Journal of Cleaner Production 93 (2015) 18–25

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Sustainable management of excavated soil and rock in urban areas – A literature review

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ARTICLE INFO

Article history:
Received 30 September 2014
Received in revised form
19 December 2014
Accepted 5 January 2015
Available online 10 January 2015

Keywords:
Excavated soil and rock
Construction and demolition waste
Material flow analysis
Sustainable management
Resource

ABSTRACT

Construction in urban areas implies use of construction materials from quarries and excavation of soil and rock. From a resource perspective, there could be benefits from using excavated soil and rock as a construction material. The aim of this paper is to describe the material flow and management practices of urban excavated soil and rock from the perspective of resource efficiency. A conceptual model for the urban flow of excavated soil and rock was developed and a literature review concerning the management of excavated soil and rock was conducted. The conceptual model was subsequently used to clarify the different perspectives of the scientific literature and knowledge gaps. Conclusions drawn are that there is little knowledge about the quantities and the fate of excavated soil and rock in urban areas. Current research is focusing on the waste flows of construction material and little is known about the overall management practices of excavated soil and rock. Clearly, excavated soil and rock are often disposed at landfills and the recycling rate for high quality purposes is low. There is a need to evaluate the potential for an increased use of excavated soil and rock as construction material. However, the overall efficiency of urban construction material management can only be evaluated and improved by also including construction materials produced in quarries.

1. Introduction

The need for resource efficiency and reduction of climate impact from urban areas is crucial for a global sustainable development. Ongoing urbanization and growth of cities will likely lead to significant increases in the demand for natural resources such as water, land, energy, and mineral resources (Huang et al., 2010). Urban areas emits about 80% of the global CO_2 emissions (Heinonen and Junnila, 2011) and is responsible for about 80% of global energy consumption (Grubler et al., 2012). In rapid growing cities, the construction sector has shown to be one of the major sources to CO_2 emissions (Weber et al., 2007). In order to reduce climate impact from construction, there is a need to improve resource efficiency and increase the reuse of construction materials (Blengini and Garbarino, 2010; Eras et al., 2013; Gangolells et al., 2014; Huang and Hsu, 2003; McEvoy et al., 2004; Miliutenko, 2012; Simion et al., 2013; Toller et al., 2011).

The use of natural resources for construction in urban areas was described by Wolman (1965) as one of the components in the metabolism of cities. The metabolic requirements of a city was defined as all the material and commodities required to sustain the city's inhabitants, such as food, water, clothes, durable goods, electric energy, and construction material. A metabolic approach can be helpful to evaluate the sustainability in urban management of construction materials. A methodology for material flow analysis where material flows are structured and quantified, gives a better understanding of the metabolism (Huang and Hsu, 2003; McEvoy et al., 2004). Such methodology has been used in other research fields such as for biomass, phosphorus and energy to describe sustainability, self-sufficiency and resource security (Chowdhury et al., 2014; Decker et al., 2000; Rosado et al., 2014; Welfle et al., 2014).

Construction of buildings and infrastructure require use of construction materials, earthwork, transportation and management of large volumes of materials such as aggregates and

Abbreviations: C&D, Construction and Demolition.

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http://dx.doi.org/10.1016/j.jclepro.2015.01.010

excavated soil and rock. This paper is mainly focusing on the metabolism of excavated soil and rock which consist of all materials generated when digging/blasting in the ground for urban construction purposes.

Depending on local geological conditions and anthropogenic activities, excavated material can be rock, stones, gravel, sand, clay, organic material and materials from previous constructions or industrial activities. The quantities of excavated soil and rock can be considerably big and hauling and handling costs high. In infrastructure projects, on-site handling and hauling of excavated soil and rock and construction material from quarries, i.e. quarry material, can be up to 30% of the total project cost and generate significant amounts of CO_2 emissions. Optimization of the management in projects has large potential to reduce both costs and climate impact (Kenley and Harfield, 2011). The management alternatives of excavated soil and rock vary between construction projects. Lafebre et al. (1998) and Eras et al. (2013) has described possible management alternatives for excavated soil and rock as 1) use on-site 2) use in other projects 3) pretreated before use in other projects 4) store for later use, 5) use as landfill cover or dispose at landfill.

Other parameters affecting management possibilities are geotechnical properties, geo environmental properties, availability of recycling facilities, landfills and quarry materials (Chong and Hermreck, 2010; Wilburn and Goonan, 1998).

It is important to notice that geotechnical properties are basis for what functions can be achieved. Particle size, density, water absorption, hydraulic conductivity, deformation properties and bearing capacity are some of the most important aspects that have to be considered. Also, geo environmental properties such as PH value, organic content, total concentration and leachate concentration set the conditions for what material can be acceptable at the project site (Arulrajah et al., 2013). There is an increasing awareness of the possibilities of reusing materials such as soil and rock for construction purposes. Laboratory tests and field studies proves that excavated soil and rock, brick, glass, concrete, asphalt and ceramics can be used beneficially for civil engineering purposes and hence replace quarry materials (Arulrajah et al., 2012; COWASTE, 2014, 2014; Gabr and Cameron, 2012; Kreft-burman et al., 2013; Mohammadinia et al., 2013; Rahman et al., 2014; Taha and Nounu, 2009).

