TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Civil Engineering and Architecture

COMPARATIVE ENVIRONMENTAL IMPACT ANALYSIS OF WASTE ROCK AND CONVENTIONAL MATERIAL USING LIFE CYCLE ASSESSMENT: THE CASE STUDY OF RAIL BALTIC RAILWAY EMBANKMENT MATERIAL

AHERAINE JA KONVENTSIONAALSE MATERJALI VÕRDLEV KESKKONNAMÕJU ANALÜÜS KASUTADES OLELUSRINGI HINDAMIST: RAIL BALTIC RAUDTEE MULDKEHA MATERJALI JUHTUMIUURING

MASTER THESIS

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AUTHOR’S DECLARATION

Hereby I declare, that I have written this thesis independently.
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DEPARTMENT OF CIVIL ENGINEERING AND ARCHITECTURE

THESIS TASK

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1. Assess if using oil shale waste rock has lower environmental impacts compared to conventional material if using it in constructing Rail Baltic railroad embankment;
2. Find out the circumstances (transport distances) in which using oil shale waste rock has lower environmental impacts than using conventional materials for constructing Rail Baltic railroad embankment.

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PREFACE

This master thesis is about analysing if using waste rock in Rail Baltic railway embankment is preferred to using conventional materials from environmental life cycle perspective. Both alternatives are compared in a certain scenario which was set together with the help of supervisors, Eesti Energia employees and experts that were connected to previously made studies concerning the matter. I was engaged in researching and writing this thesis from February 2021 to May 2022. I was also an intern in Eesti Energia from March to July 2021 to carry out this analysis.

I would primarily like to thank my supervisors Arina Szczygielska from Eesti Energia, and Viktoria Voronova from Taltech, for their excellent guidance and support during this process. I thank Arina for contacting the university and proposing this very interesting topic. Without her I would not have been able to conduct this study. I would also like to thank employees from Eesti Energia who helped me gather the data needed for carrying out this study and showing me processes linked to waste rock in Estonia mine. I would also like to thank Sven Sillamäe and Andrus Paat from Taltech, and Epp Zirk from Hendrikson & Ko, for consulting and answering to my questions.

I hope you enjoy reading this master thesis.
Markus Kivimägi

Tallinn, May 23, 2022

Key words: Life Cycle Assessment, oil shale waste rock, Rail Baltic, Eesti Energia, master thesis

1. INTRODUCTION

Rail Baltic railway which is the biggest infrastructure project in the history of Estonia is planned to be built in near future. Colossal amounts of raw materials are needed to construct the railway, especially aggregates that will go under the railway track [1]. However, at the same time it is getting harder to open new quarries and to provide steady supply of materials already, without the additional demand. Other planned projects like constructing Tallinn-Tartu four-lane highway also need their share of aggregate materials. Due to environmental and social problems that are linked with mineral extraction, locals are not very keen on seeing new quarries near residing areas.

At the same time, over 100 million tons of limestone gravel has already been extracted from the ground by the oil shale industry in Ida-Virumaa Estonia mine and it is being generated as long as the industry is operating. As there is little use for this leftover material from oil shale extraction and enrichment, it is carried and left to dump sites as waste. This has and continues to cause formerly untouched nature areas to become covered by vast technogenic hills. However, this material has been proven to have suitable properties for using it in Rail Baltic embankment by a previous study from Paat *et al.* [2]. It means that this already extracted gravel could be used to alleviate demand for opening new quarries and extracting raw materials.

As needed material amounts are exceptionally high it is important to consider environmental impacts before choosing whether to use this waste rock in Rail Baltic embankment. Even more so as public awareness about environmental impacts and expectations for the government to consider these has risen. At first sight it would seem wise to use waste rock as it does not cause environmental impacts like conventional material that still has to be quarried. However, the actual environmental impacts are unknown as it has not been assessed and compared with the baseline scenario of using conventional materials for constructing the embankment. Waste rock is located far away from the projected railway track and transporting it could outweigh the environmental benefits that come from not needing to quarry it like conventional materials. A thorough assessment of needed processes connected to the use of both materials and environmental impacts linked to it is necessary to find out which material is preferrable.

1.1 Research overview

The general aim of this research is to conduct a comparative life cycle assessment of waste rock and conventional material used in constructing Rail Baltic railroad embankment by following cradle to gate approach. Limestone rock gravel which comes from Estonia oil shale mine due to mining and enrichment activities is meant by waste rock. Typical aggregates used for constructing railroad embankment that include sand and gravel are meant by conventional alternative.

