KTH Industrial Engineering
and Management

Sustainable mass handling

Modelling quantities of excavated soil and rock in residential construction projects

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Master of Science Thesis
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2014-06-03	Peter Hagström	Peter Hagström

Abstract

An efficient handling process of aggregates and excavated soil and rock will be of increasing importance in expanding urban regions. The construction of residences, infrastructure and commercial areas generate significant amounts of soil and rock that can be re-used more efficiently as construction material, minimizing transportation and environmental impact. A key element is the implementation of central intermediate storage sites for re-use purposes and cooperation between several construction projects in a region. The evaluation of storage capacities and optimal site locations is in turn dependent on comprehensive knowledge about what quantities of aggregates and excavated soil and rock that will be generated and utilized in the region.

The calculation model presented in this thesis provides a way of estimating the amount of excavated soil and rock generated during the construction of new residential areas at an initial stage of the planning process. The excavated volume is expressed as a function of the number of residents and the number of floors in the buildings of the planned area, allowing for an early estimation that may effectively influence the logistical planning of the mass handling process. The simplified calculation model applied to a case study of the existing residential area Annedal in Stockholm produces an estimated amount of 577 500 ton excavated soil and rock, approximately 3.8 % lower than the reference value of 600 000 ton.

Regional storage sites are advantageous as different construction projects generate and utilize different types of soil, rock and aggregates, resulting in a higher possible re-use share than in individual projects. When regarding the energy usage in transportation, it is shown that intermediate storage sites located within 10 km of the construction site may allow for more than 15 % energy reduction if re-using 25 % of the excavated amount of soil and rock. A distance of 5 km may yield more than 20 % reduction of transportation energy for the same share of re-use.

Sammanfattning

En effektiv hantering av ballast och utgrävda jord– och bergmassor blir allt viktigare i stadsregioner under utveckling. Byggnationer av bostäder, infrastruktur och kommersiella områden genererar betydande mängder jord och berg som kan återanvändas mer effektivt som konstruktionsmaterial med mindre transporter och miljöpåverkan som följd. En förutsättningar är centrala platser för mellanlagring där återanvändning och samarbete mellan olika byggnationprojekt i en region kan ske. Utvärderingen av mellanlagrens plats och kapacitet är i sin tur beroende av kunskap om vilka mängder utgrävda jord – och bergmassor och ballast som kommer att genereras och användas i regionen.

Beräkningsmodellen som preseneras i denna rapport möjliggör en tidig uppskattning av den mängd jord – och bergmassor som uppstår vid nybyggnationer av bostadsområden. Den utgrävda volymen uttrycks som en funktion av hur många människor som förväntas flytta in i området samt hur många våningar husen kommer att ha. Detta möjliggör en tidig uppskattning som kan påverka planeringen av hur de utgrävda massorna kan hanteras på ett effektivt sätt. Den förenklade beräkningsmodellen applicerad på det befintliga bostadsområdet Annedal i Stockholm producerar en uppskattad utgrävningsmängd på 577 500 ton, vilket är ca 3.8 % mindre än referensvärdet på 600 000 ton.

Regionala mellanlager är fördelaktiga när olika byggnationsprojekt använder och genererar olika typer av ballast och jord– och bergmassor eftersom det möjliggör en högre återanvändning än i individuella projekt. Sett till den energi som används i transporten av dessa massor är det visat att mellanlager inom 10 km från byggnationsplatsen kan möjliggöra en minskning av energianvändningen på över 15 % om 25 % av de utgrävda jord- och bergmassorna återanvänds. För mellanlager 5 km från byggnationen kan energianvändningen i transporterna minska med över 20 % för samma andel återanvändning.

Acknowledgements

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The thesis' supervision of Peter Hagström has also been greatly appreciated.

Filip Israelsson

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Nomenclature

This section contains a list of notations and abbreviations used in this thesis.

Notations

Symbol	Unit	Description
A	m^2	Area
a_p	-	Share of parking spaces located underground
d	m	Excavation depth
ε	-	Excavation factor
E	kWh	Energy usage in transportation
L	km	Transportation length
l	m	Road and trench length
M	ton	Mass of aggregates and excavated soil and rock
n_a	-	Number of apartments
n_b	-	Number of buildings
n_f	-	Number of floors in the buildings
O	m	Perimeter of buildings and excavation areas
P	-	Number of residents
P_a	-	Number of residents per apartment
Q	kWh/t-km	Energy usage per ton-kilometer of freight
R	-	Re-use share
r	m	Excavation range from building edge
ϱ	ton/m^3	Density of aggregates and excavated soil and rock
V	m^3	Volume of aggregates and excavated soil and rock
w	m	Road width

Abbreviations

ESAR	Excavated soil and rock
GFA	Gross floor area
PF	Perimeter factor

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1 Project description

The master's thesis is performed at Ecoloop AB within the framework of the larger project *Optimass*, whose purpose is to develop a more sustainable and energy-efficient handling process of aggregates and excavated soil and rock, ESAR, in urban regions. As it is an interdisciplinary problem tied to different levels of urban development, Optimass is carried out in cooperation between actors in several related fields such as construction, transport, city planning and academic research.

One of the challenges when attempting to achieve a more sustainable handling process of aggregates and ESAR is the ability to plan ahead and knowing where, what quantities and what types of ESAR that will be generated within a region years in advance. This thesis is aiming to address this issue by developing a calculation model able to estimate the amount of ESAR that is generated when constructing new urban residential areas at an initial stage of the planning process. As an evaluation of its applicability, the calculation model is applied to the existing residential area of Annedal in Stockholm.

One way of achieving a more efficient handling process is the use of intermediate storage sites that enables a higher share of ESAR to be re-used and utilized in construction. Using excavated soil and rock as construction aggregate may not only reduce the amount of masses being transported to and from construction sites, but also lower the production of new aggregates and the disposal demand of excess ESAR. In this thesis, the potential of using intermediate storage sites to reduce the transportation is evaluated from an energy usage point of view.

2 Introduction

Stockholm is a growing region and in order to satisfy future demand of housing, jobs and communication it is necessary to continuously construct and maintain residential areas, commercial buildings and urban infrastructure. As a consequence, an increasing amount of aggregates and ESAR will be transported in the region; a material flow that is currently only exceeded by the energy sector (Vaivars, 2010). A growing city also means a more decentralized mass handling where quarries, storage sites and landfills are moved further away from construction-intensive areas, resulting in longer and more energy-inefficient transportation. It is difficult to prioritize central areas for mass handling activities such as landfills, deposits and intermediate storage as such areas are often high in demand by numerous other actors. Additionally, urban-adjacent quarries and landfills may have to shut down operation due to depletion, geological limitations or to satisfy social and environmental criteria, also resulting in longer and more inefficient transportation.

A significant amount of material is being transported and even a relatively small increase of transportation distances may have a large impact on the energy usage down the line. Between 2000 and 2011 an annual average of 6.72 million metric tons of aggregate was delivered in Stockholm County as construction material (SGU, 2013), and this does not include rubble, debris and ESAR generated from construction sites being transported to landfills, as well as the supply of other construction materials such as steel, wood and glass. Aggregate alone is estimated to account for half of all goods transported by trucks and lorries in Sweden (Hultkvist, 2001), and in addition to higher energy usage and emissions; higher traffic load, road wear and noise problems may be expected to occur if the handling process of ESAR and aggregate is not improved.

As of now there is no generalized practice that allows actors involved in construction projects to coordinate their mass handling process efficiently or to encourage different projects to cooperate when regarding logistics, re-use of ESAR and utilization of mutual storage sites. As there are many different actors involved in the process, it is not clear on what level, or by whom, the challenges with achieving a sustainable situation needs to be addressed.

2.1 Purpose of the thesis

The goal of this thesis is to highlight potential energy savings when applying a more efficient handling process of ESAR and aggregates in residential construction projects. It also aims to produce a calculation model for future construction projects which is able to estimate the amount of ESAR and aggregate related to a planned residential area at an early stage. As of now, this is not a common practice and mass handling inefficiencies arise later on in the construction process. A better knowledge about what quantities of ESAR that will be generated in a region is a prerequisite for being able to plan more efficient logistics and reserve areas for intermediate storage. These areas may in turn enable a higher share of re-used ESAR within construction projects and act as cooperation nodes between several adjacent projects in a region. In this way, ESAR from one construction project may more efficiently be utilized in another, minimizing transportation and the demand of new material.

The objective of the thesis can be broken down and clarified with the following two questions:

- Can the amount of ESAR and aggregate related to a residential construction project be estimated at an early stage of the planning process?
- Can the handling process of ESAR and aggregate be made more energy-efficient with the use of intermediate storage sites and a larger share of re-used masses?

A better knowledge about ESAR and aggregate quantities when planning future construction projects enables the possibility to control and influence the handling process at an earlier stage and the results of this thesis are intended to be of importance to numerous actors involved in the planning process of new residential areas. Additionally, the economic feasibility of implementing and operating storage sites is highly dependent on the amount of ESAR and aggregate that will be handled in a region in the future and the results of this thesis is intended to be able to give such indications.

The thesis is however not intended to give indications regarding technical aspects of construction, which types of aggregates are to be used or how they should be utilized. A more thorough and comprehensive evaluation of specific constructions projects must be carried out at a later stage in order to determine the construction approach. This is typically done in a detailed plan which is also specifying environmental aspects of the project, as seen in section 3.2.

2.2 System boundaries

Figure 1 illustrates the system boundaries of the thesis and how it relates to the parent project Optimass.

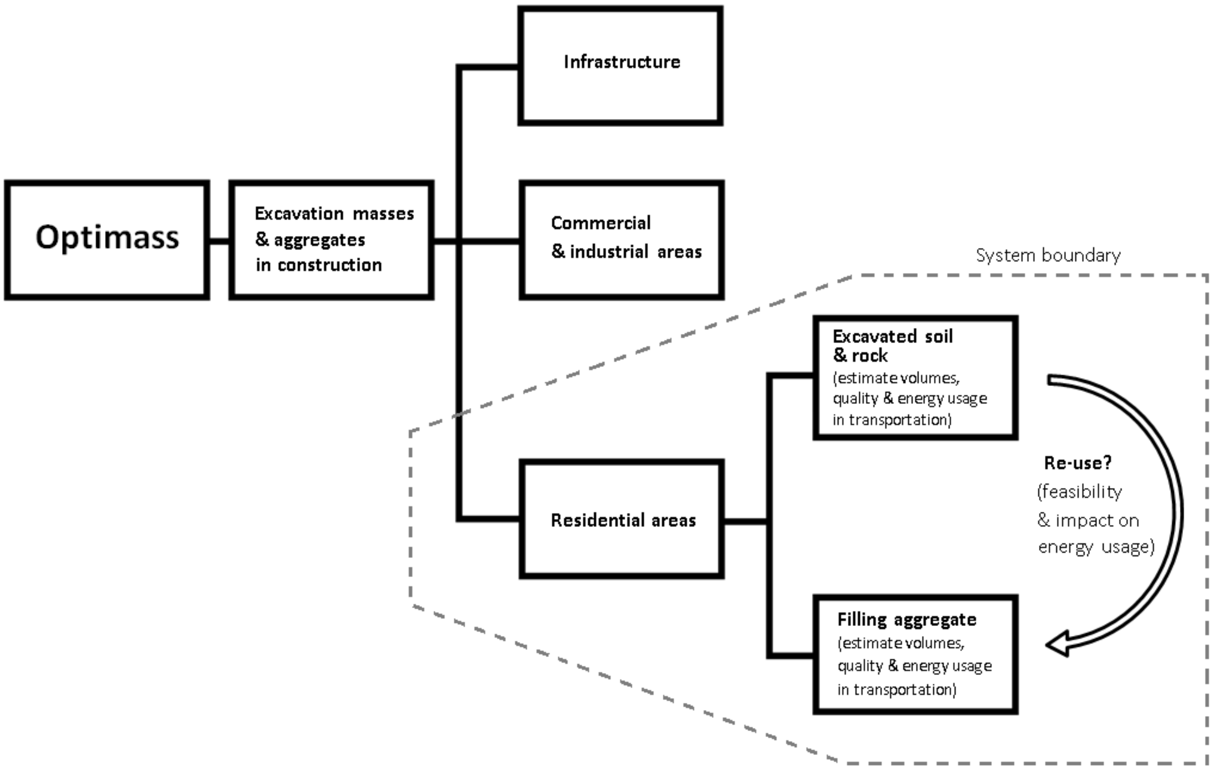

Figure 1. System boundary of the thesis

In parallel to this thesis, similar projects are aiming to assess the volumes of ESAR and aggregates related to the construction of infrastructure, industrial and commercial areas. Figure 1 only show one branch of the Optimass project which is also including several other aspects of sustainable mass handling, such as analysis of related actors and new technologies for improving and upgrading lower quality ESAR.

2.3 Scope

The calculation model in this thesis is coupled with several simplifications and generalizations in order to make the model applicable as early as possible in the planning process of urban development. The system boundaries include a well-defined area for residential exploitation with regards to an estimated growth in population. Only the residential area itself is included and other major construction projects that may be integrated in the exploitation are not considered, such as major infrastructural projects related to the residential area (i.e. road and public transport projects). Accordingly, only road construction within the residential area itself is included in the calculation model. Furthermore, the model is not applicable to other types of exploitation areas, such as industrial or commercial, as the construction process and layout of these areas is often very different.

Simplifications are also made when regarding construction techniques in order to achieve a generalized calculation method. Construction techniques may have an impact on the generated and utilized amount of ESAR and aggregate, but it is estimated that such impacts are negligible for the purpose of this thesis. It is a difficult aspect to address comprehensively and many different construction practices may be used in the same residential area as there are often numerous entrepreneurs involved in the same project.

Only aggregate for filling purposes are considered as utilized masses in this thesis. Many other materials are used during construction, such as concrete, steel, glass, wood etc. but filling aggregates are assumed to comprise the major share, both in weight and volume. Additionally, the type and usability of the ESAR is highly dependent on the previously usage of the area and demolition debris and contaminated soil may be significant if the area has, for example, been an industrial site. In this thesis, such masses are not accounted for and the residential areas are assumed to be constructed on previously un-used sites. Excavation volume contributions from large topographic deviations are also neglected in the calculation model.

Energy usage in the handling process is referring to the energy used in transportation of masses by truck only. Energy is used in many other areas of the process, such as crushing, sorting and treating ESAR, and different means of transportation is also affecting the efficiency. In the Stockholm region, truck transportation is considered to be an integral part of the handling logistics; while other means of transportation might be more efficient, they are also more dependent on geographical conditions and are as such often limited.