This paper is one of the outcomes from the research project “Optimass”. The project aim for “Optimass” is to provide conditions for a more sustainable management of soil and rock in dense city regions. The idea in both the “Optimass” project and this paper is that there is a potential to reduce environmental and economic costs by coordinating the soil and rock material produced in quarries and material excavated due to construction. In this paper this is done in a regional context.

The aim of this paper is to describe the material flow and management practices of urban excavated soil and rock. Focus is on excavated soil and rock due to construction and resource efficiency. This study will look at all materials as potential resources regardless of the specific material properties. This is done even though the geotechnical and geo environmental conditions and hence environmental risks affects the potential use of excavated soil and rock. In this study the primary focus is to reveal the quantities of material flows in urban regions from a resource perspective.

The paper is based on a literature review. The aim is also to identify knowledge gaps and needs of future research. For this paper, the research questions are:

- What is the knowledge about the flow of urban excavated soil and rock?
- What are the benefits of using excavated soil and rock in construction?

2. Methodology

The methodology of this study consists of a literature review in the research field of soil, rock and sustainable management. The purpose of the review is to give a presentation of literature related to the research field and the different perspectives on soil and rock. A model illustrating the urban flow of building materials was developed and used to clarify different types of scopes and material flows described in the scientific literature. Information was collected by using key words for the types, names, processes and objects significant to the flow of excavated soil and rock in urban areas and the methods relevant for describing its sustainability. The results were analyzed and conclusions drawn are presented in this paper.

2.1. Conceptual model for construction material flows

A conceptual model for construction material flows was developed and is presented in Fig. 1. The model can be applied at different spatial system levels, from project level to transnational level to illustrate how construction materials are managed. The model illustrates the demand, supply, stock and internal flows of construction materials for a system.

The demand for construction materials can be met by either domestic sources within the system or by imported sources which are illustrated with blue/dashed boxes. Sources can come from natural extraction such as production in quarries or residues from construction or industry. Construction materials are used domestically in the system or exported from the system and are illustrated with red/bold boxes. The construction material that is used domestically ends up as stocked material of two types: active stock and inactive stock. The active stock represents material that is typically used and cumulated in buildings, roads and other constructions while the inactive stock is material that has been permanently taken out of use and serves no purpose. The latter is usually construction and demolition (C&D) waste ending up at disposal sites (Johansson et al., 2013). In the considered system, there is also a flow through, i.e. external material passing through the system. The conceptual model was developed with inspiration from previous work on construction mineral flows by McEvoy et al. (2004), the work on biomass demand by Welfle et al. (2014), the work on urban material stocks by Johansson et al. (2013), the work on regional management of building materials by Frostell et al. (2009).

2.2. Applying the conceptual model to excavated soil and rock

In this paper, the flows in Fig. 1 are referred to as flow $A - L$. Construction in Fig. 1 was defined as all types of construction activities including demolition. Flow *A* refers to the demand and use of material in applications where excavated soil and rock can be used. Typical applications are in roads, e.g. as sub-base where crushed rock can be replaced (Arulrajah et al., 2012; Kreft-burman et al., 2013). Flow *B* corresponds to the supply of extracted material from domestic sources such as sand, gravel and rock that are usually produced in quarries. Flow *C* is the excess excavated soil and rock generated at the construction site which is sent away as waste to a building material supplier. The building material supplier processes the material before it is used in construction (flow *D*) or sends the material to landfill (flow *E*). Flow *F* is excavated soil and rock generated at the construction site which is either needed on-site for use in construction or needed in other construction projects, as described by Eras et al. (2013). The use of flow *F* materials is often preceded by some kind of treatment, for example crushing and sorting.

