müller B., 2006	Netherlands	1900-2100	Forecasting and comparing future input and output flows. Study the influence of several parameters on future flows	Dynamic material flow analysis stock driven model	Building stock
3	Hashimoto et al., 2007	Japan	1970-2030	Estimate construction waste and future supply of recycled crushed stones	Bottom-up stock analysis	Construction mineral
4	Daigo et al., 2007	Japan	1980-2000	Estimation of in use stocks and obsolete stocks steel stocks	Dynamic material flow analysis	Steel stocks
5	Tanikawa, Hashimoto, 2009	Wakayama, Japan and Salford, UK.	1849-2004	Forecast and compare future input and output flows of construction materials and clarify the recyclability of materials accumulated.	Bottom-up stock analysis	Buildings, civil infrastructure stock
6	Pauliuk, Müller, 2014	China, Norway	2000-2050	Understanding in use stocks and their dynamics to evaluate the possible environmental advantages of emissions reduction and other sustainable development measures	Dynamic stock models	Transportation, buildings,and industry
7	Krausmann et al., 2017	Global scale	1900-2010	Understand the relationship between economic growth, energy use, and CO2 emissions with stocks, inflows, and outflows within a society.	Dynamic stock flow model	11 types of in use stocks
8	Guo et al., 2019	China	1949-2010	Estimating the accumulated and existing stock	Bottom-up stock analysis via GIS	Building stock
9	Nguyen et al., 2019	Vietnam	2003-2013	Estimate the material stock of the road network and road stock efficiency.	Bottom-up stock analysis	Roadway and Railway

10	Tanikawa et al., 2021	Japan	1990-2015	The proposition of a new framework that binds material stock and flows to societal benefit and natural capital	Bottom-up stock analysis	Buildings, civil infrastructure stock

Despite multiple case studies on Material Stock and Flow Analysis, the available research in developing countries is still limited (Miatto et al., 2017; Nguyen et al., 2019b). In Mongolia, MSFA related studies (Table 2) have considered estimating the building CDW in Ulaanbaatar (UB) using the MFA methods (Tommaso T., Somi L., 2017). Other studies have also applied the bottom-up approach in Mongolia (Ishdorj, 2019); (Enkh-Amgalan, 2021); however, the studies are limited to the capital city, UB, with an emphasis on waste generation, energy use, and increased material consumption.

Table 2 *Related studies conducted in the case of Mongolia*

SN	Author	Scope	Purpose	Methodology	Target
1	James West et al., 2015	National scale	Estimating Material Footprint	Material Flow analysis	Material Flows
2	Tommaso Troiani, Somi Lotfi, 2017	Ulaanbaatar (UB) area	Estimation of CDW in UB city	Material Flow analysis	Building
3	Ishdorj, Narantsetseg, 2019	Area scale	Estimate the material stock of buildings in UB city	Bottom-up stock analysis	Building
4	Ariunnyam, Enkh-Amgalan, 2021	Area scale	Estimate the material stock of buildings in a particular area of UB	Bottom-up stock analysis	Building
5	Bat-Ochir, Tsedevsuren, 2022	Area scale	Impact factors analysis for resource and stock productivity estimation in Mongolia.	Bottom-up stock analysis	Building, Roads, Railway

1.2 Circular economy in the Construction and Transport sectors

Circular Economy (CE) in the construction and transportation sectors focuses on maximising resource efficiency, reducing waste, and extending the life of materials. On a global scale, CE principles are seen as a driver for material use efficiency, and several regions and industries are increasingly integrating these practices to address the environmental impacts of material extraction, use, and disposal. In the construction industry, for example, several strategies include designing buildings for disassembly, using recycled materials as secondary raw materials, and implementing closed-loop systems of operation, where waste materials are reintegrated into production processes (Ghisellini, 2016). Current studies on the relevance of CE in the construction and transportation sectors highlight how adopting these initiatives can reduce the environmental footprint of these industries and offer economic benefits by lowering associated costs of raw material extraction and waste management (Adams, 2017).

In the transportation sector, CE principles help emphasise the need for sustainable design and manufacture of vehicles, the reuse and recycling of vehicle components, and the promotion of alternative transportation modes that reduce reliance on finite resources (Singh, 2018). In Mongolia, the adoption of CE principles in the construction and transportation sectors is still in its preliminary stages. However, the growing awareness of environmental sustainability and the need to manage increasing amounts of construction waste has spurred an interest in circular approaches (Geissdoerfer, et al, 2017, Zorigt, 2020). Emerging studies and regulations suggest that Mongolia can benefit from integrating CE strategies, particularly in urban areas where construction and transportation activities are concentrated. These strategies could help address the challenges of resource scarcity and waste management, leading to a more sustainable and resilient economy (Batbayar, 2019).

2. METHODOLOGY

This study examines the Material Stock of Mongolia's construction and transportation sectors. Given the data availability, the analysis focuses on residential and non-residential buildings, roadways, railway networks, and passenger vehicles within Mongolia (Figure 1). The bottom-up approach was utilised to estimate Mongolia's material stock based on the data availability. This study uses the bottom-up and the input-output approach because it can effectively support policy decision making and assist in estimating future recycling stock and possible demand. Furthermore, this approach provides detailed information on the construction sector's stock, location, lifespan, and material trends.