3 Background

Efficient handling of aggregate and excavated soil and rock, ESAR, is an important but complex issue. The flow of aggregate and ESAR in urban regions is managed by actors in many different levels of construction and city-planning. It is not clear by whom the challenges related to an inefficient handling situation should be governed, and as such, the solutions are not automatically assigned to any one actor involved in the industry. A more efficient transportation and material usage may also be economically unfavorable for many actors, for example less transportation for a freight contractor, and improving the situation is not always prioritized. Another central issue related to a sustainable handling of aggregate and ESAR is the lack of knowledge regarding what quantities are generated and utilized in a region and a more comprehensive mapping of the problem is required, both in terms of the mass flow and of the actors involved in the process.

3.1 A sustainable handling process

The handling process of aggregates and ESAR is coupled with several different aspects of sustainability, as illustrated in Figure 2. Many societal areas are affecting, or are affected by, how the masses are produced, handled and utilized. Economic growth and an increasing population are driving forces behind new construction projects, setting the demand for the aggregate supply and increasing the generation of ESAR. At the same time, well-developed infrastructure and available housing is a prerequisite for the expansion and development of urban regions.

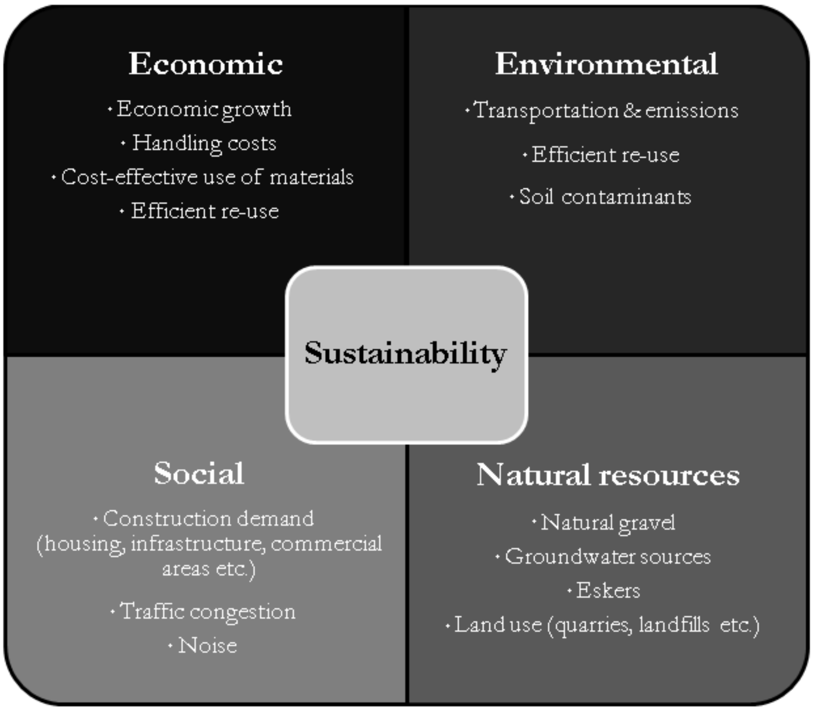

Figure 2. Societal areas affecting, or affected by, the use and handling of aggregates and ESAR

Challenges related to the handling process of aggregate and ESAR are co-developed with many aspects of a growing city region. Urban expansion is continuously producing larger volumes of ESAR and setting a higher demand of construction material, while the same time requiring longer transportation and producing higher emissions. As the region expands, population wise and geographically, efficient handling of aggregate and ESAR will be of increasing importance and many different challenges must be addressed in order to achieve sustainability. There are several feasible methods that may have a positive impact on the handling process, but it is likely that none of them alone is a solution. The ability to estimate what quantities of ESAR that will be generated in an area is however essential for any of them to be efficiently applicable.

- *More efficient transportation* methods can be utilized to achieve a more sustainable situation, such as rail and sea freight instead of trucks. This is highly dependent on geographical and infrastructural limitations and is required to be supported by extensive logistical planning.
- *Cooperation nodes* between operators in construction and logistics can increase awareness and allow for a "smarter" use of aggregates, i.e. buying and selling ESAR to more adjacent construction projects. Such cooperation requires good planning and knowledge of what quantities are excavated and how much aggregate is needed in specific projects. There is also a classification problem related to this method as aggregate in construction is often subject to very strict requirements. It is important to know the exact properties of the ESAR that are traded to ensure they measure up to the requirements and are not contaminated.
- *Intermediate storage sites* in central areas can enable a higher share of re-used ESAR within construction projects, as well as cooperation between several projects in a region. Implementation of central storage sites may not only shorten transportation distances but also lower the demand of new aggregate from quarries and the disposal of excess ESAR in landfills or deposits.
- *New technologies* for upgrading and treating ESAR can provide ways of utilizing a higher share in construction. Such methods can allow for more re-used ESAR as filling and construction aggregate as well as a more efficient re-use process. This may for example be referring to the removal of certain contaminants in an efficient way or stabilizing soft soil and clay instead of excavating and replacing it when developing an area.

3.2 The construction planning process

The planning process to develop a new urban residential area in Sweden is progressed in primarily four different phases. The time of validity for each phase may differ depending on the rate of development in the area and several phases may overlap as they cover different levels of detail (HMK bygg & anläggning, 1996):

- The *regional plan* is an early and not very detailed plan that acts as guidance for a region's future development. The regional plan covers long-term changes that will be affecting the entire region, such as communication and health care, but also the need for new residential areas.
- The *comprehensive plan* is presenting a municipal's long-term plans regarding future construction projects, resource usage, land-use etc. It is mandatory for all municipals in Sweden and is purposed to show how the municipal will develop within the next few years while still catering to national interests. The comprehensive plan is more detailed than the regional plan and covers specific development areas more thoroughly.
- A *deepened comprehensive plan* is used as an advisory tool for a specific development area, such as a planned residential area, and covers more details than the comprehensive plan within a smaller geographical area.
- A *detailed plan* is established to gain building permits for a development area in order to let the actual construction process commence. The detailed plan covers very specific aspects and requirements of the construction and is the product of a more careful planning phase, typically involving thorough environmental testing and evaluations of how the surrounding area will be affected.

This thesis is considered to be of relevance primarily within the regional and comprehensive plans, but in some cases all the way up to the initial part of the detailed plan. Subsequent assessments in the detailed plan has the ability to take more project specific aspects of a proposed residential area into consideration, enabling more accurate estimations of the amount and quality of ESAR, as well as the feasibility of different logistical solutions. However, as the detailed plan is established, the timeframe of developing a sustainable plan for handling the excavated volumes is more limited than in the previous stages. An earlier estimation may in such cases have a greater impact than a more comprehensive and accurate one as it can be incorporated in the planning process from the start.

3.3 Aggregate and ESAR

Aggregate is a collective term for crushed rock, gravel, till and sand that is used in various construction applications. Combined with cement and water it forms concrete, and as such its supply is essential for the expansion and maintenance of a modern society. Aggregate is also used as filling material in construction foundations and trenches, as structural support for infrastructure and as asphalt when gravel is combined with bitumen. Aggregate is the most mined commodity in the world by volume and second only to fossil fuel it terms of production value (Solar et al., 2004). The production process normally consists of mining or quarrying, followed by crushing and sorting by grain size. Different grain sizes are suitable for different construction applications and may range anywhere from 0-2 millimeters up to a few centimeters (SGU, 2007). When used in more sensitive construction areas, the aggregate can be washed in order to remove dust particles and harmful substances.

3.3.1 Natural gravel

Natural gravel is a finite resource produced by the ice sheet and glaciers several thousand years ago. It has been widely used as aggregate in Sweden but national environmental goals aim to lower its share of the total aggregate production and prohibit new extraction sites from opening (Göransson, 2011). Between 1985 and 2011, the use of natural gravel decreased from 76 % to 17 % of the total amount of aggregate delivered in Sweden (SGU, 2013). The purpose of the reduction is to economize the use of a finite resource and to preserve eskers and associated natural groundwater sources. Eskers have an important role when regarding geohydrology as they naturally purifies water, a function that is essential for certain natural water reservoirs.

In many cases, crushed rock can efficiently replace natural gravel as aggregate but there are still some applications where it is difficult to use substitutes; for example, the grain shape of natural gravel may give concrete rheological properties necessary for a specific construction project. Today, more than 40 % of the excavated natural gravel is used in concrete while less performance-demanding areas are largely covered by crushed rock and other aggregates (Göransson, 2011).

3.3.2 Sand, silt and clay

Sand, silt and clay are granular soils with smaller grain fractions than gravel. Sand is comprised of grain sizes between 0.063 – 2.0 mm, silt between 0.002 - 0.063 and clay below 0.002 mm (LTU, 2009a). Soil containing silt and clay are often difficult to use in construction as they may be softer and more prone to settle and compress over time. There is also a risk of frost heave when utilizing these soils as their permeable properties are often too low for many filling purposes, making them less suitable than masses with larger grains such as gravel and crushed rock. Frost heave is caused when soils retaining water swell up during freezing conditions.

3.3.3 Till

Till is an unsorted soil type consisting of granular masses with very different grain sizes, ranging from clay particles of 0.002 mm up to large blocks of rock (Avén, 1984a). As such, excavated till is a mix of several soil types, including sand, silt, clay, gravel and rock, and its applicability in construction is dependent on this distribution. In applications where gravel is required, for example, till with high gravel content will be more suitable and a larger share of the till can be used, rather than till with high clay content and a large volume of very small soil particles.

3.4 Generation and re-use of ESAR

At an early stage of a construction project it is necessary to develop and prepare the ground within the project area. This earthwork includes excavation of soil and rock to construct building foundations, removal of debris and contaminated soil, digging trenches, smoothing uneven areas, dredging water streams and much more. During this process, large quantities of soil and rock are excavated and removed from the construction site. From an economic and environmental point of view, as much as possible of the ESAR are to be re-used within the construction project, or in an adjacent project, in order to minimize transportation and the demand of new aggregate. This is often difficult in practice due to the lack of storage areas and the possibilities of upgrading and refining ESAR on-site. Short deadlines and quick decisions make it even more difficult for entrepreneurs to coordinate their mass handling efforts as the timeframe for planning is limited. Additionally, ESAR must be classified and categorized before re-use to make sure they measure up to specific standards, in terms of gain size, contaminant content, organic content, durability etc., that is required in many construction areas (Hultkvist, 2001). Classification requires testing, sampling and sorting that could prove challenging for time-pressured construction projects.

3.5 Aggregate in construction

In 2011, approximately 7.5 million metric tons of aggregate was delivered in Stockholm County and the different areas of usage was divided as illustrated in Figure 3 (SGU, 2013). The segment *other* may typically include the use of aggregate in natural form, but not for sole filling purposes, such as in road gritting, playgrounds, walking trails or in other types of recreational areas.

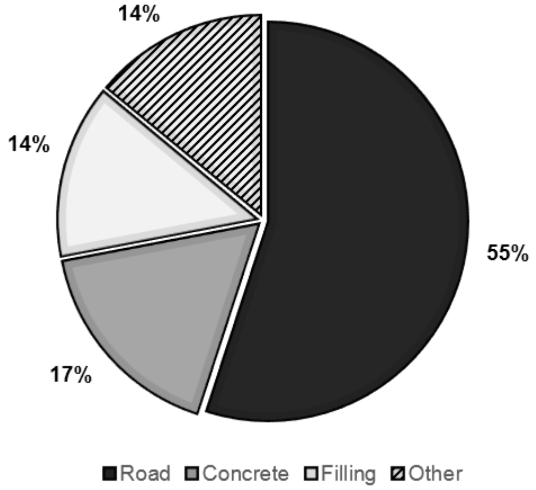

Figure 3. Delivered aggregate in Stockholm County distributed by area of usage (SGU, 2013)

3.5.1 Concrete

Concrete is made by mixing aggregate particles, such as gravel, with cement and water. The proportion of aggregate is govern by the desired concrete properties but may typically be 80 % of the weight if used for housing construction (Hertzell, 2002). The choice of aggregate, cement, additives, casting frame and production method also influences esthetic properties of concrete such as brightness and surface structure. Additives is primarily substances that alter physical properties of concrete or speeds up the hardening process, but may also be coloring pigments to make non-gray concrete.

3.5.2 Filling and structural support

Utilizing aggregate as filling material is essential when constructing residential areas. It is done to provide protection and ground stability to buildings, roads, parking lots and underground pipe and cable trenches, as well as giving surrounding soil desired properties such as suitable permeability. Buildings, for example, require permeable material around its foundation to enable water drainage and cable trenches requires very fine aggregate to avoid wear damage.

3.5.2.1 House foundations

There are many ways of utilizing aggregate as filling material when constructing residential houses. The different filling procedures are dependent on the foundation structure of the house and local geological and topographical conditions, but some key elements are important regardless of construction method. Permeable material is filled under and close to the lower parts of the foundation; this layer of aggregate may typically consist of coarse gravel or crushed rock and has the function of breaking the capillary forces of water in the surrounding soil, stopping it from damaging the foundation. The backfill above the permeable layer also need to possess some capillary breaking properties and should not retain water and moisture. The filling aggregate will also need to have a low content of organic material as organic substances decompose over time, causing the ground to settle and exposing the structure to stress.

3.5.2.2 Roads and walkways

Road construction is an area subjected to high requirements of correct filling aggregate as they are load bearing, exposed to wear damage and needs to have a long life span. Specific technical requirements of filling material in the roads may depend on factors such as surrounding soil type, climate and traffic load (Svensk Byggtjänst, 2011a). In general, filling material in roads consists of crushed rock or gravel to provide stability, load support and water drainage, even if other types of masses can be used under specific circumstances. The filling is typically divided into 4-5 layers with different properties such as a load bearing layer, a stability layer and a wear protection layer (Vägverket, 2008; Gullberg et al., 2012), each one with specific requirements regarding grain size, the presence of larger blocks, organic content, densification etc.

3.5.2.3 Pipe and cable trenches

Filling aggregate in pipe and cable trenches is similar to that in roads and is also subject to strict requirements. The lower layer typically needs to provide load support and stability while the layer directly around the pipe or cable is protecting against wear damage. Permeability is also an important property of filling material in trenches to limit the risk of water damage and frost heave. The top layer, or backfill, of a trench may consist of sand, gravel or even certain types of clay if treated properly to ensure low organic content and softness (Chittoori et al., 2012). What material is used as backfill is also depending on what the overlaying area is used for and trenches under roads and other paved surfaces will have more strict requirements.

4 Methodology

In order to highlight the importance of planning the handling process of ESAR and aggregate at an early stage, the calculation model developed in this thesis is applied to a case study of the existing residential area Annedal in Stockholm. The result of the case study is purposed to be used as an evaluation of the calculation model and the discrepancy between the calculated result and a reference value is analyzed. Additionally, the result of the case study is used as a basis for evaluating possible energy savings in transportation by re-using the ESAR generated in Annedal as filling aggregate.