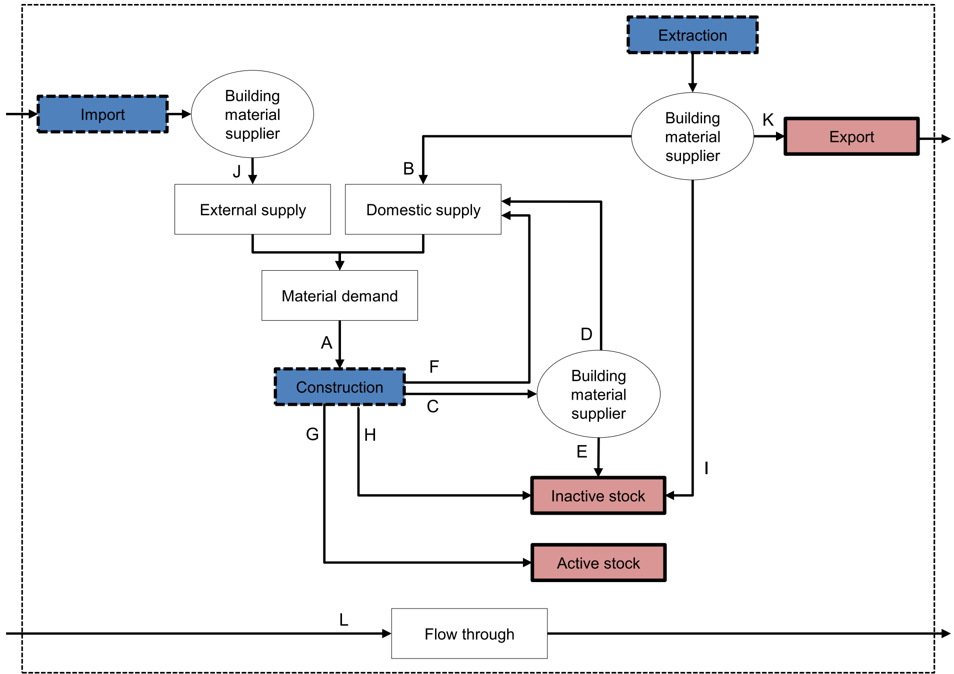

Fig. 1. Construction material flows and the demand and supply in construction.

With exception for exported materials, excavated soil and rock is cumulated in the material stock. Flow *G* refers to all excavated soil and rock that is used in construction and hence cumulated in the active stock.

Flow *H* refers to excess excavated soil and rock which is sent to landfills or other sites where it is inactively stocked. At closing landfills and quarries, it is used as cover material. Such management practice is in the literature regarded as recycling. However, landfill covering has been described as recycling of very low quality (Blengini and Garbarino, 2010). In addition, some argue that landfill cover material is a potential resource that could be extracted and used for other purposes (Frändegård et al., 2013). In the model, material ending up in landfills is therefore regarded as disposed material cumulated in the inactive stock. Flow *I* refer to fractions of extracted quarry materials that are not used, such as rock flour. The Flow *J*, *K* and *L* respectively refers to the import, export and flow through of excavated rock and soil in the considered system, and is similar to the flow of construction minerals presented by McEvoy et al. (2004).

3. Quantifying excavated soil and rock – examples of studies and methods

3.1. Material flow analysis of construction materials

Material flow analysis is a commonly used approach for describing the metabolism and regional flows of construction materials. It was used by McEvoy et al. (2004) to study the flow of rock, sand, gravel and other aggregates in the North West region of England and by Huang and Hsu (2003) to study regional flows of construction materials in Taipei with focus on sand, gravel, concrete, asphalt and construction waste (flow *A*, *C* and *H*). Regional material flows of construction materials and waste (Flow *A* and *H*) in 25 mega cities has also been studied by Decker et al. (2000). Further, Rosado et al. (2014) studied the flow of non-metallic minerals in Lisbon Metropolitan Area which was primarily stone, cement and sand (Flow *A*, *C*, *G* and *H*). Some results from material flow studies are presented in Section 3.3.

The given examples of material flow studies used data both from measurements and estimations. McEvoy et al. (2004) collected statistics from authorities and business organizations. However, due to lack of data, some estimations had to be made. The quantities of excavated soil and rock were not studied specifically. However, the share of excavated soil and rock that is managed as waste (Flow *C* and *H*) was included in available data for construction mineral waste. Waste and recycling quantities was gathered from environmental agencies. Also data on crushed rock and soil used in construction and data on aggregates and soil used for covering purposes at landfills was available.

Huang and Hsu (2003) used estimations of construction material demand combined with waste statistics. Construction material demand (Flow *A*) was calculated by using building and infrastructure production data from regional and national authorities. Construction waste (Flow *C* and *H*) data was taken from previous waste generation estimations. Waste of excavated soil and rock was not calculated separately from other construction wastes.

Rosado et al. (2014) based calculations on consumption statistics for goods and services and the use of construction materials (Flow *A and G*) such as non-metallic minerals, sand, cement, clay and stone. Construction waste (Flow *C* and *H*) was quantified from data on total C&D waste flow.

The material flow studies presented are focusing on the metabolism at a city or regional level with a strong focus on the input and output of materials. The internal flows i.e. how materials are moving inside the considered system has not been studied. Most studies focus on the presented waste situation and status while Rosado et al. (2014) forecasts the future regional development in order to describe future challenges for material reuse.