This research is based on information and data gathered from Eesti Energia, other parties related to the Rail Baltic project and previously published literature. Defined processes and data is linked with input parameters from Ecoinvent 3.7.1 life cycle assessment database and calculations are made using Microsoft Excel and OpenLCA software. All relevant information about the processes, reference datasets and data used for conducting the analysis is documented in Appendix 1.

Objectives of this research include:

- Assess if using oil shale waste rock has lower environmental impacts compared to conventional material if using it in constructing Rail Baltic railroad embankment;
- Find out the circumstances (transport distances) in which using oil shale waste rock has lower environmental impacts than using conventional materials for constructing Rail Baltic railroad embankment.

Hypothesis of this research is that using waste rock in Rail Baltic embankment has overall lower environmental impacts than using conventional materials.

Tasks of this research include:

- Creating two economically most viable alternative scenarios (one that uses waste rock and the other that uses conventional materials) for constructing Rail Baltic embankment by considering lowest environmental impact possible approach;
- Calculating environmental impacts of using waste rock material alternative for Rail Baltic embankment construction;
- Calculating environmental impacts of using conventional material alternative for Rail Baltic embankment construction;
- Comparing impact category results of two alternatives;

- Calculating optimal transport distances for using waste rock material for Rail Baltic embankment construction from environmental impact point of view.

This research paper starts with an overview of the theoretical background which surrounds the subject area. It consists of legal context, information about the Rail Baltic project, activities and environmental impacts connected to usage of both material alternatives and overview of other relevant studies done for assessing environmental impacts of conventional and unconventional material. It is followed by descriptions of the methodology used in this research which includes information about used parameters, study scope and assumptions made for conducting the assessment. Detailed descriptions of both alternative scenarios are also provided. Finally, results of both alternatives are presented together with information about contributing processes, optimal transport distances for using waste rock, uncertainty assessment, discussion and conlcusions.

2. THEORETICAL BACKGROUND

2.1 Policy and legal context

In 2015 the United Nations General Assembly adopted a sustainable development plan for transforming the World by tackling several global problems present today [3]. 17 grand goals and 169 smaller goals within them were set to be achieved by the year 2030. In addition, indicators for each target were set to measure each nation's achievements and progress in meeting these targets. One of the goals is to ensure sustainable consumption and production patterns by reducing waste generation through prevention, reduction, recycling, and reuse. Estonia has included these goals in the national sustainable development strategy for year 2030 [4]. Waste reduction, however, is far from being the only target. Some examples from the list include that greenhouse gas emissions must be lowered, water quality and biodiversity preserved, not to mention goals that are linked to increasing human well-being and economic growth. It is also brought out that whole life cycle impacts of products must be lowered. The vision is to have an integrated planning set in Estonia by year 2030 which includes assessing environmental impacts as one input for making decisions.

National legislation and policy connected to quarrying and mining statute that mineral resources extracted from the ground should be used as economically efficiently and in as sustainable manner as possible [5, 6]. This means that environmental, social, and economic impacts need to be analysed and considered before extracting resources. To avoid negative outcomes in the long run by balancing economic growth with environmental protection and nature preservation. Mineral deposits in the Earth's ground that are economically viable for extraction are finite, but the economy is more than ever depending on it to thrive and make new constructions like the Rail Baltic. Therefore, sooner or later already used resources need to be redirected back as raw materials if economic stability and long-term growth is wanted to be achieved. It is also important to not do it at the expense of permanently affecting population well-being that can be linked to environmental impacts but not solely.

More precisely, national policy document that states the general principles of Earth's crust use until 2050 includes that local resources and mining wastes should be used as much as possible to prevent excessive environmental degradation and wasteful extraction [6]. To enhance this, it is expected that in the constructions ordered by the state and local government, those two construction material options should be used to maximum possible extent compared to other material options. Furthermore, goals set in the National Development Plan for the Use of Oil Shale until 2030 indicate that more waste rock from oil shale sector must be used as raw material [7]. This means that more opportunities must be found in order to give this waste type new purpose areas. In addition to public sector, it should also become a preferred material by other groups of society. To facilitate this shift, innovation and pilot projects must be supported.