The general methodology used in this thesis is illustrated further by the following four sections:

- Assessment of what types of ESAR and aggregates are related to the construction of residential areas and how they are generated and utilized during the process. See section 0.
- Development of a calculation model for estimating the quantities of ESAR and aggregates that are generated and utilized during the construction of a residential area. The development process begins with a detailed, comprehensive model followed by simplifications in order to achieve a more easily applicable model. See sections 0 - 0.
- Evaluation of possible energy savings in transportation by implementing intermediate storage sites for a higher share of re-used ESAR. See section 0.
- Application of the calculation model to a case study of the existing residential area Annedal in Stockholm. Both the detailed and simplified models are applied and evaluated. See section 0.

All calculations in this thesis are done using MATLAB (MathWorks, 2013) and Microsoft Excel.

4.1 Calculation of ESAR and aggregate volumes

The calculation model is aiming to estimate the amount of ESAR and aggregates related to the construction of a residential area; how much soil and rock is being generated from excavation and earthwork and how much aggregate is utilized as filling material. The purpose of the calculation model is to serve as an initial estimation tool when planning future residential areas in order to influence and coordinate the handling process, as well as evaluation of potential locations and capacities of storage sites.

ESAR and aggregates are expected to be generated and utilized in two major areas within a residential construction project:

- House construction (including underground parking garages)
- Roads and trenches

These areas are assumed to be the major sources of generated soil and rock from excavation and ground preparation. It is also assumed that the large majority of filling aggregate and construction material will be utilized within these areas. Some masses can be expected to be handled in other areas as well, for example dredging water streams or constructing recreational areas, but these are not included in the generalized calculation model. For specific construction projects where such areas are a considerable contributor to the total amount of ESAR, they can be evaluated separately and then be combined with the calculations presented in this thesis.

4.2 Development and applicability of the model

The amount of ESAR generated from house construction is estimated using two different models. One detailed model which relies on data specific to each building within the residential area and one simplified model which uses mean and standardized values and relates the quantity of ESAR to the number of residents in the area. The amount of ESAR generated from roads and trenches are also calculated using two different models; one considering individual widths and excavation depths of different road and trench segments, and the other using a joint, typical value of the cross-section in order to express to mass volume as a function of road and trench length. In order to simplify even further, the latter model is relating the road and trench lengths to the housing areas. By doing this, the total volume of ESAR from all construction areas can be expressed using the same input parameters. The detailed and simplified models are both applied to the Annedal case study.

The progression from the detailed model to the simplified model goes through several steps as seen in Figure 4.

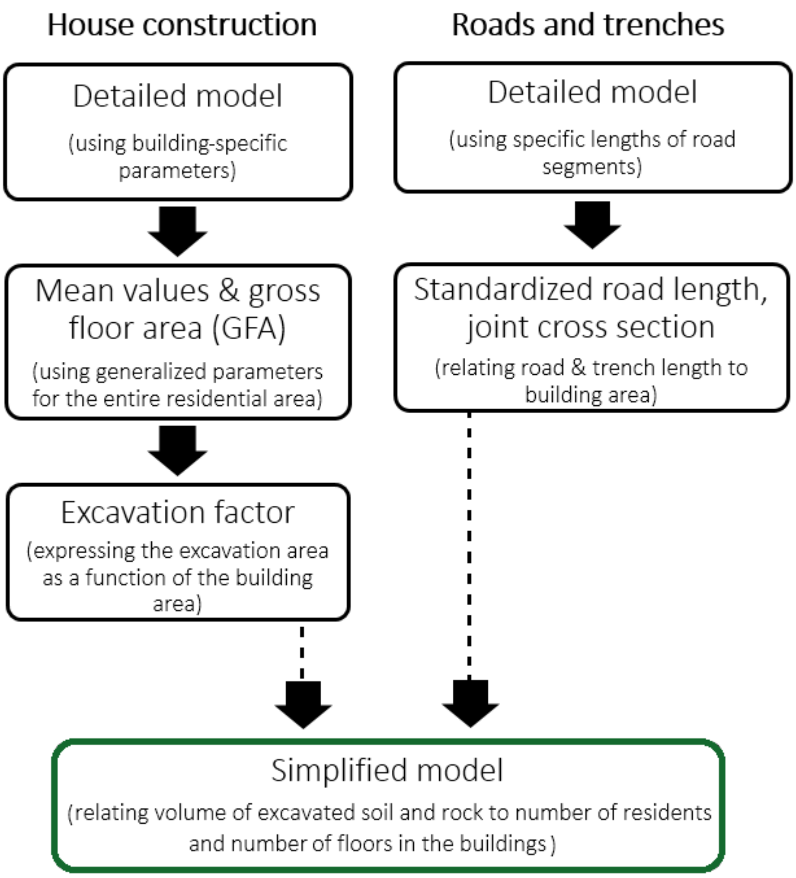

Figure 4. The simplification process

The driving force behind a new residential area is typically an expected or desired growth in population, and as such, the number of residents is estimated in an initial planning phase. The aim of the simplification process is to reduce the complexity of the detail model and relate the amount of ESAR and filling aggregate only to the number of residents and the number of floors in the buildings. This produces a calculation model that is usable as early as possible and increases its impact when planning a region's future mass handling and logistics of its material flow.

The simplified model (primarily Equation 5.29 - 5.30) is developed from the calculation and is presented in section 5.3. This is essentially a combination of the simplified approaches of estimating the amount of ESAR from house, road and trench construction, and is more suitable as a planning tool as the detailed models are very time-consuming and requires many construction parameters to be determined. As seen in section 3.2, this is not the case at an early stage of the planning process and a more generalized approach of estimating ESAR volumes must be implemented. When the planning phase has progressed and a more detailed layout of the residential area is known, the calculation model presented in this project may be obsolete if more thorough investigations has already commenced. The primary purpose of the detailed model is to be used in section 0, the Annedal case study, in order to give indications of the applicability and validity of the simplified model.

The amount of utilized filling aggregate is calculated in both a detailed and simplified approach in section 0. Only the simplified method, which is expressing the filling volume as a function of the ESAR volume, is applied to the case study.

Using the calculation model in a real application is in contrary to Figure 4 starting with the simplified model. As the planning progresses with more details determined about the area, the calculation approach may move towards the detailed model, considering more construction-specific parameters and producing a more accurate estimation.

5 Excavated volumes of soil and rock

The volume of ESAR includes the total volume that is excavated when constructing a residential area and when preparing the ground for construction. This does not only consider excess ESAR transported off the site and leaving the system boundary (Figure 1), but all ESAR generated within the construction site before potential re-use. Volume denotations of ESAR can be seen in Table B-1, Appendix B.

5.1 House construction

Construction of the house foundation can be done in a wide variety of ways depending on project specific conditions, for example local soil type, topography, structural design, number of basement levels etc. In this thesis, the volume of ESAR from house construction, V_i (Figure 5), is generalized to a volume directly around and below a building, i.e. the area to be excavated, A_{ei} (Figure 6), multiplied with an excavation depth, d_i, as shown in Equation 5.3.

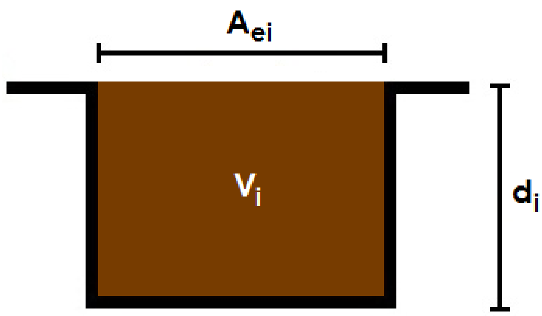

Figure 5. Excavated volume of soil and rock from the construction of a house foundation

5.1.1 Detailed model

The approach of the detailed model is to calculate the amount of ESAR generated from the construction of each individual building and then sum them together. This method takes the different shape and area-to-perimeter ratios of each building into consideration, which in turn is affecting the area to be excavated.

The input parameters used to calculate the amount of masses produced from house construction are presented in Table 1.

Table 1. House and underground parking parameters

Input parameter	Unit	Description
O_i	m	Perimeter of building i, see Figure 6
n_b	-	Number of buildings in the area
n_a	-	Number of apartments in the area
n_f	-	Number of floors in the buildings. The mean value is used if buildings have different number of floors
r_i	m	Excavation range of building i, see Figure 6
A_i	m^2	Ground area covered by building i, see Figure 6
Ae_i	m^2	Excavation area of building i, see Figure 6
d_i	m	Excavation depth of building i, see Figure 6
ρ_i	ton/m^3	Bulk density of ESAR from building i
α_p	-	Share of parking spaces situated underground
GFA	m^2	Gross floor area of the residential area. GFA is the total floor area in all buildings enveloped by the external walls

The volume of ESAR from a building foundation is greater than the volume directly below the building itself as a larger area is being excavated, as seen in Figure 6. Firstly this is due to an engineering aspect of constructing the building; it is necessary to excavate a greater area in order to build a foundation and set up retaining walls. Secondly, it is necessary to fill the volume directly around the building with permeable material to enable water drainage. Figure 6 illustrates how the excavation range r_i around a building increases the area from the ground area covered by the building, A_i, to the excavation area of the building, A_{ei}. O_i and O_{ei} are the perimeters of the building are and the excavation area respectively.

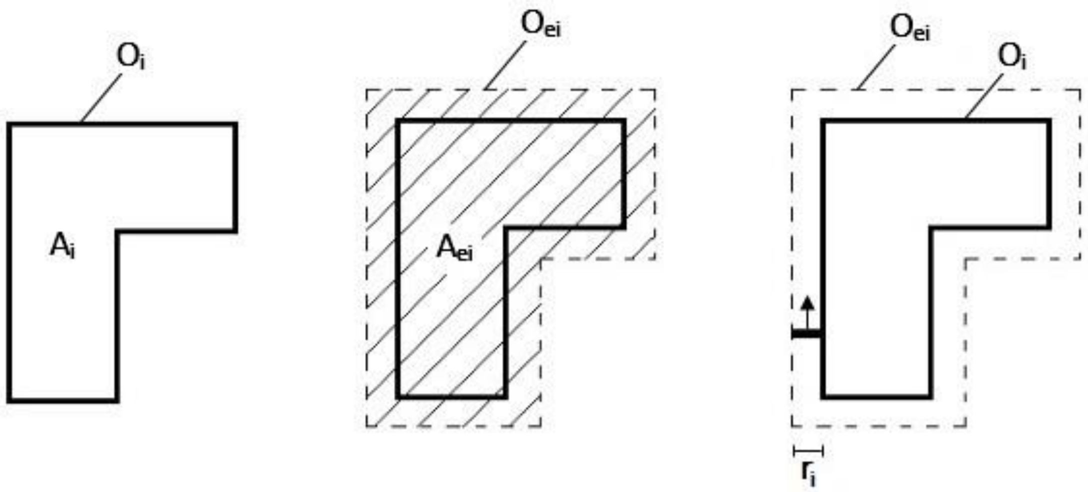

Figure 6. Excavation area and perimeter of a building

The excavation area A_{ei} of a building is expressed as Equation 5.2. This is the striped area in Figure 6 and in order to calculate A_{ei}, the ground area covered by the building, A_i, and the building perimeter, O_i, is measured. The excavation perimeter O_{ei} in Figure 6, is calculated using Equation 5.1.

$$O_{ei} = O_i + 2 \cdot 4 \cdot r_i \tag{5.1}$$

The second term of Equation 5.1 is the distance r_i contributing to an increase of the perimeter from O_i to O_{ei} on four sides of a perpendicular building, twice on each side. The coefficient 4 in Equation 5.1 is valid for buildings where all corners are perpendicular but not for buildings with a more complex architecture. It is however a valid approximation for all buildings where $O_i >> r_i$. From the perimeter O_{ei}, the excavation area A_{ei} is calculated using Equation 5.2.

$$A_{ei} = A_i + r_i \cdot \frac{(O_i + O_{ei})}{2} \tag{5.2}$$

The second term of Equation 5.2 is illustrated by letting a segment of width r_i sweep along the average value of the perimeters O_i and O_{ei} (Figure 6) and let the swept area contribute to the increase of area from A_i to A_{ei}. The volume V_i and mass M_i of the ESAR from a building is calculated using Equation 5.3 - 5.4, where d_i is the excavation depth and ρ_i the bulk density of the ESAR from building i.

$$V_i = A_{ei} \cdot d_i \tag{5.3}$$

$$M_i = V_i \cdot \rho_i \tag{5.4}$$

From the volume and mass of ESAR, V_i and M_i, for each individual building, the total amount of ESAR generated from housing construction is calculated using Equation 5.5 - 5.6. V_h is the total volume and M_h is the total mass of ESAR from house construction and n_b is the number of buildings in the residential area.

$$V_h = \sum_{i=1}^{n_b} V_i \tag{5.5}$$

$$M_h = \sum_{i=1}^{n_b} M_i \tag{5.6}$$

5.1.1.1 Simplifications using mean values, gross floor area and perimeter factor

In order to eliminate building-specific parameters, mean values and approximations of the entire residential area are used to express the amount of ESAR instead of considering individual houses. The purpose is to enable mass and volume estimations of ESAR for construction projects where individual housing parameters are not yet determined. The mean building area A_m (the mean ground area covered by a building in the residential area) is calculated using Equation 5.7. Equation 5.7 is expressing A_m from the total GFA value, Gross Floor Area, of the buildings in the area, the number of buildings, n_b, and the average number of floors in the buildings, n_f.

$$A_m = \frac{GFA}{n_f \cdot n_b} \tag{5.7}$$

GFA is a measurement of the total floor area of all levels of a building enveloped by the external walls, which is a commonly used parameter in early planning stages of residential areas. The approach of finding the mean building area using Equation 5.7 can be illustrated by projecting the total GFA value down to the ground level and dividing by the number of buildings, resulting in an approximation of A_m. It is important to distinguish between GFA and *light* GFA, as the latter only includes floors above ground level. Which GFA value is used will determine if the average n_f value should include basement levels or not. Neither GFA nor light GFA include external roof areas.