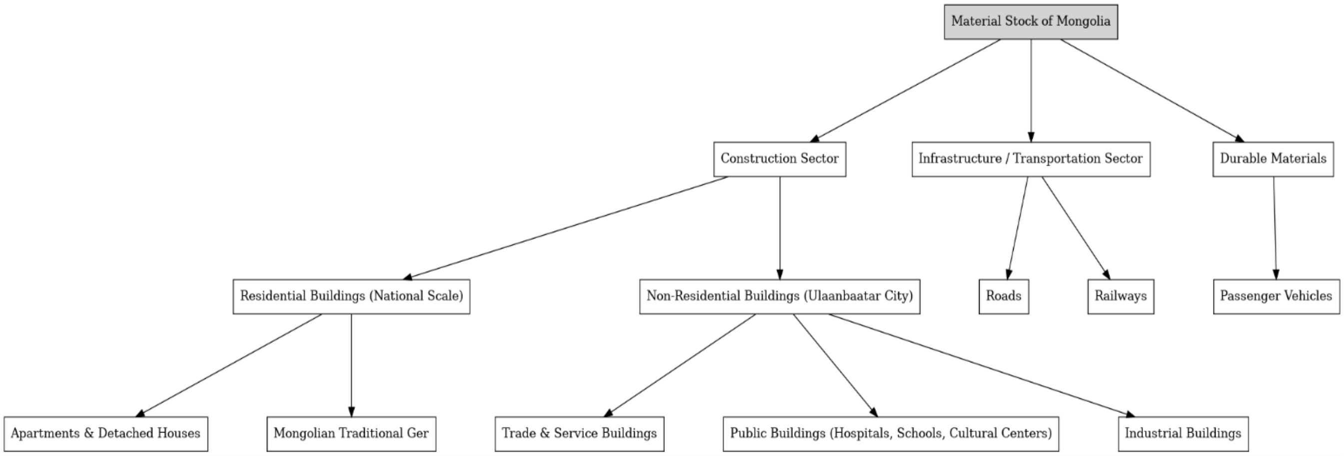

Figure 1. Framework for the Material Stock of Mongolia

2.1 Data source

The statistical data used in the study were extracted from various sources: building information (Mongolia City's Urban Development Agency (MCUD) and UB City's Urban Development Agency, railway, road and passenger vehicles (Ministry of Road and Transportation Development (MRTD)), and National Statistics Office of Mongolia (NSO) and vehicles imports and exports (General Customs Authority of Mongolia (GCAM)), and deregistered passenger vehicles (National Road and Transport Center of Mongolia (NRTC)) shown in Table 3.

Table 3. *Source of the Used Data for the Study*

SN	Description of Data	Period	Data Source	Data processing
1	Material Flow Accounting data, including detailed information on each sub-category of biomass, non-metallic minerals, metallic minerals, fossil energy materials, and others	2005-2020	National Statistics Office, Mongolia	Material Flow Accounting data, including detailed information on each sub-category of biomass, non-metallic minerals, metallic minerals, fossil energy materials, and others
2	Population and Housing Census Data (2020) - including Residential buildings, construction year, material type, and total floor area.	2020		Raw data provided by NSOM were segregated according to age, wall type, and total floor area using SPSS to estimate the MS of residential buildings.

3	Ulaanbaatar's (UB) public, trade, office, hospital, and school buildings include the construction year, material type, and floor area.	2021	UB City’s Urban Development Agency	Raw data were segregated according to age, wall type, and total floor area using SPSS to estimate the MS of residential buildings.
4	Statistical dataset Mongolian roadway network data, including road length, width, and pavement type	2021	Ministry of Road and Transportation Development (MRTD)	Datasets were used to estimate the MS of International, State, and Local roadway network
5	Roadway network of UB Capital city	2019	Capital Road Development Agency	Datasets were used to estimate the MS of the Capital city roadway network
6	Roadway design: Mongolian construction norms and rules (32-01-16)	2022	Ministry of Road and Transportation Development (MRTD)	Based on material composition stated in roadway design construction norms and regulations, the Mongolian Road material intensity data were estimated with the help of the Road Construction Association of Mongolia.
7	Statistical dataset of Mongolian railway network data, including road length, road type	2020		Datasets were used to estimate the MS of the Railway network.
8	Regulations for the railway and road infrastructure budget for Mongolia TZNBD 01-II-03-2020	2022		The material intensity data for the Mongolian railway were estimated based on the material composition.
9	Population and Socio-Economic data	2005-2020	National Statistics Office	The population and socioeconomic data of Mongolia between 2005 and 2020.
10	Number of vehicles	2010-2021	MRTD, General Customs Authority of Mongolia (GCAM)	Annual imported passenger vehicles 2000-2021, Annual registered and inspected vehicles 2010-2021
11	Number of deregistered vehicles	2013-2019	National road and transport center of Mongolia	“Current status of waste generated during vehicle use" (2019)

3. ESTIMATION OF THE MATERIAL STOCK

3.1 Residential Buildings

In Mongolia, residential buildings fall into two main types: buildings (including apartments and detached houses) and Gers (Enkh-Amgalan, 2021). The National Statistics Office of Mongolia's residential building database with information on the building type, use, living conditions, age, construction method and floor area (m²) (Mongolia, 2020), provides detailed information on 521,202 buildings, covering all structures (private dormitories, public buildings for students, employees, military personnel, prisons, orphanages, abandoned houses, and temporary shelters), were used to estimate the material stock of residential buildings. The obtained data was processed and categorised based on building type, age, and wall construction method (Bat-Ochir, 2022). From the extracted data, 58% of apartments were steel-concrete structures, and 42% were brick-concrete. Similarly, the data highlighted that detached houses, including single-family dwellings, are connected to a centralised utility network or have an independent heating and ventilation system and water supply. The data also showed that 2% of detached houses are steel-concrete structures, 34% brick-concrete, 61% wood, 2% wood-brick, and 1% steel structures (Ishdorj, 2019). The other category of residential buildings is the Gers. The Ger is a traditional Mongolian house made of wool and wood. However, this study did not involve estimating the lifespan of Gers. The MS of the 216,841 apartments and detached houses in Mongolia are calculated by (Equation 1).

$$MS_r = FA_{j,\,i,\,t} \times MI_{m,\,i,\,j,\,t} \quad (1)$$

where MS_r Is the Material Stock of the buildings; $FA_{j,\,i,\,t}$ Is the total floor area of the building item$j$ of type i in t year, expressed (m^2); $MI_{m,\,i,\,j,\,t}$ Is the material intensity of material m in building type i, functional type j in t year.

The material intensity database for residential buildings is classified into five different categories based on their construction materials, namely, brick concrete (BC), steel concrete (SC), brick wood (BW), wood (W), and steel (S) (Yang et al., 2020b) (Table 4).