The European Union has also come out with ''EU principles for sustainable raw materials'' that brings all raw material sustainability related directives and policies together in one document [8]. It is one of the key topics for achieving a sustainable economy in Europe. Therefore, raw materials need to be extracted and processed by using best environmental practices and contribute to circular economy whenever possible. It is important that the extraction of raw materials goes toward improving and promoting efficient energy use and supporting climate change mitigation not to counter against it. The Rail Baltic project does contribute to combatting climate impact as transport by using electrical railway has lower emissions as other transport ways when fuelled by renewable clean energy. On Figure 2.1 raw material use and related processes are shown that are connected to the principles of sustainable use of minerals. Waste rock generated from oil shale mining belongs under the production of secondary materials stage if it is indeed used and not dumped as waste.

Figure 2.1 Stages connected to the European Union principles for sustainable raw materials [7]

However, recently the European Parliament has also come out with an initial Taxonomy Regulation which purpose is to set certain rules that will more precisely distinguish sustainable economic activities from not sustainable ones [9]. This classification system is still under development but is expected to be applied to all sectors in the near future, including companies dealing with mining and construction activities. For an activity to be classified as a sustainable, it will need to contribute towards at least one of six objectives which include climate impact mitigation, climate adaptation, sustainable use and protection of water sources, transition to circular economy, pollution prevention and control, and biodiversity protection and restoration. But it is also important that the activity does not do any significant harm to any one of the other categories. This means that in order to call an economy activity sustainable, a full spectrum of environmental impacts should be considered. Emphasising only on one aspect such as transition to circular economy is not enough and other impacts like for example pollution prevention should also be considered.

2.2 Rail Baltic project

Rail Baltic is one of the most ambitious infrastructure projects up to date in Estonia and the Baltic region. All general information about the project is found on it's official web pages (rbestonia.ee and railbaltica.org). The plan is to build 870 km long electrical railway that connects Baltic countries with mainland Europe by expanding the already constructed railway from Poland and Lithuania border all the way up to Tallinn. Whole map of the planned railway is presented in Figure 2.2. In Estonia, the planned railway will go through three counties - Harjumaa, Raplamaa and Pärnumaa, with a total length of 213 km. In Estonia alone, 24 wildlife crossings, about 80 amphibian passages and over 20 km of noise barriers are to be constructed in addition to the railway, with the aim to mitigate impacts to nature and people [10].

Figure 2.2 Rail Baltic projected railway and station locations [11]

Estimated total costs for the whole project is expected to be about 5.8 billion euros and it will take over a decade to complete from planning phases up to finishing the construction [12]. Originally it was planned that railway construction begins in 2019 and it will be opened in 2026. However, the project has had many delays and current deadline set for starting construction is 2023. Expected opening of the railway is set for 2030. Due to unforeseen events and changes that have happened in the recent years like the COVID-19 pandemic and war in Ukraine, it is possible that these will get postponed again as market conditions that were originally considered have significantly changed and seem to keep on affecting the plans.

Other transport ways by car, bus, plane and ferry will get partly substituted by this new railway system as it is expected that Rail Baltic will annually transport about 4 to 7 million passengers and 15 to 25 million tons of goods by year 2055 [13]. This new electric train transport will be more energy efficient, quieter, safer, more secure, faster and generate less air pollution than any of the other aforementioned long journey transport ways (if fuelled by renewable energy). Therefore, it can be seen that Rail Baltic is an essential sustainable development project that provides a new transport system with lower negative environmental and social impacts in addition to generating economic value, new jobs and ensuring connectivity with rest of Europe.

However, the construction and operation phase of the railway also has several negative impacts on the environment which should not exceed the generated positive impact, for it to be justifiable. Strategic environmental assessment was conducted in the early phases of planning in 2017 to analyse these factors by considering information known at the time. In summary, some of the conclusions were that [14]:

- The construction of the railway is preferred mainly because of the overall long-term positive effect through climate impact mitigation.
- Negative impacts linked to the construction phase such as impacts on local ecosystems through physically altering the natural environment surrounding the railway area and negative environmental impacts which are caused by transporting and mining of the needed construction materials should be mitigated as much as possible.
- Transporting construction materials should be done within 50 km radius to prevent excess emissions. But at the same time, it is also important to use reusable materials where possible, to be in accordance with material circularity principles. Oil shale residue use in railway construction is stated as one example on how to achieve it.

Whether and when it is from an environmental point of view better to use raw materials located near the area (that have to be quarried) or reusable materials which might not be as close but are already extracted from the ground, is not discussed.