Similar to Equation 5.1 - 5.2, the mean excavation perimeter and excavation area, O_{em} and A_{em}, are calculated using Equation 5.8 - 5.9 where r_m is the average excavation range and O_m the mean perimeter of the buildings.

$$O_{em} = O_m + 2 \cdot 4 \cdot r_m \tag{5.8}$$

$$A_{em} = A_m + r_m \cdot \frac{(O_m + O_{em})}{2} \tag{5.9}$$

When the mean perimeter of the buildings, O_m, is unknown and cannot be measured, a perimeter factor, PF, is used to estimate it. The PF_i value of building i is calculated using Equation 5.10 and is a dimensionless measurement of the building's perimeter-to-area ratio which indicates the shape of the building. More complex architecture will generally have a higher PF value as the perimeter will be larger in relation to the area. An average PF value is estimated by using the PF value of a typical building that is representative for the residential area, i.e. the PF of the most common building shape. The average PF value, PF_m, is used in Equation 5.11 to find the mean perimeter O_m.

$$PF_i = \sqrt{\frac{O_i^2}{A_i}} \tag{5.10}$$

$$O_m = PF_m \cdot \sqrt{A_m} \tag{5.11}$$

The amount of ESAR generated from each house is calculated using Equation 5.12 - 5.13, where ρ_m is the mean bulk density and d_m the mean excavation depth. V_m is the volume and the M_m the mass of the ESAR from a building when using the mean value approach presented in this section.

$$V_m = A_{em} \cdot d_m \tag{5.12}$$

$$M_m = V_m \cdot \rho_m \tag{5.13}$$

The total volume and mass, V_h and M_h, of the ESAR is the sum of V_m and M_m for each building as shown in Equation 5.14 - 5.15, where n_b is the total number of buildings.

$$V_h = V_m \cdot n_b \tag{5.14}$$

$$M_h = M_m \cdot n_b \tag{5.15}$$

5.1.1.2 Simplifications using an excavation factor

Further simplifications to the calculation are made by using an excavation factor, ε, as an expression of the area increase between A_m and A_{em}, as shown in Equation 5.16. In other words, ε is an expression of how much larger the excavation area is compared to the ground area covered by the house itself, as seen in Figure 6. This approach is eliminating the perimeter and excavation range from the calculation model.

$$A_{em} = \varepsilon \cdot A_m \tag{5.16}$$

The excavation factor simplifies the calculation model and expresses the total volume of ESAR generated from house construction as Equation 5.17. The excavation factor is essentially simplifying the method of using Equation 5.8 - 5.9 to find the excavation area A_{em}.

$$V_h = \varepsilon \cdot \left(\frac{GFA}{n_f}\right) \cdot d_m \tag{5.17}$$

For specific values of r_m and PF, and for finite intervals of A_m, the ε coefficient may be considered to be constant. Numerical values of the ε coefficient are produced by using Equation 5.8 - 5.9 and 5.11 with constant r_m and PF, and expressing the mean increase of area for different intervals of A_m. For PF = 5 and r_m = 1.5, 1.75, 2 and 2.25, numerical values for four different intervals of A_m are shown in Table 2. It is assumed that houses with a smaller area require a smaller excavation range r_m. These values of r_m are estimated mean values based on Svensk Byggtjänst (2011b) and Chudley (1995), and PF = 5 is approximated by considering typical building shapes of residential houses in urban regions (examples of PF values for the Annedal residential area can be seen in Appendix A).

Table 2. Excavation range and excavation factor for different house area intervals

Mean house area, A_m [m²]	Mean excavation range, r_m [m]	Excavation factor, ε [-]
0 – 400	1.5	1.54
401 – 700	1.75	1.40
701 - 1000	2	1.36
1001 –	2.25	1.35

5.1.1.3 Underground parking

Underground parking garages may account for a significant excavation volume. The number parking spaces is govern by construction regulations in Sweden and is considering specific aspects of the area such as the number of residents and availability of public transport options (Trafikverket, 2013). In urban regions, a number of these parking spaces may be required to be located underground due to spatial issues. The approach in this section is assuming one parking space per apartment and a standard volume for each parking space underground. With an area of 25 m² for each parking space (room for turning and driving in and out of the garage included, estimated in accordance with (Trafikverket, 2004), and a height of 3 m, this volume is 75 m³ per parking space. The total excavation volume for underground parking, V_p, is expressed in Equation 5.18, where α_p is the share of parking spaces located in underground garages and n_a the number of apartments in the area. The denominator 2 in Equation 5.18 is an approximation that half of the underground parking is already accounted for in the excavation volume from house foundations, i.e. half of the underground parking is located directly beneath houses.

$$V_p = \frac{(75 \cdot n_a \cdot \alpha_p)}{2} \tag{5.18}$$

The total volume of ESAR from house and garage construction, V_{htot}, is calculated using Equation 5.19, which is the sum of Equation 5.17 and 5.18.

$$V_{htot} = V_h + V_p = \varepsilon \cdot \left(\frac{GFA}{n_f}\right) \cdot d_m + \frac{(75 \cdot n_a \cdot \alpha_p)}{2} \tag{5.19}$$

5.2 Roads, walkways and trenches

This section covers the method of estimating the quantities of ESAR generated during the construction of roads and infrastructural trenches in a residential area.

5.2.1 Detailed model

Calculating the amount of ESAR from road and walkway construction is a straightforward approach where the volume from a road segment, V_{rj}, is considered to be the product of the segment's width w_{rj}, length l_{rj} and excavation depth d_{rj}. This is done for as many different types of roads and walkways as required. For a road segment j, the volume V_{rj} and mass M_{rj} of the ESAR is calculated using Equation 5.20 - 5.21, where ρ_j is the bulk density of ESAR in the specific road segment.

$$V_{rj} = w_{rj} \cdot l_{rj} \cdot d_{rj} \tag{5.20}$$

$$M_{rj} = V_{rj} \cdot \rho_j \tag{5.21}$$

The total volume and mass, V_r and M_r, of ESAR from road construction is calculated using Equation 5.22 - 5.23, where n_r is the number of different road types or road segments in the area.

$$V_r = \sum_{n=1}^{n_r} V_{rj} \tag{5.22}$$

$$M_r = \sum_{n=1}^{n_r} M_{rj} \tag{5.23}$$

The layout of cable and pipe trenches is highly dependent on surrounding infrastructure as electricity, water, waste and district heating must be connected to the corresponding grid. The dimensions of the trenches may also differ depending on their desired capacity and the surrounding soil and land-use. Main trenches are often excavated alongside, or under, major roads in urban areas and as such, the road length is used to approximate the trench length. Typically, separate trenches are used for different applications, for example electricity and telecommunication in one, water and wastewater in a second and district heating in a third trench (Brodin, 2014). A drainage trench is also often constructed on each side of the road to enable water runoff. In this thesis, these four different types of trenches are assumed to have the same length as the major road length in the area, l_r. The cross section of each trench type is presented in Table 3 where A_t is the total cross section of the trenches.

Table 3. Cross section of different types of trenches

Trench type	Cross section [m^2]
Electricity, telecommunication	0.5 (Brodin, 2014)
Water and wastewater	2.5 (Brodin, 2014)
District heating	6 (estimated)
Drainage	1 + 1 (Brodin, 2014)
A_t	**11**

The cross section A_t is contributing to the amount of ESAR per length of road, and the total volume generated from road and trench construction, V_{rtot}, is expressed as Equation 5.24.

$$V_{rtot} = \left(\sum_{n=1}^{n_r} V_{rj} \right) + l_r \cdot A_t \tag{5.24}$$

5.2.1.1 Simplifications using typical road length and joint cross section

In the simplified approach of calculating the amount of ESAR from road and trench construction, the road dimensions are also expressed using a typical cross section. Furthermore, the road length is estimated by considering the construction intensity of buildings in the area. How much road and infrastructural trenches are built is related to the building area in urban regions as they need to provide communication and resources to all residences. As such, the length of road in an area is expressed in terms of building area (as meter road per square meter building) which also relates the road length to the term GFA/n_f that is used to estimate the volume of ESAR generated from house construction, as seen in Equation 5.17.

From evaluation of the relationship between road length and construction intensity in three different residential areas in Stockholm; Långbrodal, Annedal and Årstafältet (Stockholms Stad, 2014a), the length of road per m^2 of ground area covered by buildings is between 0.03 – 0.05 m/m^2. If using the mean value of 0.04 m/m^2, the road length in a residential area, l_r, is expressed as Equation 5.25.

$$l_r = 0.04 \cdot \frac{GFA}{n_f} \tag{5.25}$$

A typical road width is considered to be 10 m within an urban residential area if including roadside parking and cycling paths (Brodin, 2014). Sidewalk is not included as it is often adjacent to houses and thus already accounted for within the house excavation area, as seen in Figure 6. Together with an excavation depth of 0.6 m (Brodin, 2014; Gullberg et al., 2012) and the total trench cross section A_t of 11 m^2 from Table 3, the joint cross section expressing the volume of ESAR per road length is 17 m^2. Accordingly, the total volume of ESAR generated from road and trench construction, V_{rtot}, is expressed as Equation 5.26.

$$V_{rtot} = 17 \cdot l_r \approx 0.7 \cdot \frac{GFA}{n_f} \tag{5.26}$$

5.3 Simplified model using number of residents

The total volume of ESAR generated from house, road and trench construction in a residential area, V_{out}, is expressed as Equation 5.27, which is the sum of Equation 5.19 and 5.26.

$$V_{out} = V_{htot} + V_{rtot} = \left(\varepsilon \cdot \left(\frac{GFA}{n_f}\right) \cdot d_m + \frac{(75 \cdot n_a \cdot \alpha_p)}{2}\right) + 0.7 \cdot \frac{GFA}{n_f} \tag{5.27}$$

According to Equation 5.27, V_{out} is related to the excavation factor ε, the GFA value, the number of floors in the buildings n_f, the excavation depth d_m, the number of apartments n_a and the share of parking spaces situated underground α_p. By using the standard values and approximations presented in Table 4, Equation 5.27 is simplified to Equation 5.28 which relates the volume of ESAR to the number of residents P. Figure 7 illustrates the approach of Equation 5.28 which is combining the generates volumes from the different areas of construction.

Table 4. Standard values used in the simplified calculation model

Parameter	Standard value	Description
A_{GFA}	0.8 [-]	Unit living area per unit gross floor area of the buildings (Löfdahl, 2003)
A_p	38 [m^2]	Living area per resident (Dagens Nyheter, 2007)
P_a	1.85 [-]	Number of residents per apartment (Dagens Nyheter, 2007)
ε	1.40 [-]	The excavation factor for houses between 401 – 700 m^2 is used as a standard value for multi-family houses in urban regions (see Table 2)
d_m	4 [m]	An excavation depth of 4 m is an approximation for houses constructed with one basement level and where a non-complex foundation is considered (i.e. no stabilized clay, deep piling, significantly sloping terrain etc.)
α_p	0.5 [-]	Simple mean-value approximation that half of the parking spaces are situated underground
ϱ_m	1.65 [ton/m^3]	Mean bulk density of the ESAR, approximated from Table 7

$$V_{out} = P \cdot \left(\left(\frac{\varepsilon \cdot d_m \cdot \frac{A_p}{A_{GFA}}}{n_f} \right) + \left(\frac{0.7 \cdot \frac{A_p}{A_{GFA}}}{n_f} \right) + \left(37.5 \cdot \alpha_p \cdot \frac{1}{P_a} \cdot \right) \right) \tag{5.28}$$

$$V_{out} = P \cdot \left(\boxed{\begin{array}{c}\text{Volume} \\ \text{from houses}\end{array}} + \boxed{\begin{array}{c}\text{Volume from} \\ \text{roads} \\ \text{\& trenches}\end{array}} + \boxed{\begin{array}{c}\text{Volume from} \\ \text{underground} \\ \text{parking}\end{array}} \right)$$

Figure 7. Calculation approach of the simplified model

With the numerical values from Table 4, the volume of ESAR is expressed as Equation 5.29. Accordingly, the total volume of ESAR from constructing a residential area is simplified to a relationship only between the number of residents and the number of floors in the buildings. Equation 5.30 is expressing the total mass of ESAR, M_{out}, using the same approach where ρ_m is the mean bulk density.

$$V_{out} \approx P \cdot \left(\frac{300}{n_f} + 10 \right) \tag{5.29}$$

$$M_{out} \approx P \cdot \left(\frac{300}{n_f} + 10 \right) \cdot \rho_m \tag{5.30}$$

Equation 5.30 is illustrated in Figure 8, which shows the estimated amount of ESAR as a function of the number of residents in a planned residential area, P, for three different building types.

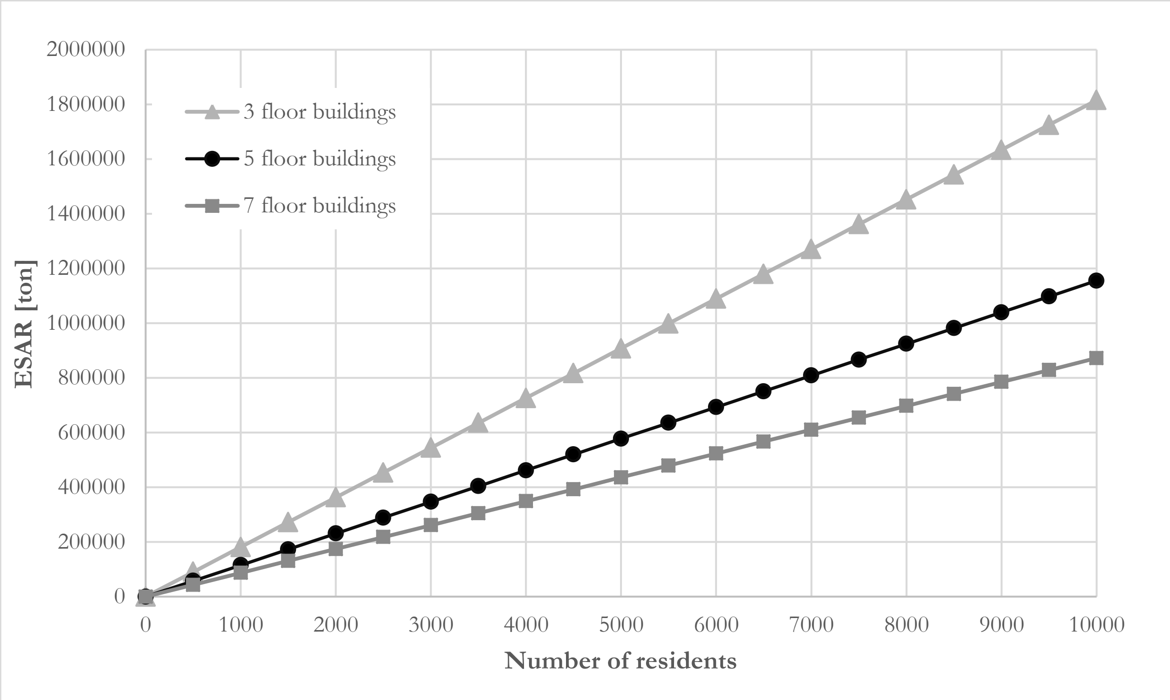

Figure 8. Amount of ESAR estimated using the simplified model for three different building types; 3 floors, 5 floors and 7 floors

5.4 Type and quality of ESAR

At an early planning stage of a new residential area it is likely that thorough geological investigation of the ground has not been performed. At this stage, a geological map can be used to estimate what types of ESAR will be generated in the area and to determine if they are suitable for re-use as filling aggregate. This approach is limited as it will not give any information regarding potentially harmful substances and contaminants in the soil, but it may act as a first indicator of what types of ESAR that can be expected to occur. Figure 13 shows such a map for Annedal in Stockholm.