3.2. C&D waste studies

The flow of excavated soil and rock has in some cases been described in C&D waste studies. However, available data on the generation of C&D waste is generally uncertain. This is mainly due to illegal dumping activities and lack of proper measurements of C&D waste facilities (Simion et al., 2013). Further, uncertainties are even larger due to the fact that the definition of C&D waste varies. Simion et al. (2013) and Coronado et al. (2011) defines C&D waste to be concrete, asphalt, wood, metal, drywall, paper and plastics while Hao et al. (2007) includes all surplus materials from construction. Further, Blengini and Garbarino (2010) include and Hiete et al. (2011) exclude excavated soil and rock from the C&D waste definition.

Different methods have been used to quantify C&D waste, some were based on the waste amounts processed at recycling facilities (Flow *C*) while other used estimations on generated waste (Flow *C* and *H*) from a certain amount of construction work. Hsiao et al. (2002) based C&D waste estimations on the number of square meters permitted for C&D in the region together with estimations on material need.

The environmental and economic benefits of C&D waste recycling (Flow *C* and *H*) within a region has been estimated in a few studies. Blengini and Garbarino (2010) evaluated the energy and climate performance of the C&D waste recycling chain in an Italian province. The flow of C&D waste including waste of excavated soil and rock was quantified by collection of data from recycling facilities (Flow *C*). Hiete et al. (2011) studied the federal state Baden–Württemberg in Germany and the generation of C&D waste. The amounts of waste of excavated soil and rock was recorded. Estimations on C&D waste (Flow *C* and *H*) generation for construction activities was combined with data on cumulated materials in buildings and construction, refurbishment and demolition rates.

3.3. Presentation of data from previous studies

A presentation of some data from a selection of studies is found in Table 1. In most studies, there have been no quantification of separate waste fractions. Instead, the total amounts of C&D waste have been used. Bold data represents pure quantities of waste of excavated soil and rock.

The scopes of presented studies in Table 1 are not identical and there are differences regarding the system boundaries and types of materials quantified. The majority of the studies make no quantification of the waste fractions which means that the data resolution is low. Further, it is important to stress that the waste quantities presented also include other types of construction waste than excavated soil and rock. From the example of studies in Table 1, the generation of C&D waste including waste of excavated soil and rock varies with a factor of 10. From the studies reporting specific quantities of waste of excavated soil (Flow *C* and *F*), it can be seen that the generation varies even more.

The literature gives some examples of recycling rates of waste from construction and excavated soil and rock. Blengini and Garbarino (2010) described the waste management in Torino. About 58% of the C&D waste was directly landfilled (Flow *H*). The other 42% were sent to recycling facility (Flow *C*). About 55% of the produced recycled aggregates, i.e. 23% of total C&D waste was used in high quality and medium quality construction purposes such as construction of concrete, road, harbor or airports (Flow *D*). This means that 77% was ending up in landfills and depleted quarries as waste or as covering materials and for rehabilitation purposes (Flow *E*). Another example is the management in the Federal state of Baden–Württemberg in Germany. Hiete et al. (2011) describe that about 79% of excavated waste and 91% of C&D waste was processed in recycling plants (Flow *C*). The recycling plant produced 4.4 Mton of which 2 Mton was processed concrete and 1.6 Mton was sand, gravel, cobbles and excavation materials. By assuming that all 1.6 Mton is excavated soil and rock, the maximum possible recycling rate (Flow *D*) can be estimated. The assumption implies that the use of excavated soil and rock in construction of roads and infrastructure could not be more than 8.5% of the total amount entering the recycling facilities while the rest was sent to

Table 1
Generation and recycling of C&D waste and waste of excavated soil and rock, and the use of construction materials.

Region or country	Capita	Generation of C&D waste including waste of excavated soil and rock		Recycling rate	Construction material use or material extracted in quarries	
	[10^6]	[Mton]	[Ton/capita]	[%]	[Mton]	[Ton/capita]
Taipei[a]	6.2	40.1	6.47	“minimal”	9.41	1.52
English region[b]	6.9	10.2	0.68	31.7%	31.4	4.55
Italy[c]	n/a	n/a	0.8	n/a	n/a	6–11
Italian region[c]	n/a	n/a	n/a	23%	n/a	n/a
German region[d]	11	**18.9**	**1.72**	**8.5%**	87.4	7.95
German region[d]	0.77	0.77	1	n/a	n/a	n/a
Finland[e]	5.46	**20–30**	**3,7–5,5**	n/a	n/a	n/a
Lisbon region[f]	3	1.25	0.42	n/a	19.5	6.51
European Union[g]	n/a	n/a	**0.10–0.32**	n/a	n/a	4.8
Chinese region[h]	8.46	6.0	0.71	n/a	n/a	n/a