Furthermore, the population and housing census data estimated 304,361 Gers as of 2020 (Mongolia, 2020). A Mongolian ger is a round hut made from wood and wool felt and is famous for its easy assembling and disassembling quality that meets the needs of nomads. The MS of Mongolian Ger was calculated by:

$$MS_g = TN = \times MI_m \quad (2)$$

where MS_g: the MS of the Ger, TN is the total number of Gers. MI_m: the material intensity of five walled Gers with m type of material, expressed as kg/m^2 (Table 5).

Mongolian Gers have varied sizes based on the number of wooden walls (ranges from four to six) Gers. In this study, all the Gers were assumed to be five-walled Ger, and the material intensity of the Ger was calculated based on the Mongolian national standard with MNS 0370:2003. The material density per five-walled Gers was calculated using each structural element (Enkh-Amgalan, 2021).

3.2 Non-Residential Buildings

The data on non-residential buildings are limited since there is no governmental census or previous studies, and only UB city's data is available. UB city's non-residential building database is based on a GIS database, with the details of buildings` location, number of floors, construction year, floor area, and material type. Over 7,000 non-residential buildings were registered and listed in the ArcGIS dataset from UB City's Urban Development Agency (Ts. Amarsanaa et al., 2019). In this study, only 3,014 non-residential building data contained all relevant information. From the data, 37% of non-residential buildings in UB have steel-concrete structures, 60% brick-concrete structures, and 3% steel structures. The MS of non-residential buildings is expressed as,

$$MS_n = FA_{j,i,t} \times MI_{m,\,i,\,t} \quad (3)$$

where MS_n: the MS of the non-residential buildings; $FA_{j,i,t}$ the total floor area of the building type i in year t, expressed (m^2); $MI_{m,i,j,t}$: the material intensity of material m in building type i, in t year.

As the material intensity database for non-residential buildings is currently unavailable, this study utilised the dataset from the material intensity in Chinese urban buildings (Yang et al., 2020b). The reason for selecting the material intensity for China in this study is due to the similarity in building structures.

3.3 The Material Stock of the Roads

According to the Roadway Law of Mongolia, all national road networks are categorised into four types: capital city road network, international, state, and local roads (Ministry of Road and Transport Development of Mongolia, 2021a). This study calculates the MS of paved and gravel-improved roads. However, this study does not cover the materials from sidewalks, pedestrian and bicycle roads, tunnels, and bridges. As of 2020, Mongolia's road network is estimated at 111.9 thousand kilometres, of which 10.2 thousand is paved. 1.2 thousand are paved with gravel, 604.9 improved gravel roads, and 99.8 thousand simple gravel roads (Transportation, 2020a). The MS of the road network is calculated in Equation 4 as,

$$MS_r = TL_{i,j} \times W \times MI_i \tag{4}$$

where, MS_r: the MS of the Roadway; $TL_{i,j}$: the total length of i type j road expressed in km, W is the width of the road expressed (m), MI_i : the material intensity (kg/m2) is material investment per km corresponding to pavement type.

Material intensity types are classified based on material finishing for the Mongolian road network. The classification is based on the Mongolian standard for road construction, titled "Standard norms for production of highway construction work" ZZBNbD 83-015-2016 (Ministry of Road and Transportation, n.d.).

3.4 The Material Stock of Railways

The railway network in Mongolia is approximately 1,949.4 km, with 1,010.26 km of reinforced concrete railway sleepers and 939.14 km of wooden railway sleepers (Bat-Ochir, 2022). To estimate the MS of railways, the total length of the railway, excluding the stations, trains, and other supporting infrastructure, is analysed. The MS of the road network of Mongolia is expressed in Equation 5 as,

$$MS_{rw} = TL_{i,j} \times MI_i \tag{5}$$

where, MS_{rw}: the MS of the Railway; $TL_{i,j}$: the total length i type j rail, it is expressed in km, MI_i: material intensity investment per unit corresponding to railway track type (t/ km). The material intensity of the railway was calculated based on the Basic norms and regulations for the railway and road infrastructure budget for Mongolia (TZNBD 01-II-03-2020) (Ministry of Road and Transportation, 2020).

3.5 The Material Stock of Passenger Vehicles

In Mongolia, 709,498 passenger vehicles were registered (2020 records - Ministry of Road and Transport Development of Mongolia, 2021b). Each passenger vehicle's weight depends on the class and the materials used in manufacturing. As Mongolia does not have sufficient data on the weight of all categories of passenger vehicles, we assumed a uniform weight for all passenger vehicles. The average weight of passenger vehicles is estimated at 1.5t (Buberger et al., 2022) ("The Circular Economy a Powerful Force for Climate Mitigation," 2018) (Rodrigue, 2020). It is necessary to address the fact that newly produced vehicles have less steel and more aluminium and plastic tiles, reducing the vehicle's weight and promoting fuel efficiency. However, new-generation hybrid and electric vehicles are relatively heavier. Each vehicle has more than 100 systems (engine, transmission, cooling, steering, braking, among others), with an estimated 8,000-10,000 different components (Table 9). The estimation of the number of materials contained in passenger vehicles was calculated in Equation 6 as,

$$M_t = W \times m_c \tag{6}$$

where M_t : the total weight of the passenger vehicle, W is the number of the passenger vehicle fleet, and m_c: the weight component c in the passenger vehicle. Rodrigue approach to the material intensity of passenger vehicles is utilised in this study, as it provides a comprehensive qualitative and quantitative approach to analysing transportation systems, which is beneficial for influencing relevant public policies (Rodrigue, 2020).