The geological map can be paired with a land-use plan to identify in which soil type construction and excavation will be most intensive. As seen in Figure 13, housing in Annedal is predominately constructed on glacial and postglacial clay while the relatively small area of rock is occurring in recreational areas. This enables the method of estimating the quantities of different types of ESAR with a geological map to be made with a varying level of accuracy depending on where in the planning process the estimations are made. At an early stage it might not be possible to identify the specific usage of different areas, for example where the majority of houses will be built. In order to get a rough estimation it is possible to correlate ESAR volumes to areas; for example, if 50 % of the ground area is glacial clay, glacial clay will account for approximately 50 % of the ESAR. As more details are known about the construction project a higher level of accuracy can be achieved in the evaluation as different types of construction generate different quantities of ESAR. For example, if 50 % of the *housing area* is built on glacial clay, glacial clay will account for approximately 50 % of the ESAR generated from *house construction*; which may results in more than 50 % glacial clay of the total volume generated from house, road and trench construction combined.

Estimating the amount of different types of ESAR is broken down into three methods with an increasing level of accuracy:

1. The layout of different construction areas is unknown and the quantity of ESAR is correlated to the area percentage of different soils on a geological map.
2. The layout and land-use is known to some extent and the generated amount of ESAR is divided into different construction areas. For example, 70 % of the housing construction is in areas with postglacial clay and 30 % in areas with till. Accordingly, 70 % of the ESAR from housing construction is postglacial clay and 30 % is till.
3. The layout and land-use of the area is completely known and a more detailed calculation approach can be used, essentially taking into account which types of ESAR are generated from each house. Roads and trenches can be divided into area segments and calculated individually.

Which method is most suitable is related to the planning process seen in section 3.2. How much is known about the construction layout in each phase is not explicitly determined beforehand as the planning process may look different for individual construction projects. In general, a detailed plan is required for method 3 to be usable but various feasible scenarios of the layout may be evaluated in previous stages, allowing for several estimations to be performed and evaluated. Method 1 and 2 is looked at more closely in the Annedal case study in section 0.

An important aspect to address when evaluating the types of generated ESAR is what the project area has been used for in the past. For previously untouched areas, the geological map will give a good estimation of different types of ESAR while an old industrial site might have left contaminants in the soil and construction debris in the area. In such cases, on-site evaluations are required in order to determine which types of masses are generated in the specific area and if they are suitable for re-use.

6 Utilized filling aggregate

The aggregate used as filling is categorized roughly into three different types:

- **Crushed rock**, which may be both re-used or newly produced and may comprise of several different grain size categories. The volume of crushed rock as filling aggregate is denoted V_{fcr}.
- **Sand or gravel**, which is referring only to newly produced aggregate that cannot consist of re-used ESAR, i.e. a product manufactured for construction applications. The volume of sand and gravel as filling aggregate is denoted V_{fnew}.
- **Lower quality masses**, which may consist of different types of ESAR such as till, sand, silt or clay which are useable in applications without strict requirements. However, in order to use these masses some treatment and upgrading may be required depending on the area of usage. The volume of lower quality filling masses is denoted V_{flq}.

Volume denotations of filling aggregates can be seen in Table B-2, Appendix B.

6.1 Filling aggregate in houses

The method of estimating the amount of filling aggregate required in housing construction is simplified by considering the volume illustrated in Figure 9.

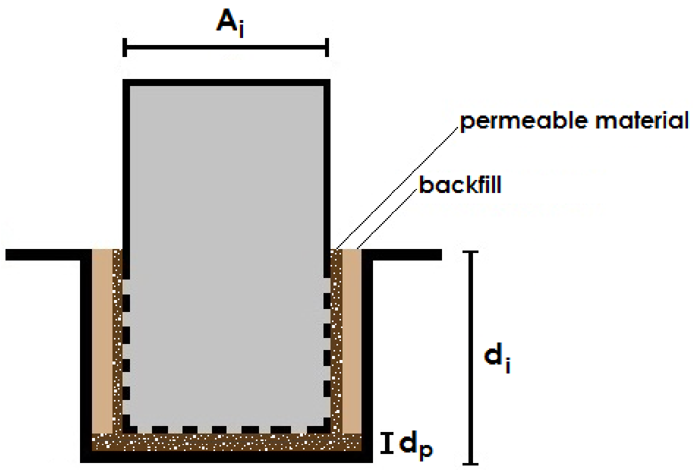

Figure 9. Utilized filling aggregate in a house foundation

The structural design of the foundation and the filling procedure with permeable material is in reality more complex, but is in this model generalized to a permeable material layer covering the bottom of the excavated volume and the basement walls, followed by a layer of backfill. The total volume of filling aggregate in the foundation is assumed to be the difference between the excavated volume V_h, Equation 5.17, and the volume taken up by the body of the house according to Equation 6.1, where d_m is the excavation depth and d_p is the layer thickness of permeable material beneath the building, as seen in Figure 9. V_{fh} is the total volume of filling aggregate in the house foundation and the term GFA/n_f is expressing the total house area according to the approach in section 0.

$$V_{fh} = V_h - \left(\frac{GFA}{n_f} \cdot (d_m - d_p)\right) \tag{6.1}$$

The thickness of permeable material beneath the building and around the basement walls should be at least 0.15 m according to (LTU, 2009b). With an additional 0.1 m margin (resulting in a permeable layer thickness of 0.25 m), the volume of permeable aggregate in the house foundations, V_{ph}, is calculated using Equation 6.2. The approach of Equation 6.2 is the same as Equation 5.8 - 5.9 which are used to calculate the excavation area. The first term of Equation 6.2 is expressing the volume of permeable material next to the basement walls while the second term includes the volume of the bottom layer.

$$V_{ph} = \left(0.25 \cdot \frac{O_m + (O_m + 2 \cdot 4 \cdot 0.25)}{2} \cdot (d_m - d_p)\right) + V_h \cdot \frac{0.25}{d_m} \tag{6.2}$$

The volume of filling aggregate is expressed as a share of the excavated volume of soil and rock from houses, V_h, in Equation 6.3, which is obtained by dividing Equation 6.1 with Equation 5.17. In Equation 6.3, a permeable layer of thickness 0.25 m (0.15 m + 0.1 m) is used.

$$\frac{V_{fh}}{V_h} = 1 - \frac{(d_m - 0.25)}{\varepsilon \cdot d_m} \tag{6.3}$$

For houses with a non-complex architecture (PF value close to 5), Equation 6.3 is approximated to be close to 33 % for excavation depths, d_m, of between 2 - 4 m and an excavation factor ε from Table 2. Accordingly, the volume of filling aggregate in house foundations is expressed by Equation 6.4. By using the same assumptions, the share of permeable material is approximated to be 20 % of the total filling volume and Equation 6.2 is expressed as Equation 6.5.

$$V_{fh} = 0.33 \cdot V_h \tag{6.4}$$

$$V_{ph} = 0.2 \cdot V_{fh} \tag{6.5}$$

The permeable layer is considered to be gravel (V_{fnew}) and the remaining backfilling volume , $V_{fh} - V_{ph}$, is considered to consist of 50 % crushed rock (V_{fcr}) and 50 % masses with lower quality (V_{flq}) (Svensk Byggtjänst, 2011b; Chudley, 1995).

6.2 Filling aggregate in roads and trenches

The filling volume in roads and trenches is approximated to be equal to the excavated volume, $V_{fr} = V_{rtot}$. Roads within residential areas are generally constructed without a large embankment, but some volume of filling and layering can be expected to elevate the road relative to the surrounding ground level. At the same time, the body of cables and pipes in the trenches contributes to the filling volume being lower than the excavated volume. In this thesis, these two aspects of construction are assumed to cancel each other out and the filling volume in roads and trenches is simply assumed to be equal to the excavated volume.

The filling aggregates in roads are simplified to consist of 90 % crushed rock (V_{fcr}) and 10 % sand or gravel (V_{fnew}) (Brodin, 2014). Many specific aspects of the road construction must be determined in order to evaluate the filling aggregate more thoroughly.

The filling aggregate in water and wastewater, district heating and drainage trenches is considered to consist of at least 40 % crushed rock (V_{fcr}) in the lower layers (Brodin, 2014) and 60 % top fill with filling aggregate of lower quality such as silt or clay (V_{flq}). Filling aggregate in electricity and telecommunication trenches is assumed to require 100 % sand or gravel (V_{fnew}) (Brodin, 2014).

6.3 Type and total volume of filling aggregate

The volumes of different types of required filling aggregates are summarized and expressed as a function of ESAR volumes from houses, V_{htot}, and road and trenches, V_{rtot}, in Equation 6.6 - 6.9. V_{in} is the total volume of filling aggregate expressed as a function of the total ESAR volume.

$$V_{fcr} = 0.13 \cdot V_{htot} + 0.57 \cdot V_{rtot} \tag{6.6}$$

$$V_{fnew} = 0.07 \cdot V_{htot} + 0.06 \cdot V_{rtot} \tag{6.7}$$

$$V_{flq} = 0.13 \cdot V_{htot} + 0.37 \cdot V_{rtot} \tag{6.8}$$

$$V_{in} = 0.33 \cdot V_{htot} + V_{rtot} \approx 0.4 \cdot V_{out} \tag{6.9}$$

If using the approach in section 5.3 and the standard values in Table 4, V_{in} is approximated to be close to 40 % of V_{out} and the volume distribution between V_{htot} and V_{rtot} is not required to be explicitly known. The mean bulk density from Table 4 is also used to approximate the total mass of filling aggregates, M_{in}.

7 Energy usage

This section presents a method of evaluating the energy used in transportation of ESAR and filling aggregate, as well as the possibilities of making the process more efficient with the use of intermediate storage.

7.1 Re-use of ESAR

By comparing M_{out}, the total amount of ESAR, to M_{in}, the total amount of filling aggregate, a theoretical maximum share of re-useable masses is evaluated according to Equation 7.1, where R_t is the percentage of re-use (i.e. how much of the excavated soil and rock that can be theoretically re-used locally).

$$R_t = \frac{M_{in}}{M_{out}} \tag{7.1}$$

In practice, the maximum possible share of re-use is often lower than R_t as the generated ESAR does not always meet the requirements of the filling aggregate. Accordingly, new aggregate must be supplied and the excess ESAR is removed from the site. Evaluating a feasible R_{max} is not straightforward as work may enable previously unusable ESAR to be utilized, such as stabilizing soft clay, sorting till grain sizes, removing organic content and contaminants etc. This work comes at the cost of energy and economic resources and at some point, increasing R may be a net loss. When, or if, this occurs is difficult to evaluate early on in a construction process as thorough knowledge of the quality of the generated ESAR is required, as well as transportation distances between quarries, the construction site and landfills. By re-using ESAR, resources are saved in several instances of the process as higher re-use lowers the demand of newly produced aggregate and the amount of excess ESAR transported away from the construction site simultaneously.

An example of how the net energy saving from re-using ESAR as filling aggregate on-site is dependent on the share of re-use is illustrated in Figure 10. Typically, the most conveniently treated and most suitable ESAR are re-used first and gives the largest energy savings. As these masses starts to run out, more energy is required to continue re-using ESAR and the net energy saving is increasing more slowly. In many cases, a large share of certain masses does not meet the construction requirements and cannot be re-used regardless of treatment and upgrading, which is not shown in Figure 10.

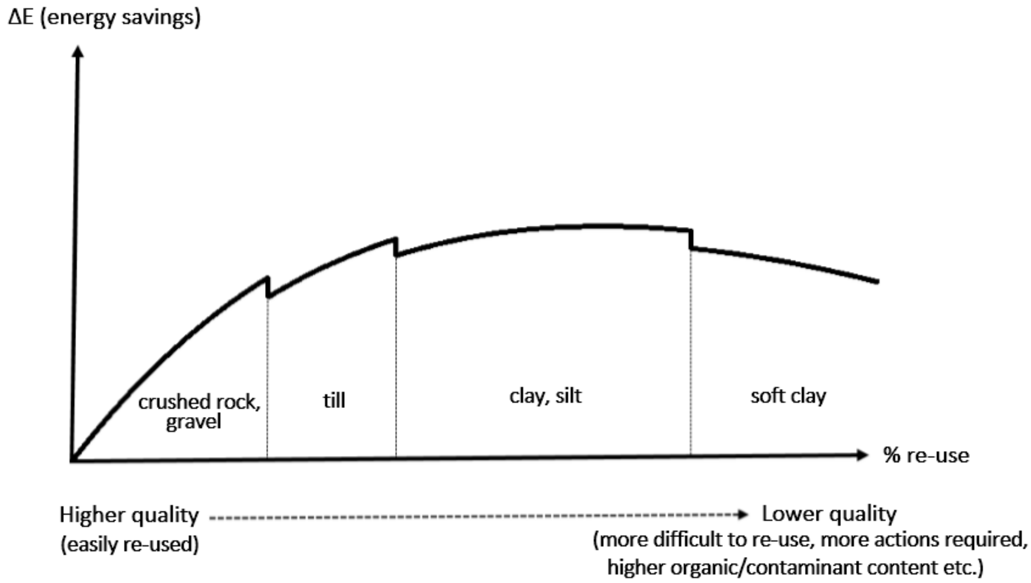

Figure 10. Illustration of how the amount of energy saved may be related to the re-use share

Primarily, the energy is saved by having shorter transportation routes when using an adjacent storage site, but also in other areas of the process; more re-used masses means less production of new aggregate and less disposal of excess ESAR. However, many preparatory activities, such as the crushing of rock, are still required regardless of which masses are used (newly produced aggregate or re-used ESAR), and these energy costs amounts to a net zero change. The sharp decreasing breakpoints of the energy savings in Figure 10 illustrates the need to implement new technologies and equipment in order to enable re-use of certain masses. If this is to be feasible from a resource point of view, it is required that a sufficient amount of such masses are excavated from the site.

7.2 Intermediate storage

A simplified approach of evaluating the energy usage in transportation is illustrated in Figure 11. Three different distances, L, for transportation of re-used ESAR to the intermediate storage site are evaluated; 0.5 km *on-site* re-use (masses re-used within or in direct proximity of the construction site), 5 km to an *adjacent* storage site and 10 km to a *regional* storage site. It is also possible that masses are re-used in other construction projects but the net energy reduction in transportation is considered to be the same, as the lower demand of new aggregate and the lower amount of ESAR transported away would be applicable in both cases.