[a] Data gathered from *Materials flow analysis and emergy evaluation of Taipei's urban construction* (Huang and Hsu, 2003). Construction material use refers to the use of sand and gravel.
[b] Data gathered from *Managing the Flow of Construction Minerals in the North West Region of England – A Mass Balance Approach* (McEvoy et al., 2004). Recycling rate refers to reuse in roads and planings. Reuse in landfills (1.18 Mton) is here excluded. Construction material use refers to rock, sand and gravel.
[c] Data gathered from Resources and waste management in Turin (Italy): the role of recycled aggregates in the sustainable supply mix (Blengini and Garbarino, 2010). Recycling rate refers to use in concrete, road, harbor and airport construction.
[d] Data gathered from Matching construction and demolition waste supply to recycling demand: a regional management chain model (Hiete et al., 2011). C&D waste only refers to excavated materials. Recycling rate refers to highest possible rate of recycling and has been calculated based on the fact that 79% of the 18.9 Mton i.e. 14.9 Mton excavated material was processed. The production of sand, gravel, cobbles and excavated material from recycling facilities was totally 1.6 Mton. Assuming that these 1.6 Mton of produced material origins from excavated soil and rock, the recycling rate is calculated to 1.6 Mton/18.9 Mton = 8.5%. Construction material use refers to the production of minerals in quarries in the studied area.
[e] Data gathered from Experiences of utilizing mass stabilized low-quality soils for infrastructure construction in the capital region of Finland – Case Absoils Project (Forsman et al., 2013), which has estimated the generation of excavated soil to 20–30 Mton. A value per capita was calculated by using population data gathered from Finnish public authority for statistics (Statistics Finland, 2014).
[f] Data gathered from A Material Flow Accounting Case Study of the Lisbon Metropolitan Area using the Urban Metabolism Analyst Model (Rosado et al., 2014). Construction material use refers to the use of non-metallic minerals.
[g] Data gathered from Comparing environmental impacts of natural inert and recycled construction and demolition waste processing using LCA (Simion et al., 2013). Generation of C&D waste refers to excavated soil only.
[h] Data gathered from A SWOT analysis of successful construction waste management (Yuan, 2013).

landfill (Flow *E*). McEvoy et al. (2004) describe the recycling rate of construction waste in Northwest England where about 31.7% of C&D waste was recycled and used in construction (Flow *D*). Also, 11.5% of C&D waste was used at landfills as cover.

The demand of construction materials for construction purposes has been estimated in some of the studies presented in Table 1. The definition of construction materials varies but common for all is that the material has primarily been extracted from quarries. Also there is a difference between material demand and use of quarry materials, since some of the material that is generated due to construction can also be reused, such as excavated soil and rock that has never been accounted as a recycled/used material (Flow *F*). In the examples of studies presented in Table 1, the use of quarry materials (Flow *B*) is between 1.5 and 11 tons per capita.

4. Identifying environmental and economic benefits of reusing excavated soil and rock

4.1. Reusing excavated soil and rock on-site

Several studies describe the environmental gains with reusing excavated soil and rock (Flow *F*) at the construction site (Chittoori et al., 2012; Eras et al., 2013; Kenley and Harfield, 2011; Lafebre et al., 1998). Eras et al. (2013) showed that by planning for mass balance of earthworks in an industrial construction project, it was possible to relocate and reuse 44% of the excavated materials, i.e. about 700 000 m^3, and hence reduce earthwork and transports to landfill as well as the production and use of quarry materials. The total climate impact from transports could in this example be reduced with about 4000 tons of CO_2 from fuel savings. Further, costs could be reduced with 1,76 million dollars. Similar results has been presented by Chittoori et al. (2012) who described the cost and environmental benefits of reusing excavated soil within a pipeline construction project. The increased reuse reduced the material management costs and climate impact by 85%.

Stabilization is a technology for improving geotechnical properties in terms of increased strength, reduced permeability and compressibility of soil. The technology makes it possible to use low quality materials in construction, such as soft soils that are usually landfilled (Makusa, 2012). Chemical stabilization means that cement or other binder materials such as fly ash and lime is mixed with soil which leads to chemical reactions that stabilizes the soil. Forsman et al. (2013) described the experiences in the Absoils project of stabilizing excess soft soils that are usually excavated, transported to landfill and replaced with natural aggregates. The environmental and economic impact of soft soil stabilization for construction purposes compared to the use of new construction materials was not assessed.

In order to reuse excavated soil and rock on-site, there is a need for space at the construction site. In dense city regions, the availability for space at the construction sites is limited and the possibilities for on-site sorting of C&D waste including excavated soil and rock are often low. This has been described by Hao et al. (2007) regarding the situation for waste management in Hong Kong.

4.2. Reusing excavated soil and rock in other projects

Reuse of excavated soil and rock directly in other projects (Flow *F*) means that materials are transported between construction sites. Such reuse is possible when there are several construction projects going on in the same region. In Helsinki, landfills are starting to get full, due to the disposal of excavated soil and rock. This in turn leads to increased transportation to landfills further out from the city center, about 50 km. The coordination of excavated soil and rock between construction projects has been one of the aims of the Absoils project. However, no data on environmental or economic benefits has been published (Forsman et al., 2013). The benefits of using excavated soil and rock in other projects have been studied by the English non-profit organization CL:AIRE. They conducted a study of a cluster project which consisted of four remediation projects located relatively close to each other in Northwest England (CL:AIRE, 2013). In these projects, large amounts of contaminated soil were excavated and transported to a temporary hub located at one of the construction sites where the materials were treated and thereafter transported to construction sites for reuse. The cluster approach resulted in an increased reuse of totally 30 000 m^3 of excavated material and emission reductions of about 100 tons of CO_2. Furthermore, transportation, landfilling, and use of new construction material were reduced. The cost savings was estimated to 30% (CL: AIRE, 2013).