4. RESULTS AND DISCUSSION

4.1 Residential Buildings

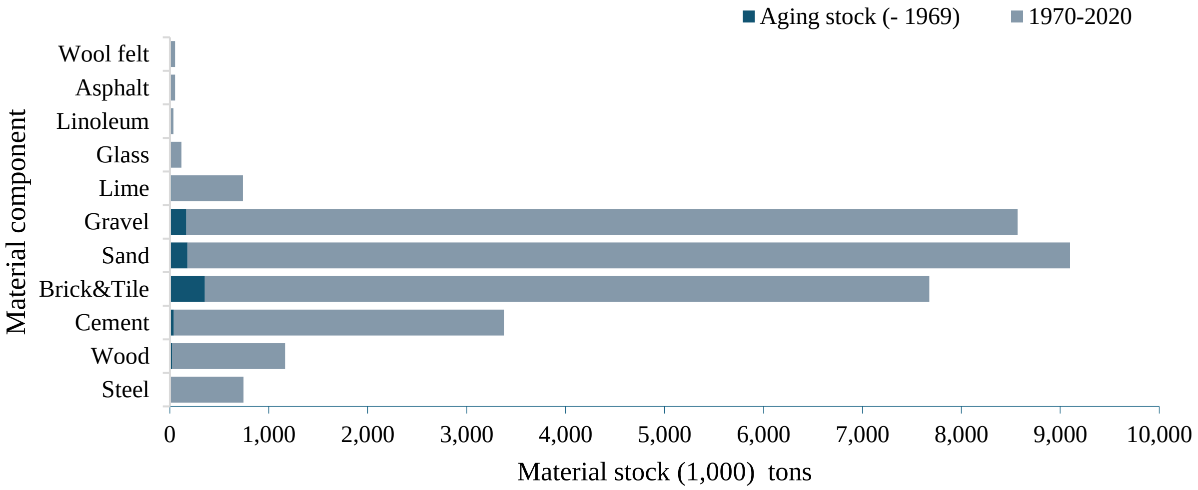

Figure 2. Total Material Stock of Residential Buildings and Gers

This study estimated the MS of residential buildings comprising apartments, detached houses, and Gers (Figure 2). The results estimate that the total MS of residential buildings is 31.6 Metric tons (Mt), comprising steel, wood, cement and brick tile. Other material components include sand, gravel, lime, glass, linoleum, asphalt (51.5kt) and wool (50.9kt) (Figure 2). The top three building materials are sand (28.8%), bricks (24.3%) and cement (10.7%). From the analysis, 10% of apartments and 2% of detached houses have a lifespan of over 50 years and are considered “ageing stock”. According to the building lifespan standard of Mongolia, buildings categorised as ageing stock require thorough examination, with the outcome leading to renovation or demolition. If this policy is implemented, approximately 787.6 thousand tons of construction and demolition waste (CDW) could be produced.

4.2 Non-residential Buildings

The estimated total MS of non-residential buildings is 7,527.8 thousand tons, comprising steel, wood, cement, brick, and tile. Some other commonly used materials for non-residential buildings include sand, gravel, lime, glass, linoleum and asphalt (Figure 3). The non-residential buildings are categorised as all public buildings (38%), hospitals (14%), and schools (15%) in UB that are aged 50 and above, which, according to the Mongolian standard, are required to undergo examination for either renovation or demolition, potentially leading to a discharge of 589.2Kt of CDW.

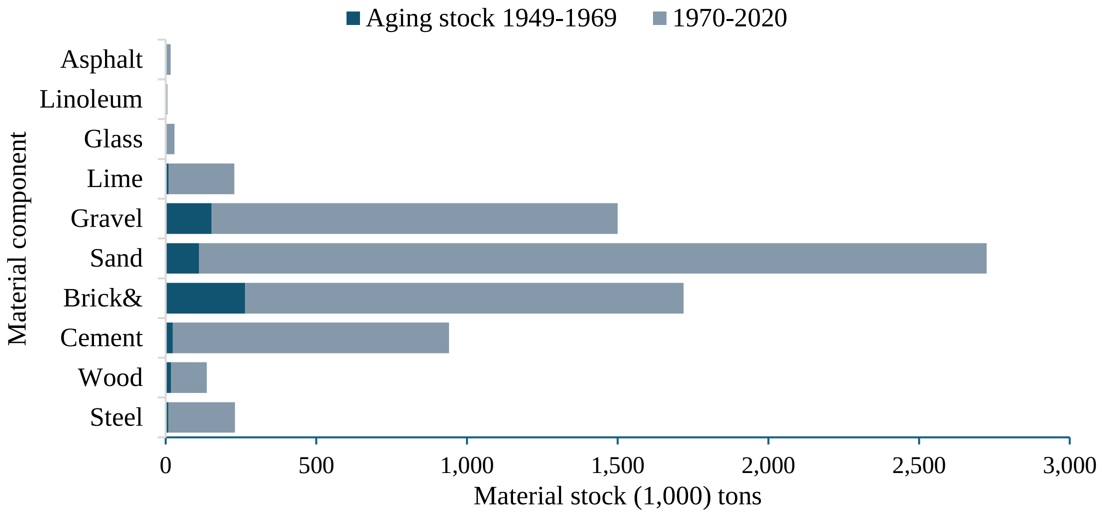

Figure 3. The Material Stock of Non-Residential Buildings in UB.

4.3 Roadways

The Road Network Law of Mongolia classifies all national highways into four categories: Capital, International, State, and Local roads. The total length of the Mongolian road network is approximately 111,916.7 km (2020), which consists of normal unpaved roads (99,978.63 km (89.3%)) and only 12,098.43 km (10.7%) paved and improved roads. Only the MS of paved and improved roads are considered. The road network data is categorised based on the Mongolian road classification system, using the pavement type and total road length (Ministry of Road and Transportation, 2019). The MS of each roadway class is calculated based on the road layers instead of different materials. The estimation method is adopted due to its simplicity in highlighting the potential recyclability of road materials. The result indicates that the total MS of the roadway network of Mongolia is approximately 129.1 Mt, which contains asphalt concrete, cement-concrete, coarse asphalt, cement-strength aggregate, and sand and gravel, respectively. Further analysis shows that 86.3% of Mongolia roads comprise cement aggregate (52,1%) and sand and gravel (34.2%) (Figure 4).