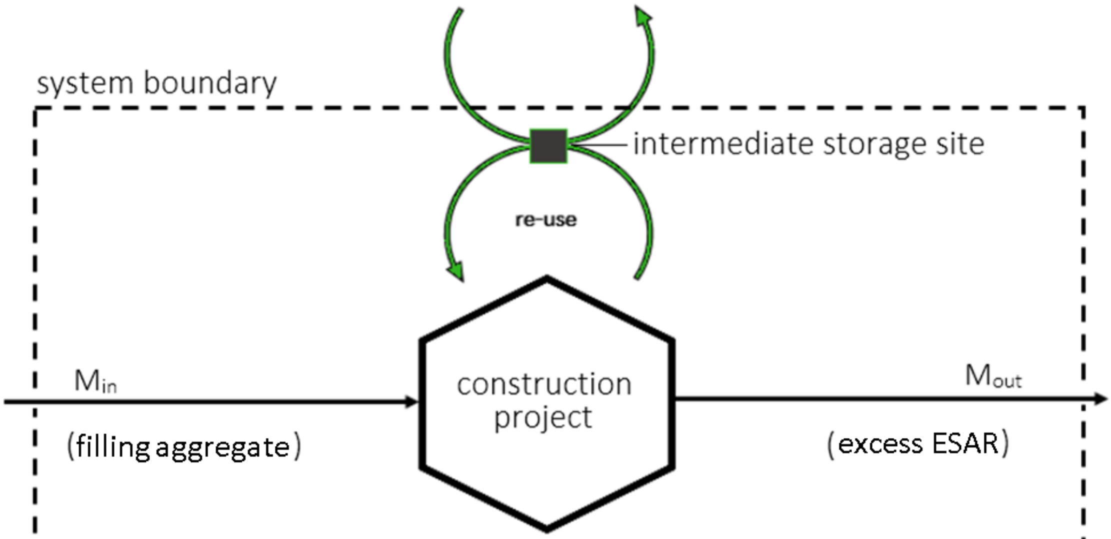

Figure 11. Re-use process of ESAR through an intermediate storage site

By re-using R percent of the ESAR, M_{out}, the amount of new aggregate required and the amount of excess ESAR transported away from the construction site are consequently reduced by the same amount. Equation 7.2 - 7.5 illustrates the model of evaluating the energy use in transportation as a function of the re-use share, R, and the input parameter of the model are presented in Table 5.

Table 5. Parameters used in the transportation energy evaluation

Input parameter	Unit	Description
E	kWh	Energy usage in transportation
R	-	Share of ESAR re-used as filling aggregate
M_{in}	ton	Mass of filling aggregate
M_{out}	ton	Mass of ESAR
Q	kWh/t-km	Energy usage per ton and kilometer of freight transportation by truck
L_{50}	km	Distance of 50 km from quarries to construction site and from construction site to landfills
L	km	Distance to intermediate storage. L = 0.5, 5 and 10 km is evaluated

Equation 7.2, E_{in}, is expressing the energy used for transporting filling aggregate to the site, equation 7.3, E_{out}, is expressing the energy used for transporting excess ESAR off the site and equation 7.4, E_{re}, is expressing the energy used for transporting re-used ESAR to and from the intermediate storage site. Equation 7.5 is expressing the total energy usage in transportation. The transportation distance for new aggregate and excess ESAR used in this model, L_{50}, is set to 50 km, i.e. the distance between quarries and the construction site as well as between the construction site and landfills. The L_{50} distance is set by considering the location of quarries and landfills in the Stockholm region (Stockholm Läns Landsting, 2010). There are sites located closer to the central areas of Stockholm but ESAR and aggregate may also

be transported to and from external quarries and landfills located outside of the Stockholm region. 50 km is an estimated average distance for this transportation. The transportation distance to the intermediate storage site is accounted for twice as the ESAR must be transported back to the construction site or to another adjacent construction project in order to be utilized as filling aggregate.

$$E_{in}(R) = (M_{in} - R \cdot M_{out}) \cdot Q \cdot L_{50} \tag{7.2}$$

$$E_{out}(R) = (1 - R) \cdot M_{out} \cdot Q \cdot L_{50} \tag{7.3}$$

$$E_{re}(R) = R \cdot M_{out} \cdot Q \cdot 2L \tag{7.4}$$

$$E(R) = E_{in}(R) + E_{re}(R) + E_{out}(R) \tag{7.5}$$

Typically, the energy usage Q is greater when transporting shorter distances as such routes corresponds to more inefficient transportation. Adalberth (1997) is using the Q values of 0.75 kWh/t-km if $L \leq 50$ km and 0.28 kWh/t-km if $L > 50$ km. Federici et al. (2008), which is a more recent study, is using approximately 0.28 kWh/t-km without regarding the transportation distance. In this thesis, Q is set between 0.3 and 0.6 kWh/t-km and is expressed as a function of the distance L, varying according to Equation 7.6 between $L = 0$ and $L = 50$. For distances above 50 km, Q is considered to stay constant at 0.3 kWh/t-km.

$$Q(L) = 0.6 - 0.006 \cdot L \tag{7.6}$$

8 Annedal case study

Annedal is a residential area in Bromma and Sundbyberg, northwest of Stockholm City, and covers a total area of 200 000 m². The residential area is being constructed between 2008 and 2016 (Stockholms Stad, 2014b) and it is estimated that a total of 600 000 metric tons of ESAR are generated during the construction process (Dalenstam, no date). Annedal is used as a case study for evaluating the calculation model developed in this thesis and 600 000 metric tons of ESAR is used as a reference value. Both the detailed calculations and the simplified model from section 0 are applied in order to evaluate the applicability of the simplified model. The amount of filling aggregate used in Annedal is only estimated according to the simplified method using a percentage of the excavation amount.

The residential area of Annedal is shown in Figure 12 and includes a total of 73 houses divided into 25 blocks. The approximate areas, perimeters, PF values, excavation ranges, excavation depths and ε values of the houses are presented in Appendix A. The excavation ranges that are used in the detailed calculation are dependent on the house area according to Table 2.

In section 8.3, the feasibility of re-using ESAR within Annedal is assessed by regarding what types of ESAR are generated and what types of aggregate are required as filling material. A maximum share of re-use, R_{max}, is estimated and the impact of re-using ESAR is evaluated from an energy usage point of view in section 8.4.

Figure 12. The Annedal residential area (Stockholmsprojekt, 2013)

8.1 Estimated amount of ESAR

The amount of ESAR generated in Annedal is estimated using both the detailed approach and a simplified approach, presented in section 5.3. Table 6 presents construction data of Annedal while specific data of the individual houses is presented in Appendix A.

Table 6. Annedal data

Parameter	Value	Unit	Description
GFA	230000	m^2	Total gross floor area, estimated from Insyn Sverige (2007)
P	5000	-	Number of residents (Stockholms Stad, 2014b)
n_f	5	-	Number of floors in the buildings (estimated mean value)
n_b	73	-	Number of buildings (measured)
n_a	2300	-	Number of apartments (Bo i Annedal, 2014)
d_m	4	m	Excavation depth for houses, estimated from Dalenstam (no date)
A_m	670-700	m^2	Mean house area, dependent on calculation method (calculated)
ε	1.40	-	Excavation factor for A_m = 670-700, Table 2
α_p	0.7	-	Share of parking spaces in underground garages (Stockholms Stad, 2013)
l_{r1}	1800	m	Length of roads (measured)
l_{r2}	1500	m	Length of walkways (measured)
l_t	1800	m	Length of trenches (estimated as $l_t = l_{r1}$)
w_{r1}	9.45	m	Width of roads (Landskapslaget, 2009)
w_{r2}	3	m	Width of walkways (estimated)
A_t	11	m^2	Cross section of trenches, Table 3
d_{r1}	0.6	m	Excavation depth of roads (Brodin, 2014)
d_{r2}	0.5	m	Excavation depth of walkways (estimated)
ϱ_m	1.65	ton/m^3	Mean bulk density of ESAR, approximated from Table 7.

8.1.1 Detailed model

This section is covering the detailed calculation approach presented in section 0 applied to Annedal. The ESAR is estimated to be generated within two major areas; houses and underground parking and roads and trenches, and the total excavated volume is $V_{out} = V_{htot} + V_{rtot}$.

8.1.1.1 Houses

The detailed approach of estimating the amount of ESAR generated from house construction in Annedal is done by using the data from Appendix A and Table 6 in Equation 8.1 - 8.2. Each house is expected to have a fairly equal excavation depth, d_i, with an approximate average value of 4 m as seen in Appendix A. From Equation 8.1, the ESAR volume from each house is estimated and summed together according to Equation 8.2. The second part of Equation 8.2 is expressing the excavation volume from underground parking garages according to the method presented in section 5.1.1.3.

$$V_i = A_{ei} \cdot d_i \tag{8.1}$$

$$V_{htot} = \left(\sum_{i=1}^{n_b} V_i \right) + \frac{(75 \cdot n_a \cdot \alpha_p)}{2} \tag{8.2}$$

8.1.1.2 Roads and trenches

The roads in Annedal are approximated by one type of road for vehicles and one type of walkway for pedestrians. The former is also assumed to include trenches. The width, length and excavation depth of each type is presented in Table 6 and the ESAR volume is calculated using Equation 8.3 - 8.4, where V_{rj} is the volume generated in road type j and V_r the total volume.

$$V_{rj} = w_{rj} \cdot l_{rj} \cdot d_{rj} \tag{8.3}$$

$$V_r = \sum_{n=1}^{n_r} V_{rj} \tag{8.4}$$

The length of trenches in a residential area is estimated from the road length as seen in section 5.2.1. The volume of ESAR from trench construction in Annedal, V_t, is calculated using Equation 8.5.

$$V_t = l_{r1} \cdot A_t \tag{8.5}$$

The total volume excavated from roads, walkways and trenches combined, V_{rtot}, is calculated according to Equation 8.6.

$$V_{rtot} = V_r + V_t \tag{8.6}$$

8.1.1.3 Total volume

The total volume of ESAR is calculated by combining Equation 8.2 and 8.6, according to Equation 8.7. In the detailed approach, the total mass of ESAR, M_{out}, is calculated by adding equations 8.13 - 8.15 which are considering the bulk densities of the different ESAR types from Table 7.

$$V_{out} = V_{htot} + V_{rtot} \tag{8.7}$$

8.1.2 Simplified model

Equation 8.8 is used to estimate the total volume of ESAR generated in Annedal, V_{out}, as a function of the number of residents and the number of floors in the buildings. The mass of the ESAR is calculated using Equation 8.9 where ρ_m is the mean bulk density from Table 4.

$$V_{out} = P \cdot \left(\frac{300}{n_f} + 10\right) \tag{8.8}$$

$$M_{out} = V_{out} \cdot \rho_m \tag{8.9}$$

8.1.3 Types of ESAR

There are primarily four different soil types present in the Annedal residential area, neglecting the small moraine ridge seen in Figure 13. Glacial clay is the dominant soil followed by postglacial clay, till and rock. The share of each soil type and soil types divided in different construction areas are estimated using Figure 13 and presented in Table 7. The column *% of total area* in Table 7 is representing step 1 in section 5.4, and the columns showing the percentage of each construction type is representing step 2. Step 2, which is taking the land-use of each construction type into consideration, is a more accurate estimation of what types of ESAR are generated.

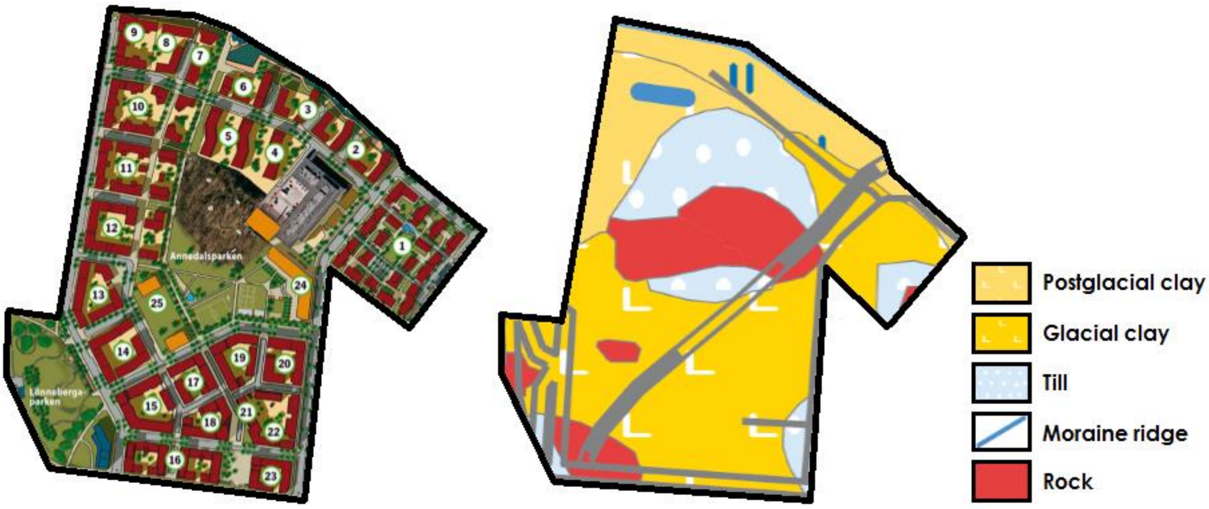

Figure 13. The Annedal residential area and a corresponding geological map showing which type soil and rock is present in the area (SGU, 2014)

Table 7. Area share of different soil and rock types

ESAR type	Volume denotation	Bulk density ρ, [ton/m³]	% of total area [-]	% of house area [-]	% of roads and trench area [-]
Postglacial clay	V_{clay}	1.6 (Tyréns, 2010)	20	25	35
Glacial clay			50	60	60
Till	V_{till}	1.7, considered loosely layered (Avén, 1984b)	17.5	10	2.5
Rock	V_{rock}	1.8, considered loosely layered (Avén, 1984b)	12.5	5	2.5

If the soil distribution and bulk densities in Table 7 are paired with the volume of ESAR generated in each construction area from section 0, the total volume and mass of each soil type is estimated according to Equation 8.10 - 8.15. As their specific properties are not comprehensively evaluated, postglacial clay and glacial clay is only considered to be clay (volume denoted V_{clay}) in this thesis.

$$V_{clay} = 0.85 \cdot V_{htot} + 0.95 \cdot V_{rtot} \tag{8.10}$$

$$V_{till} = 0.1 \cdot V_{htot} + 0.025 \cdot V_{rtot} \tag{8.11}$$

$$V_{rock} = 0.05 \cdot V_{htot} + 0.025 \cdot V_{rtot} \tag{8.12}$$

$$M_{clay} = \rho_{clay} \cdot V_{clay} \tag{8.13}$$

$$M_{till} = \rho_{till} \cdot V_{till} \tag{8.14}$$

$$M_{rock} = \rho_{rock} \cdot V_{rock} \tag{8.15}$$

8.2 Estimated amount of filling aggregate

The amount of utilized filling aggregate in Annedal is expressed as a function of the excavated volume based on the results of the detailed model. The volume of filling aggregate, V_{in}, is estimated using Equation 8.16 according to the approach from section 0. The total mass of filling aggregate, M_{in}, is estimated in Equation 8.17 where the bulk density ρ_m from Table 4 is used as an approximation.