In order to coordinate and exchange excavated soil and rock between construction sites, there is a need for joint planning. At an early stage of the planning process, it becomes important to evaluate the coordination benefits for all projects involved. The quantities and quality of excavated soil and rock over time would here be essential information.

4.3. Recycling at facility

Excavated soil and rock being classified as waste can be transported to a recycling facility (Flow *C*) where it is treated and prepared for use in other construction projects (Flow *D*). The environmental potential for recycling excavated soil and rock in such way has been studied by few. For example, Blengini and Garbarino (2010) concluded that there are environmental benefits when using recycled C&D waste including excavated soil and rock produced at a recycling facility compared to use of quarry materials. For 13 out of 14 environmental aspects studied, there were environmental gains. The CO_2 emissions were reduced with about 14 kg CO_2 equivalents per ton when recycling C&D waste compared to using quarry materials. Here, production of materials is included, not just transports. Transport distances were between 15 and 25 km for recycled aggregates and twice as high for natural aggregates. Even though transport distances are crucial for the environmental benefits, they could increase by a factor of 2 or 3 and still have a positive environmental effect. The work was developed in the EU project SARMa with the objective to achieve a common approach to sustainable management of aggregate resources (Blengini and Garbarino, 2011). Simion et al. (2013) studied the climate effects of producing natural aggregates compared to recycling C&D waste. Climate impact from natural aggregate production was about 103 kg per ton, compared to about 16 kg per ton for recycled C&D waste.

There are examples of similar studies that focus on the economic potential for recycling other C&D waste flows than excavated soil and rock. For example, Coelho and de Brito (2013) assessed the economic potential and localization of a recycling facility in Portugal for C&D waste with a plant capacity of 350 tons per hour. Excavated soil and rock was not accepted and recycled at the facility. It was concluded that such investment is viable. The main income comes from input material gate fees at the facility. The main cost is the management of the fractions of C&D waste that can't be recycled at the facility. This waste has to be transported to other treatment facilities or landfills where a fee must be paid. Different conclusions were drawn by Zhao et al. (2010) who evaluated the economic potential for a fixed recycling facility with a capacity of 100 tons per hour and a mobile recycling facility with a capacity of 50 tons per hour in the city of Chongqing in China. One conclusion was that such investment is risky due to low costs for the landfilling of C&D waste and the use of quarry materials in combination with high investment costs for the recycling facility. Galan et al. (2013) optimized localizations for waste recycling facilities due to transportation distances and total costs in the region of Cantabria in Spain. Recycling facilities with a capacity of 50 000–300 000 tons was evaluated. Assuming 8 h of operation, the recycling capacity corresponds to 17–103 tons per hour. Cantabria has about 600 000 inhabitants and no recycling facilities are in place. All material is currently landfilled. An optimal combination of recycling facilities, according to Galan et al. (2013), was three processing plants or one processing plant combined with three transfer stations. In the suggested scenarios, transport distances for C&D waste could be reduced by 35% (Galan et al., 2013).

Robinson and Kapo (2004) analyzed the suitability for recycling facilities in Maryland and Virginia of United States and Yuan (2013) studied the strengths and weaknesses for improved construction waste management in Hong Kong, China. One of the conclusions drawn was that the selection of appropriate locations for recycling facilities is critical for its economic viability, and to reduce total transports and environmental impact.

5. Analysis

The known quantities of excavated soil and rock, construction material demand and use are presented in Fig. 2.

Flow *A* corresponds to the demand and use of construction materials such as soil, sand, gravel and rock. From the review, it can be found that there is a lack of knowledge about what materials and how much is used in construction. The data presented for flow *A* are estimations on demand and use of construction minerals. Unfortunately, available data excludes excavated soil and rock. The use of construction minerals such as sand, gravel and rock, varies heavily, up to 7 times. This can partly be explained by fluctuations in economy, which impacts on the construction intensity (Huang and Hsu, 2003). Even though data in flow *A* does not cover the total demand of excavated soil and rock, it is still valuable since it gives an idea of how much material is used.

The data quality for the use of construction minerals such as sand, gravel and rock (Flow *B*) is relatively high since it is based on real production data from the construction industry and since there are less differences in the definitions of this flow. Data on flow *B* have been presented in several studies.