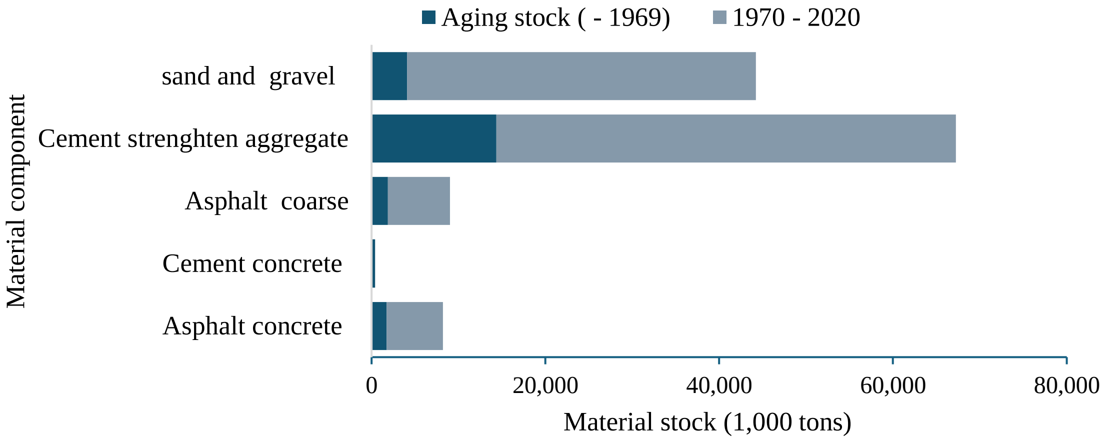

Figure 4 Total Material Stock of Road Network in Mongolia

According to the World Competitiveness Report (2017), Mongolia ranked 119th out of 140 countries in road infrastructure quality and the worst in Asia (Transportation, 2020b). Approximately 26.5% of Mongolian roads are aged 15 and over. Due to harsh winters and hot summers, Mongolia's roadway network lifespan standards range between 15 and 17 years for asphalt paved roads and 20 years for concrete paved roads (Ministry of Road and

Transportation, 2019). In this study, roads above 15 years are classified as future CDW, and the estimated future CDW of these roads is 22.5 Mt.

4.4 Railway

The total length of the Mongolian Railway network is approximately 1,949.4 km and belongs to the 15,200 mm gauge railway network, comprising P65 rails (47%) and P50 rails (53%). The railway network data is categorised by the rail and sleepers' type (Ministry of Road and Transportation, 2020). The total MS of the railway network of Mongolia is about 11.35 Mt. Gravel accounts for 85.5% of the materials (9.7 Mt). Other materials are concrete (0.8 Mt), steel (506Kt), and wood (300.5Kt) (Figure 5). From the analysis, the railways with P50-type rails and wooden sleepers would need to be renovated or changed into P65 rails or higher quality rails in the future to ensure safety standards and would generate approximately 2.7 Mt of CDW.

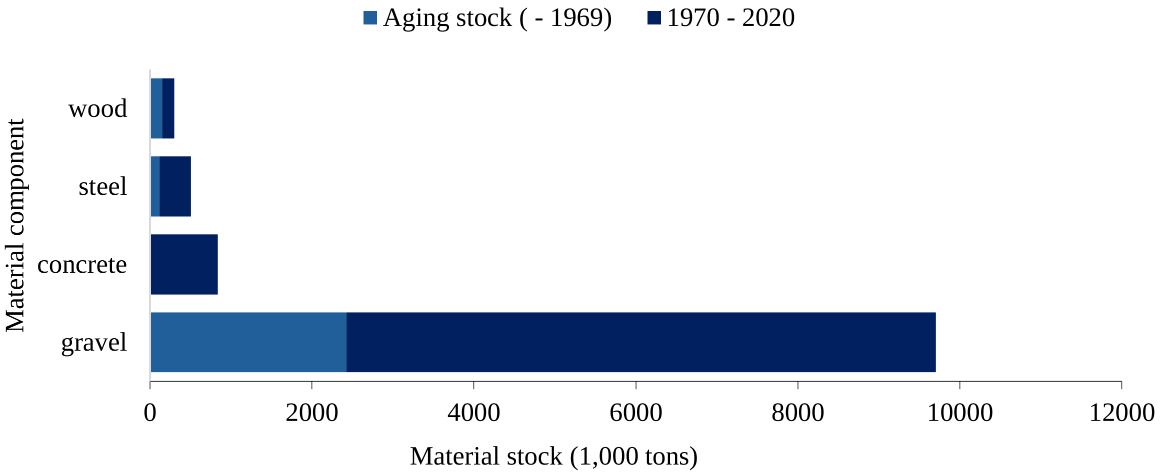

Figure 5. Total Railway Material Stock

4.5 Passenger Vehicles

The total material components of passenger vehicles are estimated at 1.06 Mt (Figure 6). 65% of the total MS of passenger vehicle materials contains steel, and 35% of other components such as plastics, aluminium, rubber, non-ferrous metals, glass and all their components, such as electric cables, respectively. In estimating the MS of passenger vehicles, the input-output method was utilised with statistical data provided by Mongolia's MRTD (Ministry of Road and Transport Development of Mongolia, 2021). Similarly, the National Road and Transport Center of Mongolia provided the number of deregistered passenger vehicles between 2013 and 2019 (National Road Transport Center of Mongolia, n.d.). We assumed that the number of deregistered vehicles equals the number of ELVs because some vehicles exported from Mongolia are negligible. ELVs are estimated at 46,771 passenger vehicles (Mongolian Statistical Office, 2022), with 0.070 Mt of waste generated, representing 6.6% of the total material stock of passenger vehicles.