$$V_{in} = 0.4 \cdot V_{out} \tag{8.16}$$

$$M_{in} = \rho_m \cdot V_{in} \tag{8.17}$$

In order to estimate the maximum possible share of re-use, R, the filling aggregates are divided into categories depending on their area of usage as seen in section 0. In accordance with the evaluation from section 6.3, the amount of different filling aggregates, V_{fcr}, V_{fnew} and V_{flq}, is evaluated using Equation 8.18 - 8.20.

$$V_{fcr} = 0.13 \cdot V_{htot} + 0.57 \cdot V_{rtot} \tag{8.18}$$

$$V_{fnew} = 0.07 \cdot V_{htot} + 0.06 \cdot V_{rtot} \tag{8.19}$$

$$V_{flq} = 0.13 \cdot V_{htot} + 0.37 \cdot V_{rtot} \tag{8.20}$$

8.3 Re-use of ESAR

The total volume of filling aggregate, V_{in}, amounts to approximately 40 % of the total ESAR volume V_{out}. However, in order to evaluate a maximum re-use share, R_{max}, the types of ESAR and filling aggregate must be considered. R_{max} is calculated according to Equation 8.21, where V_{rest} is the volume of filling aggregate that cannot be covered by ESAR according to the approach illustrated in Figure 14.

$$R_{max} = \frac{(V_{in} - V_{rest})}{V_{out}} \tag{8.21}$$

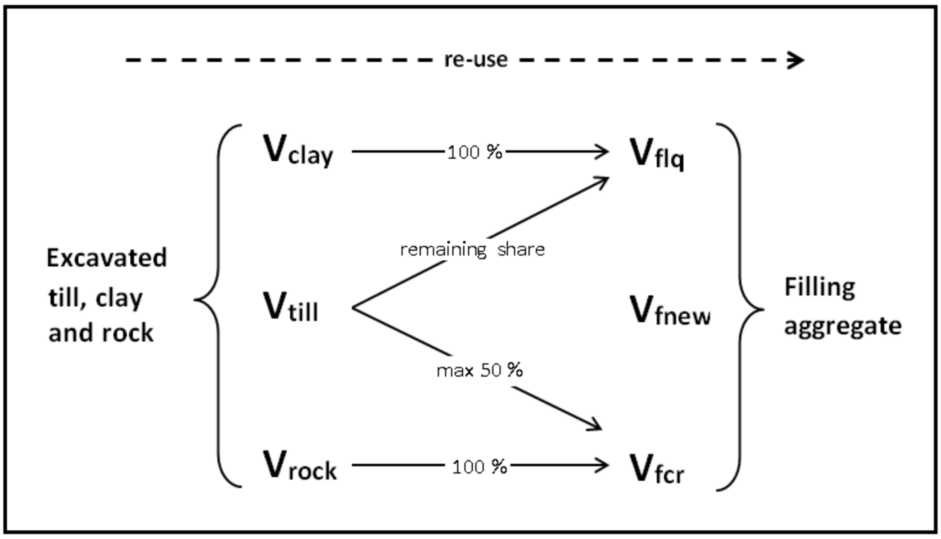

Figure 14. The re-use of ESAR as filling aggregate, illustrating which types of filling aggregate different ESAR can be utilized as

Figure 14 illustrates what quantities of ESAR from Annedal (V_{clay}, V_{till} and V_{rock}) that can be utilized as different filling aggregates (V_{flq}, V_{fnew} and V_{fcr}). Half the volume of excavated till is estimated to be usable as crushed rock and the remaining share is usable as filling aggregate of lower quality. This is by regarding the mixture of different grain sizes that till is comprised of (Avén, 1984a). The relatively small volume of rock, as seen in Table 7, is considered to be fully usable as crushed rock for filling purposes while clay is only usable as filling aggregate of lower quality.

8.4 Energy usage

The impact on the energy usage in transportation when re-using ESAR through an intermediate storage site is evaluated according to the model presented in section 7.2. The energy usage is calculated according to Equation 8.22, where E_{in}, E_{re} and E_{out} is the energy usage for transporting filling aggregate in to the construction site, ESAR for re-use to and from an intermediate storage site and excess ESAR out from the site to landfills. R is the share of re-used ESAR.

$$E(R) = E_{in}(R) + E_{re}(R) + E_{out}(R) \tag{8.22}$$

9 Results of the case study

This section presents the results of the case study; ESAR volume from the different calculation approaches, filling aggregate volume, re-use share and energy usage in transportation.

9.1 Estimated amount of ESAR

The estimated amount of ESAR from the calculation models applied to the Annedal residential area is presented in Table 8 and Figure 15. The reference value used in the case study and is estimated by WSP who has been involved in the earthwork process of Annedal (Dalenstam, no date).

Table 8. Estimated amount of ESAR by the detailed and simplified models and their deviation from the reference value

	Reference value	Detailed model	Simplified model
Estimated amount of ESAR	600 000 ton	589 215 ton	577 500 ton
Deviation from reference value	0 %	- 1.8 %	- 3.8 %

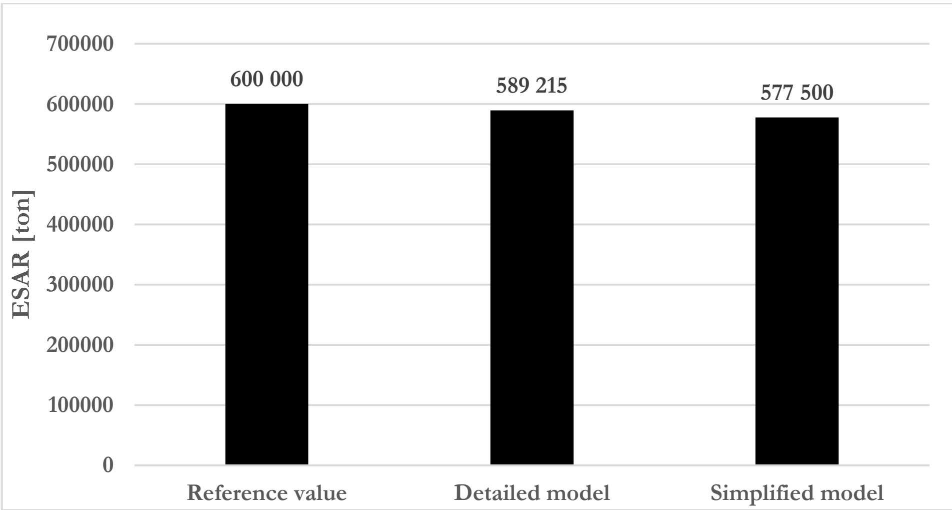

Figure 15. Estimated amount of ESAR generated in Annedal using the two different calculation models

The amount of ESAR generated from different construction areas is illustrated in Figure 16. The results in Figure 16 are weight percentage based on the detailed model and a total amount of ESAR of M_{out} = 589 215 ton.

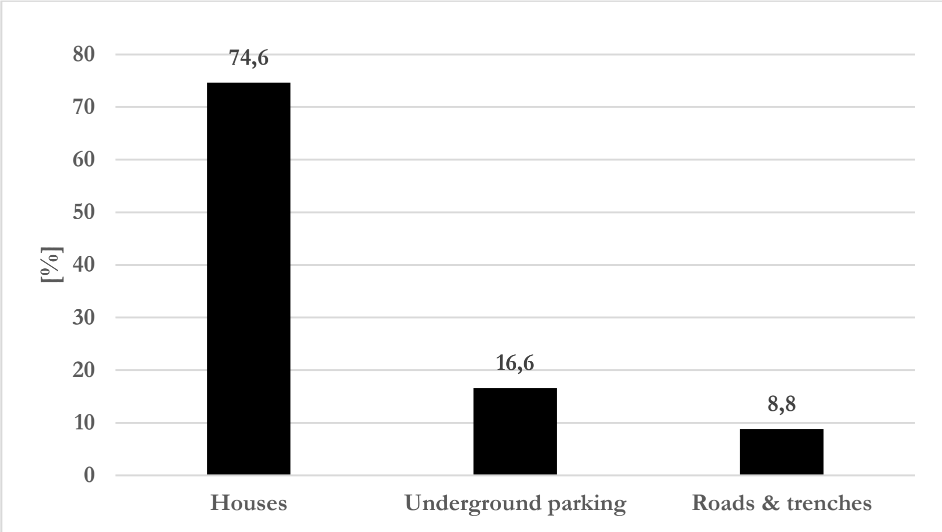

Figure 16. ESAR generated in different construction areas in Annedal

9.2 Types of ESAR

The types of ESAR generated in Annedal is estimated using two different methods; one only considering the areas of different soils and one considering the layout and construction intensity of the residential area, as seen in section 5.4 (the area approach and the layout approach, respectively). The results of the two methods applied to Annedal are presented in Figure 17, which shows the share of clay, till and rock in % of weight of the total amount of ESAR, M_{out}. The value estimated by the detailed model, M_{out} = 589 215 ton, is used as a basis of this evaluation.

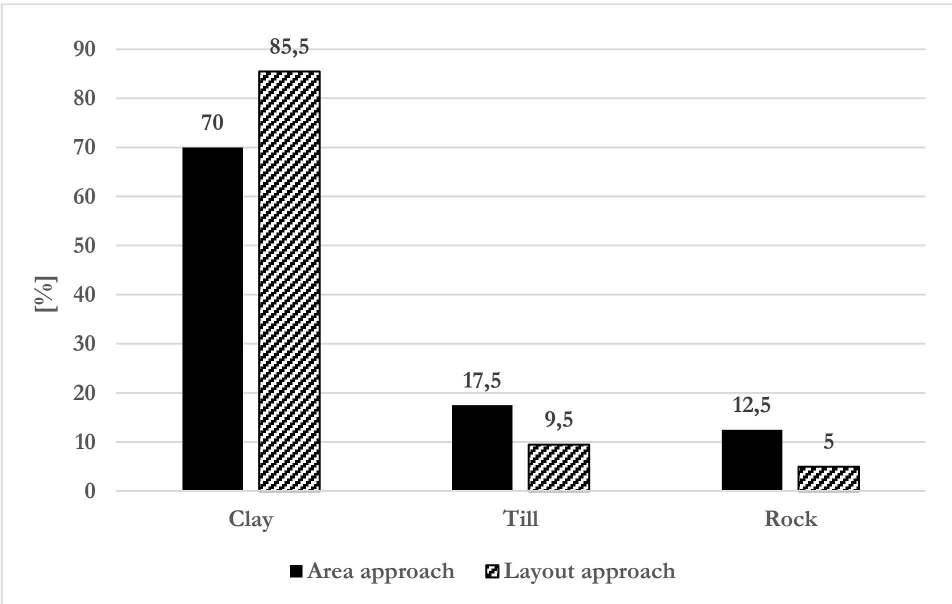

Figure 17. Types of ESAR generated in Annedal

9.3 Estimated amount of filling aggregate

The total amount of filling aggregate is estimated as 40 % of the generated amount of ESAR (by using the same value of bulk density, ϱ_m, the estimation is the same for both total volume and total mass). When using the results of the detailed model as a basis of the evaluation, M_{out} = 589 215 ton, the filling aggregate utilized in Annedal amounts to $\mathbf{M_{in}}$ **= 235 686 ton**. The share of different types of filling aggregate (crushed rock, new aggregate and lower quality filling, as seen in section 0) in % of weight are shown in Figure 18.

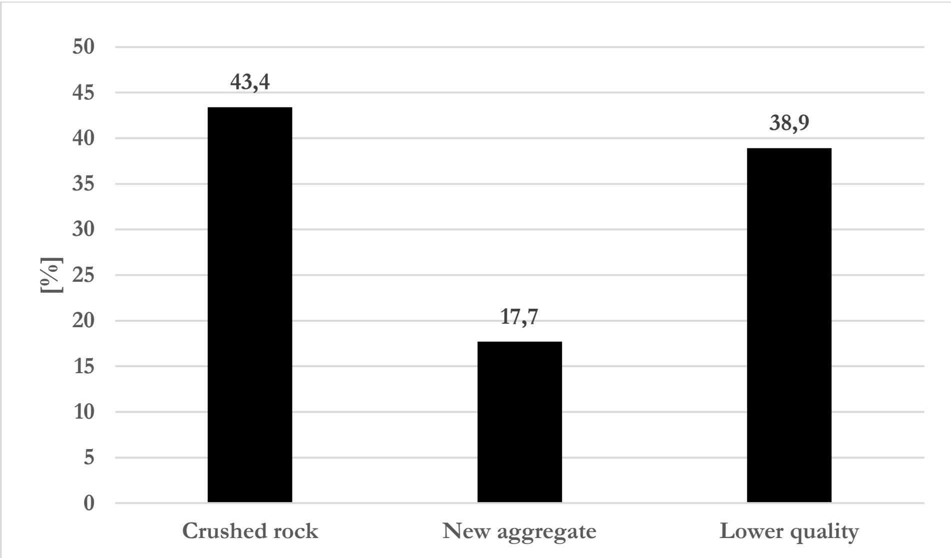

Figure 18. Distribution of different types of filling aggregates in Annedal

Based on the evaluation in section 8.3 and the results in Figure 18, the maximum share of re-usable ESAR as filling aggregate in Annedal is $\mathbf{R_{max}}$ **= 25 %**.

9.4 Energy usage

Figure 19 illustrates the possible energy reduction in transportation when utilizing intermediate storage for re-use in the case study. The first graph in Figure 19 illustrates the relative energy reduction and the second graph the absolute reduction in GWh in the case of Annedal.

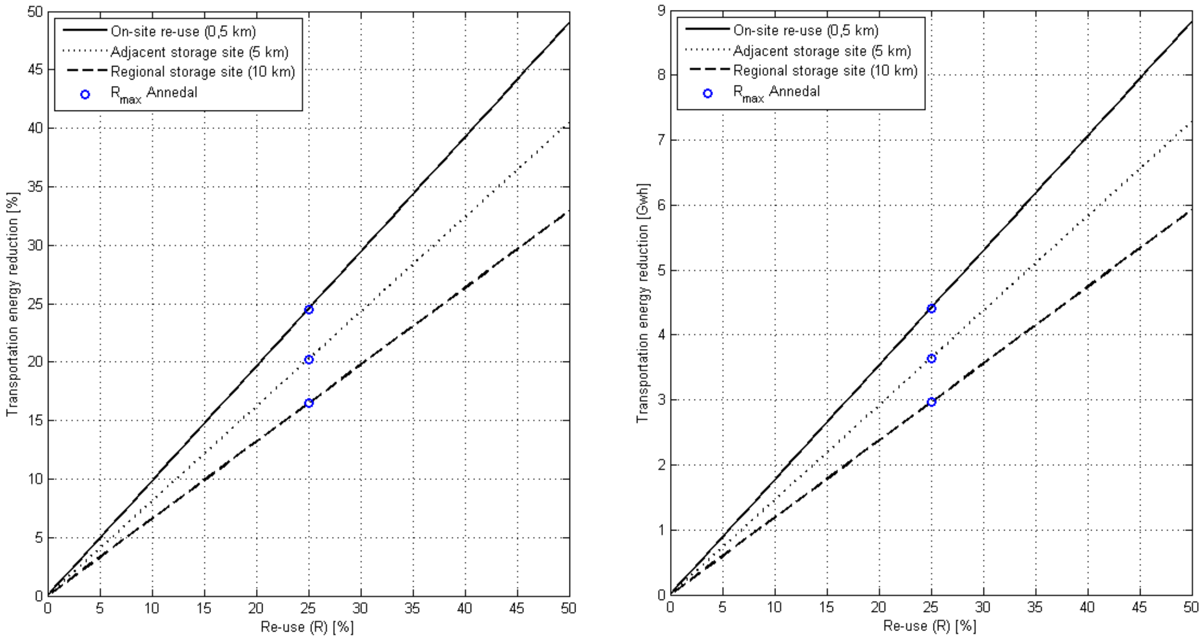

Figure 19. Reduction of transportation energy as a function of the re-use share, R

As seen in Figure 19; in a best-case scenario, on-site re-use with a maximum share of R_{max} = 25 % amounts to a transportation energy reduction of approximately 25 % in the case of Annedal. Figure 20 illustrates the feasibility of different distances to an intermediate storage site; after approximately L = 35 km, a re-use share of up to 50 % amount to an energy reduction of below 5 %.