Of the reviewed literature, there are only two studies that estimate the quantity of excavated soil and rock that is being sent to recycling facilities (Flow *C*). The studies have been conducted on two urban regions where there are significant differences between waste management practices for excavated soil and rock. In one of the regions, excavated soil and rock is sent to recycling facilities while such practices are minimal in the other region. Instead, excavated soil and rock is landfilled directly. The minimal flow (*C*) is illustrated in Fig. 2 with a zero value. The knowledge base about flow *D* and *E* is even weaker since only one example of quantification was found.

There is a major lack of knowledge regarding excavated soil and rock used within the project or sent to other projects (Flow *F*) and this management is hardly ever described in literature. It could be discussed if such knowledge lack is due to a general attitude that Flow *F* is relatively insignificant in terms of quantities, resource demand, environmental impact and waste generation. It can also be explained by the fact that Flow *F* is an internal flow which is usually not considered in urban metabolism. In addition, Flow *F* is usually not recorded in any official waste statistics since it is not sent to recycling facilities or landfills but transported directly between construction projects.

The use of excavated soil and rock in construction is a fraction of Flow *A* and is cumulated in the active stock (Flow *G*). Since no study estimates the complete Flow *A* there is thus no estimation of the complete active stock.

The direct landfilling (Flow *H*) and the use of excavated soil and rock as cover material at landfills seems to be a common management approach. The European strategy for landfills is focused on the closing of landfills (European Environment Agency, 2009). In Europe, the need for cover material at closing landfills is time-limited and there is a growing need for construction materials in urban regions. From this situation, it could be questioned if the accumulation of excavated soil and rock at landfills due to covering purposes should be labeled as recycling.

None of the flows $I - L$ are estimated in the reviewed literature and it could be discussed how significant these flows are in the context of excavated soil and rock. Flow *I* usually consist of rock flour which is excess material from extraction in quarries. This flow has little significance to the flow of excavated soil and rock and is often disposed. Flow *J* and *K* can consist of both excavated soil and rock. At the local level, it is reasonable to assume that excavated soil and rock is imported and exported, i.e. shared with other construction sites. From a regional perspective, it is reasonable to assume that these flows primarily consist of quarry materials since they have a higher market value and higher margins and thus are able to carry higher transportation costs.

The flow through of excavated soil and rock (Flow *L*) could be significant when the model is applied at a small scale. At the project level or local level, it could be used to describe the effectiveness of construction material management such as logistics and transportation.

The consequence of the general lack regarding knowledge of quantities and management of excavated soil and rock is the almost impossible task to estimate resource efficiency and the potential for improvements. Since official statistics usually not record the flows of excavated soil and rock, it can be beneficial to make qualified

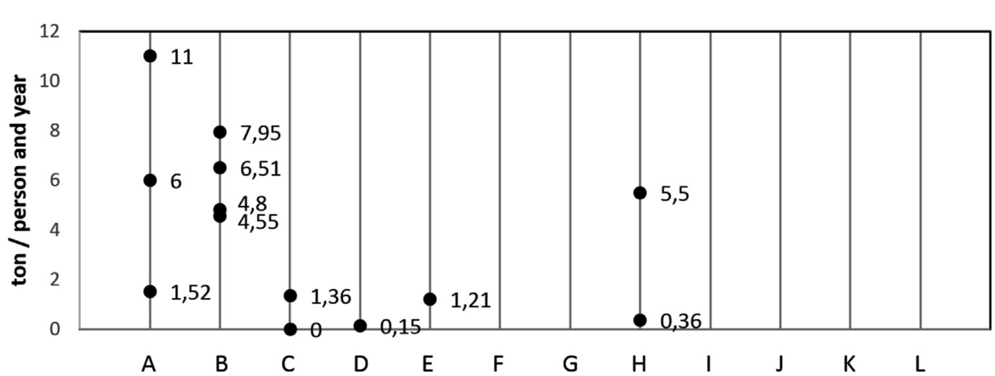

Fig. 2. Known quantities of excavated soil and rock, construction material demand and construction material use.