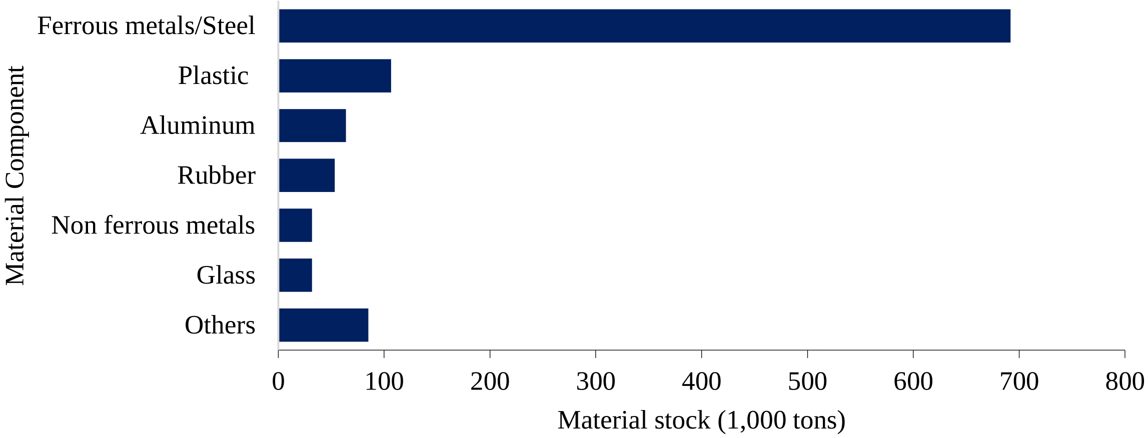

Figure 6 Total Material Stock of Passenger Vehicles in Mongolia

The estimated total MS of Mongolia's buildings, roads, railways, and passenger vehicle fleet is 180.7 Mt. The distribution of the MS in the four categories shows that roads account for 71.46% of all materials, buildings (21.67%), railways (6.28%), and passenger vehicles (0.59%) of the combined total material stock in Mongolia's construction and transportation sectors.

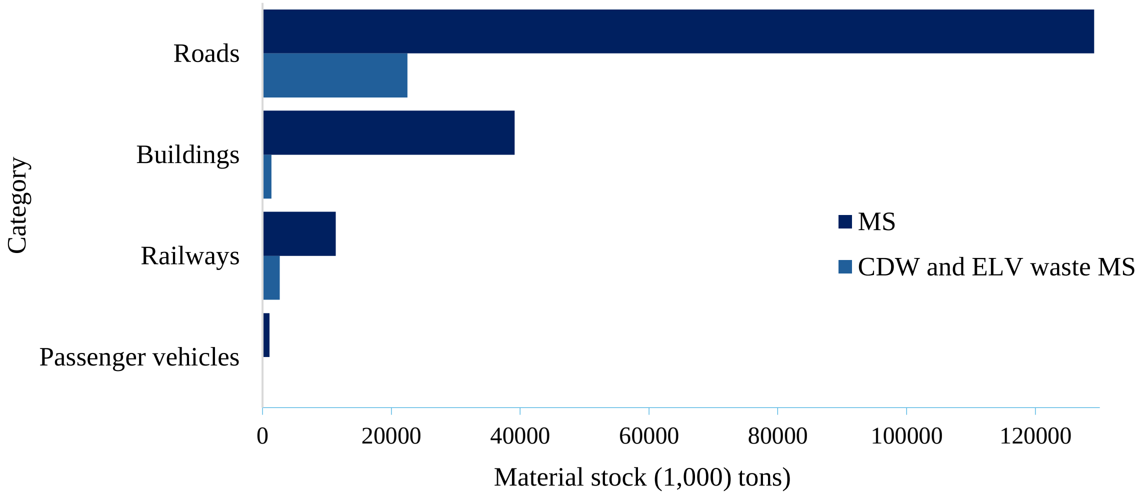

Figure 7 The Total Material Stock in Mongolia.

According to Mongolian standards, apartments (10%), detached houses (2%), roads (26.5%), railways (44.1%), and passenger vehicles (6.6%) have exceeded their lifespan in 2020. Therefore, there is an urgent need to monitor and renovate where necessary, while for those beyond repairs, demolished or recycled. Subsequently, if renovations or demolitions occur, it will generate an estimated 0.79 Mt of CDW from residential buildings, roads (22.5Kt), railways (2.7 Mt), and passenger vehicles (70.2Kt). Furthermore, public buildings (38%), hospitals (14%), and schools (15%)in UB's city are near or have exceeded the building lifespan standard of Mongolia. As such, it is imperative to examine, renovate, or demolish these structures, leading to 0.59 Mt of CDW in the future and due to the ageing infrastructures (> 50 years old) and the number of passenger vehicles (14.7%) totalling 26.6 Mt of material stock will become waste.

4.6 Circularity Implications in the Mongolian Construction and Transportation Sectors

The study helped highlight the material stock of Mongolia's construction and transportation sector. Currently, the low-capacity landfills in the centralised areas often refuse to take the CDW, leading to the illegal dumping of waste in suburban areas. Therefore, it is vital to properly track CDW and develop localised methods for improving the recyclability of waste that could reduce material intake from mining activity and thereby increase resource efficiency in Mongolia. However, the Ministry of Construction and Urban Development in Mongolia has approved regulations on sorting, reusing, and recycling CDW (Government of Mongolia, 2020). Some existing initiatives include developing a centralised database for registering (tracking and recording) and recycling CDW. The main challenge is successfully implementing these regulations on a national scale. Another challenge regarding waste generated from the transportation sector, especially passenger vehicles, is deriving how to effectively separate recyclable and non-recyclable materials, estimating how much waste could be generated from this process and how it should be handled in the future. Another setback in recycling passenger vehicles and ELVs is Mongolia's unavailability of recycling facilities.

As most of the waste generated from the construction and transportation sectors end up in landfills, coupled with the unaccounted number of illegally disposed waste, it is now vital to develop a comprehensive database that tracks all materials in-use, obsolete, and at the point of disposal. As such, establishing the MS database of Mongolia could help the Mongolian government analyse the amount of currently stocked materials and the extended lifespan of infrastructures and passenger vehicles. The knowledge obtained from this database will provide an opportunity to make monitoring, repair, and renovation plans for ageing infrastructures (Brunner, 2011). In addition, the MS database would help forecast future demand for materials and highlight the possible environmental impact resulting from improper waste disposal. It will also allow for the development of relevant policies on reducing harmful environmental impacts and implementing circular economy concepts. The study is also crucial for research on extending the lifespan of existing and ageing infrastructures and passenger vehicles to achieve sustainability and reduce environmental impacts.

4.7 Policy Implications for Circularity Initiatives in the Construction and Transportation sectors

The implications of this research extend beyond a quantitative assessment of material stock (MS) in the context of construction and transportation waste. The findings in the study intersect with significant policy developments aimed at addressing waste management challenges and fostering sustainable practices within the construction and transportation sectors in Mongolia. Multiple key policy initiatives and actions have been introduced in recent years to address the growing concerns surrounding CDW in Mongolia. For example, in 2018, the Ministry of Environment and Tourism (MET) enacted substantial updates to waste management legislation.