2.2.1 Railroad track design

Properly built and compliant railway track from top to bottom roughly consists of [15, 16] (Figure 2.3 also illustrates the railway construction parts from a cross section view):

- Ballast (together with rails and sleepers) – the upmost part that is in constant contact with the weather and therefore has more demanding requirements for the material;
- Protective layer (sub-ballast and prepared subgrade) – middle part of the construction which divides load capacity from ballast on to the embankment, provides a solid base against sinking and limits water getting into the embankment. A special material is used in this layer that is in compliance with the technical properties regarding load capacity, frost resistance and water conductivity. Thickness of this layer depends on the quality of the embankment layer that is beneath it.
- Embankment (subgrade) – the largest part of the railway which softens and distributes load pressure to natural land on which the railroad lies. Thickness of this layer largely depends on the characteristics of natural soil and bedrock under it. Materials used in this layer need to have good filtration properties.

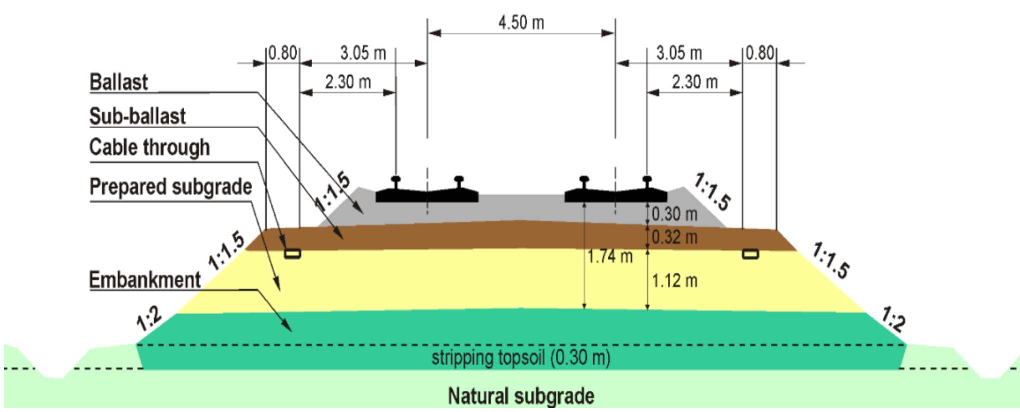

Figure 1.3 Rail Baltic track construction typical cross-section [17]

2.2.2 Construction materials and oil shale waste rock suitability

Construction of Rail Baltic needs a lot of building materials with the bulk amount being aggregates that go into the embankment of the railroad. More precisely, this means that huge amounts of filling materials like sand and gravel are needed as these are ordinary used for constructing the embankment [1, 18].

However, low grade limestone gravel, which is a direct waste from oil shale mining and with dimensions of 0-90 mm has also been proven to have suitable properties for it to be used as embankment material. Other upper layers of the track construction have higher quality standards which the waste rock does not have. For using it in the embankment, it is necessary to add 30% of construction (quartz) sand to the waste rock mass as the original 0-90 mm limestone gravel is too porous. These gaps cause tensions between the rocks which may in turn cause deformations if a lot of pressure is added (as for example a cargo train). Therefore, sand is needed to fill these empty gaps and make the material consistency more uniform. In addition, sand raises water conductivity and frost resistance which are also important parameters as railroad construction needs to be resistant to changing weather and seasonal changes. It is also possible to lower the need for sand by adding other, smaller grain composition gravel into to the mix. [2]

Nevertheless, this finer gravel is more expensive as it needs to be mechanically crushed and therefore also has a higher environmental footprint compared to the 0-90 mm gravel which comes straight from oil shale mining without additional processing. In addition, it is not certain that Eesti Energia is able to produce needed amounts of smaller fraction gravel without additional investments. Finer gravel is also a building material that has higher quality, and it should be preferred to be used in more suitable constructions where lower grade alternatives cannot be used. Because of the aforementioned reasons, the option to use exclusively 0-90 mm gravel is hereinafter only discussed, unless otherwise specified with another gravel fraction.

Altogether, it is estimated that approximately 9.85 million m3 of limestone waste rock could be used in Rail Baltic embankment construction in Estonia [2]. This substitutes the use of gravel and sand which would otherwise come from quarries and which can then be used in other projects.