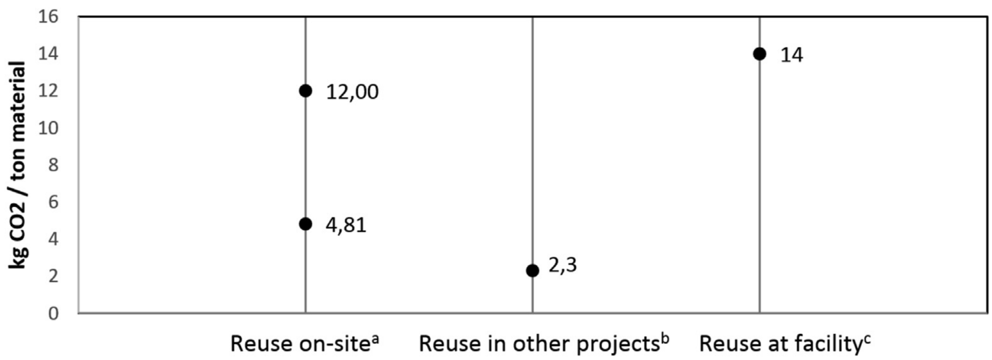

Fig. 3. CO_2 savings due to excavated soil and rock reuse on-site, in other projects and at facility. [a]Data gathered from *Improving the environmental performance of an earthwork project using cleaner production strategies* (Eras et al., 2013) *and* from *Sustainable Reutilization of Excavated Trench Material* (Chittoori et al., 2012). Assuming a density of 1.6 tons per m^3. [b]Data gathered from *Remediation of Four Sites in Northwest England: A Successfully Completed Multi-Site, Multi-Consultant Cluster Project* (CL: AIRE, 2013). Assuming a density of 1.6 tons per m^3. [c]Data gathered from *Resources and waste management in Turin (Italy): the role of recycled aggregates in the sustainable supply mix* (Blengini and Garbarino, 2010).

estimations. Key estimations would be the generation of excavated soil and rock and the demand for rock, gravel, and sand caused by construction activities.

Illustrating and quantifying the flows of construction materials can facilitate a discussion on not only construction materials and waste but also on the metabolism of these materials, with a larger focus on how they are managed and the resource efficiency in the system. Such discussions are important for developing cities where construction activity is high and where there is a lack of sites for material reuse and limited landfill capacity.

The environmental benefits for using excavated soil and rock in construction have been evaluated from different handling perspectives. The climate impact from extracting, processing and handling quarry materials has been estimated to 7.8 kg and 10,3 kg of CO_2 per ton material, respectively (Simion et al., 2013; Zuo et al., 2013). In Fig. 3, estimations are presented on CO_2 savings when reusing excavated soil and rock on-site, in other projects or by preparing the material at recycling facilities.

CO_2 savings can be achieved with all reusing strategies and can be significant. Increasing reuse on-site and hence reducing fuel consumption gives significant CO_2 savings (Chittoori et al., 2012; Eras et al., 2013). The reuse of excavated soil and rock in other projects may also result in CO_2 savings due to reduced transportation need to disposal sites and quarries. In these cases, the CO_2 impact from using new quarry material and from disposal has not been included, so the saving potential is probably underestimated. The study by Blengini and Garbarino (2010) is the only example where the environmental impacts of recycling of excavated soil and rock is assessed from a complete life cycle perspective. The CO_2 savings are mainly achieved by less landfilling of materials. Environmental data are scarce for all types of reuse. The largest knowledge gap seems to be for the environmental benefits of reuse in other projects. Coordination of construction projects and management of excavated soil and rock gave a lower climate impact, less transportation, less material landfilled and less need of quarry materials (CL: AIRE, 2013). However, there is a need for scientific evidence and further research to assess the environmental potential of reuse. The coordination of excavated soil and rock between projects would require early planning. The knowledge about future resource needs and the quantities and qualities of excavated soil and rock generated in projects is a basis for such planning.

6. Conclusions

This study concludes that a resource perspective on excavated soil and rock in urban areas is missing. A waste perspective is prominent in the scientific literature. Main focus is on recycling potential and its environmental benefits. In this paper we show that it is possible to apply a resource perspective to describe the flow of excavated soil and rock. We identify 8 potential significant flows of excavated soil and rock in urban regions. The scientific literature deals only with a few of these.

This study concludes that it was not possible to reveal the quantities of excavated soil and rock in urban regions from the scientific literature. General management of excavated soil and rock are landfilling but can also be recycling at facilities, use on-site in construction or use directly in other construction projects. A few quantifications have been made, and they show that landfilling of excavated soil and rock is in the range of 0.4 to 5.5 tons per capita and year. The use of quarry materials ranged from 4.6 to 8.0 tons per capita and year. However, the flows are all largely unexplored and more research is needed.

The reuse of excavated soil and rock in construction can reduce costs and climate impact since transportation, landfilling and use of quarry materials are reduced. The few studies available indicate that saving potentials for reusing excavated soil and rock are up to 14 kg CO_2 per ton. For a single construction project, reusing excavated soil and rock can reduce the material handling costs with 85%. However, more research is needed to clarify the environmental and economic benefits. It is concluded that the regional management of construction materials and excavated soil and rock could benefit from coordination of construction projects. This will need strategic planning at an early stage where the future demand and availability of construction material is assessed. Decisions on all levels will be needed, from construction project level for increasing reuse on-site to regional authority level for improving the conditions for reuse, such as establishments of hubs where material can be stored and sorted for later use in construction.

Acknowledgments

We would like to acknowledge the Swedish Transport Administration and The Swedish Research Council Formas, for their financial support to the study, which was conducted as a part of the project "Optimass". The support from Luleå University of Technology and Ecoloop AB are also highly appreciated and acknowledged.

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