This legal framework mandates that individual sectors and ministries take responsibility for formulating and adhering to waste management regulations. The MCUD's approval of Decree No.48 in 2020 marked a pivotal step forward. The decree delineates a comprehensive procedure for managing CDW, which covers essential aspects such as collection, sorting, transportation, recycling, disposal, and burial (*Regulation Of Cleaning Up, Collection, Sorting, Transportation, Recycling, Reusing, Disposal and Burying of the Construction and Demolition Waste, 2020)*.

Furthermore, the Ministry of Road and Transport Development of Mongolia (MRDT) approved Decree No. A/86 in 2002 regulates cleaning, collecting, sorting, transporting, recycling, reusing, destroying, and burying vehicle waste (Government of Mongolia, 2020). These regulations streamline waste management practices within the construction and transportation sectors. A notable development was the approval of MNS BS 5906:2018 Mongolian standard on waste management in construction in 2018, which reflects the strategic effort to align construction practices with environmentally conscious principles (Tommaso T., Somi L., 2017).

With this study, the Mongolian government would better understand the challenges and potential solutions surrounding CDW and ELVs. In UB city, localised efforts have been undertaken to address waste management concerns. Studies conducted by the UB city governor's office reveal that approximately 1.4 million tons of waste are collected annually, with approximately 2030% comprising construction waste. These insights underscore the scale of the CDW challenge and the need for focused interventions. In line with the imperative to improve waste management infrastructure in 2022, UB City initiated the construction of a CDW recycling facility with a projected monthly capacity of 150,000 tons that would become operational in 2024. A waste landfill facility and solid waste recycling plant are being constructed in the Moringiin Davaa region, which signifies the commitment to enhanced waste management and circularity practices in Mongolia for the construction and transportation sector. The findings of this study hold significant policy implications that would guide Mongolia's sustainable development trajectory. The robust quantification of material stock and the identification of potential waste scenarios provide a foundation for informed policymaking at the various governmental levels.

4.8 Impact of Circularity Strategies on Mongolia’s Waste Management

With a clear understanding of material stock and flow, policymakers can adopt circular economy principles that prioritise resource efficiency, reduce waste generation, and increase material reuse (UNIDO, 2017). This framework aligns with global sustainability goals and can drive Mongolia's transition towards a more circular economic model (Mendjargal et al., 2022). The adoption of circularity principles and policies should help strike a balance between urban growth and environmental sustainability. The government of Mongolia should encourage and enforce regulations that promote energy-efficient, environmentally friendly construction methods. Incentives for green building certification and eco-friendly materials can reduce urban development's carbon footprint (Ganjuurjav et al., 2015). Therefore, quantifying material stock enables a more accurate estimation of the environmental impact of the construction and transportation sectors. This data-driven approach ensures that resources are directed to sectors with higher demands, optimising material utilisation while minimising waste and towards a circular economy (Wuyts et al., 2022).

5. LIMITATIONS AND FUTURE RESEARCH

In this study, we estimated the CDW and ELV waste materials to be generated in Mongolia. One of the study's limitations is the absence of long-term data on material use from Mongolia's construction and transportation sectors. Although some required datasets were made available by various governmental and state agencies, data for residential buildings were incomplete, resulting in the study only estimating residential buildings in UB with complete datasets available. UB, home to half of Mongolia's population and hosting most of the country's buildings, served as a representative case study. However, this focus limits the generalizability of the findings to rural areas, where material stock dynamics and waste generation patterns may differ significantly. Similarly, for passenger vehicles, we had to make assumptions based on the average weight of a passenger vehicle and assume that all vehicles possess the same weight. In the future, with improved datasets, we can expand the estimation of material intensity, which would help improve the validation of MS estimations and provide a better understanding of the socio-economic metabolism of Mongolia. Future research would focus on developing quantitative models to assess the impacts of circular economy practices within critical sectors such as construction, transportation, and mining in Mongolia. By measuring and quantifying the impacts of circularity, future research would aid in identifying areas where circular strategies are most effective and provide insights towards achieving a more sustainable and resource-efficient economy. Additionally, incorporating rural areas into future analyses will be crucial for capturing the full scope of material flows and waste generation in Mongolia, ensuring that circular economy strategies are inclusive and effective across urban and rural contexts.

6. CONCLUSION

The study used the bottom-up approach to estimate the material stock of Mongolia’s national economy and the potential for obtaining durable materials. It aimed at quantifying the material stock from Mongolia's construction and transportation sectors and increasing awareness of the usage of nonrenewable minerals such as non-metallic minerals and the need to establish a national database on construction and infrastructure materials. The study established a material stock database for buildings, road and railway networks, and passenger vehicles for the first time, which can be used in further planning and supporting policymaking decisions at various governmental levels in Mongolia. As Mongolia is highly dependent on the extraction of mining minerals and exports of natural resources, it is essential to introduce material efficiency and circular economy policies through research on the recyclability of mining waste, extending the lifespan of current infrastructures, the repair, recycling, and maintenance of metals from ELV to reduce overexploitation of natural resources. Moreover, the rapid growth in construction materials consumption due to COVID-19 and logistics poses a significant challenge for the Government of Mongolia. Despite the increasing demand for construction materials by the construction and transportation sectors, the cost of acquiring the required materials is relatively high. Therefore, the Mongolian government would benefit from alternative solutions to material shortages, which can promote a sustainable circular economy and reduce the cost of construction.