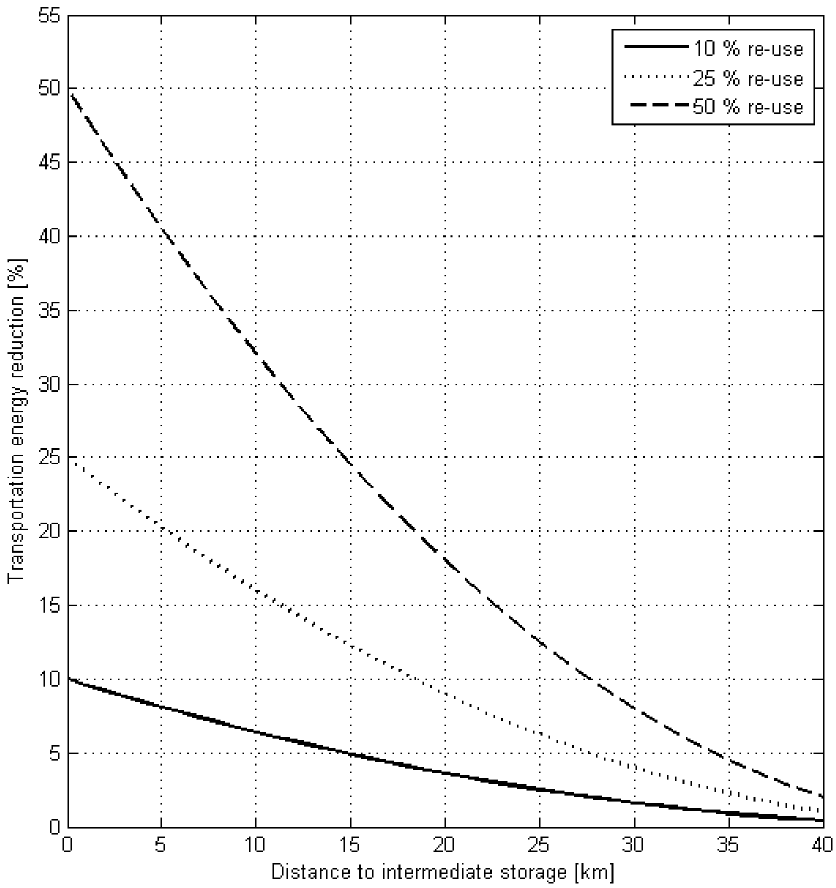

Figure 20. Reduction of transportation energy as a function of the distance to intermediate storage, L

10 Conclusions

The result of this thesis indicates that the amount of ESAR generated during the construction of a residential area can be estimated at an early stage of the planning process. The case study of Annedal shows a deviation of 3.8 % between the simplified model and the reference value in terms of total mass of ESAR, which is considered to be fairly low with respect to the purpose of the thesis and the timeframe in which the model is intended to be of use. The simplification process between the detailed and simplified model severely reduces the complexity and time-consumption of the calculation while only resulting in a 2 % lower estimated amount of ESAR (577 500 ton as compared to 589 215 ton when using the detailed model).

An assessment of the environmental impact when constructing residential buildings by Gangolells et al. (2009) shows that approximately 4.83 and 4.95 m^3/m^2 ESAR per square meter of site occupation was generated during the construction of two different multi-family houses. Similar values developed theoretically in this thesis indicate between 5.40 - 6.16 m^3/m^2 ESAR per square meter of ground area covered by buildings. These values are considering the area and excavation factors presented in Table 2 and the standard excavation depth of $d_m = 4$ m from Table 4. It is not clear whether site occupation only incorporates the area covered by the houses or a larger area including space taken up by vehicles, excavators and auxiliary equipment on the site. The comparison is however giving a positive indication of the applicability of the theoretical approach presented in this thesis, considering the implied uncertainty when estimating the volumes of ESAR at a very early stage (many specific construction parameters undetermined). Even though the theoretical values are slightly higher than the measured values by Gangolells et al. (2009), the Annedal case study shows that the calculation models produces a lower amount of ESAR than the reference value, as seen in Figure 15. It is likely that either a larger ground area (site occupation) or a smaller excavation depth was considered in the Gangolells et al. (2009) study, producing slightly lower values of ESAR per square meter.

The primary goal of the calculation model is not to as accurately as possible estimate the volume and mass of ESAR generated in a residential area, but rather provide an easy and early usable method to create a template volume for planning purposes. When such a volume is included and made aware of at an initial stage, it is easier to plan the handling process efficiently and to ultimately lower the environmental impact.

10.1 Re-use and energy

The actual re-use share within a construction projects is difficult to evaluate prior to the construction phase. In order to fully utilize ESAR as filling aggregate, the re-use share is limited by what types of masses are generated on-site and R_{max} may be evaluated as fairly low. The maximum re-use share within Annedal, R_{max}, is evaluated as 25 % and is strongly limited by the relatively small amount of excavated rock, only 5 % (using the layout approach) as compared to the 43.4 % of filling aggregate that is comprised of crushed rock. More than 85 % of the ESAR generated in Annedal is clay, resulting in a large share of ESAR currently not able of being re-used as filling aggregate on-site. An increased system boundary that incorporates adjacent construction projects may significantly increase the feasibility of re-using ESAR and a much more efficient handling process may be possible. By such evaluation, a regional R_{max} gives a better indication of what impact intermediate storage sites and cooperation between construction projects may have on the mass handling process from a sustainability point of view. While it is difficult to utilize a large volume of softer soils and clay within residential areas, they may prove suitable in very different construction applications, such as sound barriers and recreational areas.

Well-planned locations for intermediate storage is however important regardless of re-use share, as seen in Figure 20. A distance of < 20 km to a storage site is feasible for numerous construction projects in a region and at the same time allowing for a significantly higher R values. A distance of 35 km may be seen as a feasible upper limit as not even 5 % of the transportation energy is reduced when re-using up to 50 % of the ESAR.

10.2 Future work

More thorough evaluation of the simplified calculation model is required in order to determine its validity and margin of error. Primarily, it is important to apply the model to case studies of other urban residential areas with a different layout and size than Annedal. Such evaluations may not only indicate in which type of residential area, and why, the model yields a more correct result, but they are necessary for drawing general conclusions of the calculation model's ability of estimating the amount of ESAR. Some theoretical refinement may also improve the applicability of the model; for example by incorporating aspects of construction that are currently not within the scope of this thesis, such as the topography the area.

An economic evaluation of the handling process of ESAR and aggregate is another important continuation as highlighting potential savings and profitability is essential for gaining credibility and practical impact. Preferably, such evaluation is to be done as comprehensively as possible; not only to illustrate the direct cost-effectiveness of re-use, shorter transportation, lower demand of aggregate etc., but also to indicate the economic feasibility of operating intermediate storage sites in a region, for example.

In order to achieve a more thorough assessment of the beneficial implications of re-use and intermediate storage in terms of economic and environmental impact, it is very advantageous to lift the calculation model in this thesis from the residential area level to a regional or municipal level by incorporating other types of construction projects; essentially increasing the geographical boundary as well as the system boundary seen in Figure 1. This will allow for a much more comprehensive evaluation of re-use possibilities and the potential of intermediate storage as each project would not be limited to its own ESAR and requirements of filling aggregates. When taking a larger geographical area into consideration, the logistical planning may also include a wider range of infrastructural solutions and more energy-efficient means of transportation, such as rail or sea freight, might prove to be available options. At the same time, knowledge about which projects are going to produce higher quantities of ESAR, and in what time periods, enables strategic planning of storage locations closer to the most construction intensive areas. With this in mind, it is likely that a regional approach is a prerequisite for locating optimal sites for intermediate storage and to fully utilize the environmental benefits of re-using ESAR.

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Appendix A: Annedal house data

Table A-1. Annedal house data

Block (Figure 12)	House number	A [m²]	O [m]	PF [-]	d [m]	r [m]	ε [-]
1	1	282	82	4.88	4	1.5	1.54
	2	450	97	4.57	4	1.75	1.40
	3	510	105	4.65	4	1.75	1.40
	4	265	66	4.05	4	1.5	1.54
	5	170	57	4.37	4	1.5	1.54
	6	255	66	4.13	4	1.5	1.54
	7	515	105	4.63	4	1.75	1.40
	8	170	57	4.37	4	1.5	1.54
	9	170	57	4.37	4	1.5	1.54
	10	170	57	4.37	4	1.5	1.54
	11	170	57	4.37	4	1.5	1.54
	12	475	105	4.82	4	1.75	1.40
	13	190	65	4.72	4	1.5	1.54
	14	190	65	4.72	4	1.5	1.54
	15	310	82	4.66	4	1.5	1.54
	16	310	82	4.66	4	1.5	1.54
	17	590	112	4.61	4	1.75	1.40
2	18	485	105	4.77	4	1.75	1.40
	19	620	107	4.30	4	1.75	1.40
	20	485	105	4.77	4	1.75	1.40
	21	620	107	4.30	4	1.75	1.40
3	22	485	105	4.77	4	1.75	1.40
	23	620	107	4.30	4	1.75	1.40
6	24	485	105	4.77	4	1.75	1.40
	25	260	80	4.96	4	1.5	1.54
	26	170	57	4.37	4	1.5	1.54
	27	265	65	3.99	4	1.5	1.54
7	28	530	105	4.56	4	1.75	1.40
	29	345	70	3.77	4	1.5	1.54

8-9	30	560	101	4.27	4	1.75	1.40
	31	1865	277	6.41	4	2.25	1.35
	32	620	117	4.70	4	1.75	1.40
10	33	340	74	4.01	4	1.5	1.54
	34	1140	201	5.95	4	2.25	1.35
	35	540	111	4.78	4	1.75	1.40
	36	350	76	4.06	4	1.5	1.54
	37	350	76	4.06	4	1.5	1.54
4-5	38	900	147	4.90	4	2	1.36
	39	900	147	4.90	4	2	1.36
	40	900	147	4.90	4	2	1.36
11	41	405	71	3.53	4	1.75	1.40
	42	595	111	4.55	4	1.75	1.40
	43	830	153	5.31	4	2	1.36
	44	595	111	4.55	4	1.75	1.40
	45	405	71	3.53	4	1.75	1.40
12	46	440	89	4.24	4	1.75	1.40
	47	2095	341	7.45	4	2.25	1.35
	48	270	73	4.44	4	1.5	1.54
13	49	335	73	3.99	4	1.5	1.54
	50	995	191	6.06	4	2	1.36
	51	755	134	4.88	4	2	1.36
14	52	1295	233	6.48	4	2.25	1.35
	53	875	143	4.83	4	2	1.36
15	54	2040	302	6.69	4	2.25	1.35
	55	270	69	4.20	4	1.5	1.54
16	56	1615	272	6.77	4	2.25	1.35
	57	1615	238	5.92	4	2.25	1.35
23	58	1450	236	6.20	4	2.25	1.35
21-22	59	1370	143	3.86	4	2.25	1.35
	60	715	89	3.33	4	2	1.36
	61	360	280	14.76	4	1.5	1.54
18	62	1790	85	2.01	4	2.25	1.35

17	63	350	207	11.07	4	1.5	1.54
	64	1200	266	7.68	4	2.25	1.35
19	65	1430	89	2.35	4	2.25	1.35
	66	365	122	6.39	4	1.5	1.54
20	67	600	204	8.33	4	1.75	1.40
	68	1230	243	6.93	4	2.25	1.35
24	69	1620	115	2.86	4	2.25	1.35
	70	820	79	2.76	4	2	1.36
25	71	345	79	4.25	4	1.5	1.54
	72	345	138	7.43	4	1.5	1.54
	73	645	70	2.76	4	1.75	1.40
Sum	**-**	**49092**	**9029**	**-**	**-**	**-**	**-**
Average	**-**	**673**	**124**	**4.99**	**4**	**2**	**1.44**

Appendix B: Volume denotations

Table B-1. ESAR volume denotations

Volume denotation	Unit	Description
$\mathbf{V_{out}}$	m^3	Total ESAR generated in the area
$\mathbf{V_i}$	m^3	ESAR generated from house i
$\mathbf{V_h}$	m^3	ESAR generated from all houses
$\mathbf{V_m}$	m^3	ESAR generated from one house using the mean value approach
$\mathbf{V_p}$	m^3	ESAR generated from underground parking
$\mathbf{V_{htot}}$	m^3	Total ESAR generated from the house construction category (all houses and underground parking)
$\mathbf{V_{rj}}$	m^3	ESAR generated from road type (or road segment) j
$\mathbf{V_r}$	m^3	ESAR generated from all roads
$\mathbf{V_{rtot}}$	m^3	Total ESAR generated from the road construction category (all roads and trenches)
$\mathbf{V_{rock}}$	m^3	Volume of generated rock
$\mathbf{V_{till}}$	m^3	Volume of generated till
$\mathbf{V_{clay}}$	m^3	Volume of generated clay

Table B-2. Filling aggregate volume denotations

Volume denotation	Unit	Description
$\mathbf{V_{in}}$	m^3	Total volume of filling aggregates utilized in the area
$\mathbf{V_{fh}}$	m^3	Volume of filling aggregate in houses
$\mathbf{V_{ph}}$	m^3	Volume of permeable aggregate in houses
$\mathbf{V_{fr}}$	m^3	Volume of filling aggregate in roads and trenches
$\mathbf{V_{fcr}}$	m^3	Volume of crushed rock as filling aggregate
$\mathbf{V_{fnew}}$	m^3	Volume of new filling aggregate
$\mathbf{V_{flq}}$	m^3	Volume of lower quality filling aggregate
$\mathbf{V_{rest}}$	m^3	Volume of filling aggregate that cannot be covered by ESAR