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AUTHOR CONTRIBUTIONS

Mendjargal, Ighile: conceptualisation, methodology, editing the article
Mendjargal, Bat-Ochir: data collection, calculation, drafting the article, methodology, data analysis
Yamashita, Jamsran, Shirakawa, Tanikawa: review

DECLARATIONS

Competing interests: The authors declare no competing interests.
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APPENDIX

Table 4. The Material Intensity of Residential Buildings Expressed in tn/100m^2. Source: (Yang et al., 2020)

Material intensity (T/100m^2)											
Building Type	Period	Steel	Wood	Cement	Brick and Tile	Sand	Gravel	Lime	Glass	Linoleum	Asphalt
BC-R	1949-1959	0.39	7.00	2.14	91.28	33.35	47.30	4.10	0.21	0.02	0.24
	1960-1979	0.80	3.95	7.22	92.97	39.47	28.54	3.84	0.24	0.16	0.24
	1980-1989	2.32	1.88	14.60	83.29	64.62	45.81	3.39	0.33	0.12	0.18
	1990-1999	1.96	1.70	15.51	83.63	66.32	38.35	3.67	0.34	0.10	0.22
	2000-2015	2.35	1.77	15.11	53.07	59.74	33.13	3.43	0.55	0.40	0.44
SC-R	1949-1959	13.40	7.11	31.13	96.17	40.47	76.20	2.23	0.31	0.13	0.11
	1960-1979	3.26	2.07	18.60	35.56	53.46	54.72	2.24	0.32	0.12	0.13
	1980-1989	2.59	2.06	16.68	23.65	47.90	49.66	2.24	0.33	0.11	0.17
	1990-1999	1.92	2.04	14.75	11.74	42.34	44.60	2.25	0.34	0.10	0.20
	2000-2015	5.92	1.74	21.73	14.68	36.43	44.93	4.27	0.76	0.09	0.23
BW-R	1949-1959	0.10	5.96	0.68	57.78	24.98	23.48	1.38	0.15	0.01	N/A

	1960-1979	0.08	0.00	2.71	73.63	15.23	0.45	2.87	0.15	0.23	N/A
W-R	1949-1959	0.07	13.59	2.05	28.14	12.66	27.73	1.34	0.15	0.01	N/A
S-R	2000-2015	6.03	2.00	18.57	10.59	88.10	60.00	2.74	0.22	N/A	N/A

Note: BC-R=brick-concrete, SC-R=steel-concrete, BW-R= Brick-wood, W-R=wood, S-R=steel, N/A=not applicable

Table 5. Material Intensity of 5-Walled Ger by Wooden Structural Element Expressed in kg/per Ger

Components		Material Volume (m^3)	Material density (kg/m^3)	Total material (kg)
Wood	Skylight	0.132	600	79.2
	Wall	0.017	600	10.2
	Pole	0.14	600	84.0
	Pillar	0.034	600	20.4
	Wood Floor	1.03	600	618.0
	Door	0.01	600	6.0
Total (Wood)		1.4	600	817.8
Sheep Wool felt		2.39	70	167.3
Total materials				985.10

Table 6. Material Intensity of Non-Residential Buildings. Source: (Yang et al., 2020)

Material intensity (T/100m^2)											
Building structure	Period	Steel	Wood	Cement	Brick and Tile	Sand	Gravel	Lime	Glass	Linoleum	Asphalt
BC-P	1949-1959	0.41	5.74	2.41	76.86	31.92	41.91	3.65	0.20	0.07	0.24
	1960-1979	1.15	1.03	9.48	88.00	43.39	13.10	3.93	0.21	0.18	0.25
	1980-1989	2.51	1.79	15.62	83.20	65.14	49.55	3.02	0.86	0.20	0.67
	1990-1999	2.51	1.79	15.62	83.20	65.14	49.55	3.02	0.86	0.20	0.67
	2000-2015	3.18	3.36	16.17	40.66	85.15	16.09	4.70	0.76	0.20	0.67
SC-P	1949-1959	13.40	3.51	25.69	96.17	33.39	62.87	2.23	0.31	0.13	0.11
	1960-1979	2.35	0.55	11.01	65.59	41.31	13.19	2.04	0.31	0.49	0.54
	1980-1989	5.32	2.16	19.81	46.26	63.67	64.60	1.89	0.34	0.13	0.31
	1990-1999	14.60	3.09	31.05	42.32	67.08	77.25	4.24	0.40	0.10	0.20
	2000-2015	7.03	3.36	27.87	14.94	57.73	34.10	6.59	0.76	0.09	0.23
S-P	2000-2015	8.35	3.24	15.90	16.37	88.10	60.00	2.74	0.22	N/A	0.10
BC-I	1949-1959	1.21	4.72	8.78	68.83	46.24	47.05	0.94	0.22	0.19	0.89
	1960-1979	2.37	0.43	11.69	85.57	48.74	10.55	2.73	0.15	0.40	0.43
	1980-1989	2.39	1.37	13.29	73.54	55.14	52.62	2.33	0.37	0.26	0.44
	1990-1999	2.23	1.75	15.57	83.42	65.73	43.95	3.35	0.60	0.15	0.44
	2000-2015	2.76	2.57	15.64	46.86	72.44	24.61	4.06	0.66	0.30	0.56

Note: BC-P=brick-concrete public buildings, SC-P= steel-concrete public buildings, S-P=steel public buildings, BC-I= brick-concrete industrial buildings, N/A=not applicable

Table 7 Material Intensity of Roadway Network Expressed in kg/m^2

Type of Road	Material intensity kg/m^2				
	Asphalt concrete layer	Cement concrete layer	Asphalt base coarse	Cement strengthens the aggregate base	Sand and Gravel base
Asphalt concrete pavement (cement strengthen base)	112.15		134.58	976.5	510.72
Asphalt concrete pavement (crushed aggregate base)	67.29		89.72	482.43	513.16
Simplified asphalt pavement	112.15			497.7	516.6
Concrete pavement			893.2	491.2	516.6
Simple gravel road					486.17

Source: Mongolian standard for road construction "Standard norms for production of highway construction work" ZZBNbD 83-015-2016

Table 8. Material Intensity of Railway Network Expressed in t/km

Types of rails	Material intensity in tn/km			
	Gravel	Concrete	Steel	Wood
P 65 rail with concrete sleepers	2955	508.8	166.98	-
P 50 rail with concrete sleepers	2955	508.8	146.41	-
P 65 rail with wooden sleepers	2955	-	161.45	183
P 50 rail with wooden sleepers	2955	-	141.35	183

Table 9. Average Ratio of Components in a Passenger Vehicle

Material	Average content of the materials in 1 passenger vehicle (%)	Average material content in one passenger vehicle (kg)
Ferrous metals/ steel	65	975
Plastic	10	150
Aluminum	6	90
Rubber	5	85
Non-ferrous metals	3	45
Glass	3	45
Other materials	8	120

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