However, the cheapest embankment construction material option is still probably to use as much of local materials as possible (with maximum transport radius of 50 km) [1]. But it is important to note that it is very hard to project these material costs as it depends on the supply and demand which is not constant. The supply of construction materials is uncertain as it depends on the possibility of opening new quarries. Proceedings needed for it are troublesome and time consuming. The additional large demand which comes from building Rail Baltic could also exceed the supply limits which would raise the originally projected prices. Internally made calculations in Eesti Energia on using oil shale waste gravel indicate that the most economically viable and competitive option against other potential materials is in Rapla county area. This is supported by the fact that in Rapla and Pärnu county area, sand and gravel supply security is in critical condition [1]. From these two, Rapla is more realistic because it is not as far away as Pärnu regarding the oil shale waste rock origin (Ida-Virumaa) and as a consequence the transport costs are lower. It is also possible that deficit in Pärnu area could be covered by large deposits found nearby in Latvia [1]. Therefore, Raplamaa location is hereinafter focused, as probably the most economically realistic area where the choice between conventional materials and oil shale waste rock is even possible to begin with.

In Raplamaa there are not any big mineral deposits of sand and gravel. As a result, it is only possible to open smaller quarries. This means that more quarries need to be opened to provide needed volumes of material compared to other Rail Baltic areas which have larger deposits of raw materials. Quarries currently present in that area and under revision process for being opened in the near future will probably not be enough to service the unprecedented sudden spike in resource need for constructing the surrounding Rail Baltica sections. It is also important to note that this resource is also needed for other projects like road construction and maintenance, so additional permits for opening new quarries should be pursued with haste if normal demand and added demand both want to be fulfilled with local material. The average time for opening sand and gravel quarries is about 3 to 4 years and up to 8 years if environmental impact needs to be done beforehand. Rail Baltic project on the other hand is already in motion as the construction is to begin shortly (within a year) and there is not enough time for these kinds of procedures, or they would have to be significantly shortened. If this does not happen and oil shale waste rock is not selected, then resource scarcity will be solved by transporting gravel and sand from places further away and then the price will start to increase. [1]

2.3 Conventional sand and low-grade gravel quarrying

Aggregate material extraction makes up the largest volume and generates the most economic value in non-energy mineral mining sector in the European Union [19]. Extraction of this material begins like any other natural resource extraction in Estonia - from conducting a general geological investigation and a more precise geological exploration of the mineral resources. This reveals the relevant characteristics of the material and geological peculiarities of the location. After these procedures, an extraction permit needs to be given by the national Environmental Board. Only then the actual extraction can start as extraction permit states the exact requirements, including amounts that can annually be taken from the ground. Environmental Impact Assessment can also be required, if the submitted extraction amounts are high or it can be assumed that the quarry will have significant impact on the environment or if the extraction site area is under heightened attention. [5]

It is common that in sand quarries there are also gravel deposits present and *vice versa*. Methods for extracting sand and naturally occurring gravel (not artificially made gravel from more solid layers of for example limestone) are also very similar and both are often used as low-grade filling material. However, the application areas of these materials depend on the actual mineral properties which varies by location. Desired mineral layer thickness for resource extraction can also differ and therefore the environmental impact caused in terms of per resource volume gained depends on the geological factors of the area. In some cases, minerals are extracted below ground level and other cases above it. In addition, some locations have a more vulnerable surrounding ecosystem. This shows that the actual environmental impact caused by quarrying is largely dependent on the local context of the quarry area [20].

Sand and gravel are mainly extracted in Estonia by using surface mining method which involves digging the material with an excavator which then places the material straight on to transport trucks or to an intermediate stockpile [21]. The natural surface with plants and habitats on the extraction site is destroyed during process that in turn lowers biodiversity of the local area [22]. This is especially true in sand and gravel quarrying as it happens on the surface and not underground as is for example with oil shale mining. Land area must be recultivated afterwards, in order to restore the former biodiversity levels. This was rarely done in the past as additional investments are needed and regulations regarding it were missing [22].

Another option used is through underwater mining, meaning that the sand or/and gravel is extracted by pumping or/and using water already present in the Earth's crust. Water mixture is pumped out, left to dry, sieved, and transported [21]. Due to the material and water extraction, the water conductivity of local land area can change [22]. That can in turn affect the groundwater levels of the surrounding area and make groundwater more susceptible to contamination as it is easier for it to infiltrate from the land above (for example oil leaks from the machinery). If the quarrying depth exceeds the groundwater level depth, then excess water needs to be led regarding the extraction method as it will also hinder the excavation works. Pumping water out of the ground and letting it back to the environment causes impact on eutrophication levels as it changes the properties of the waterbodies where it is led to, by increasing the concentration levels of suspended solids, phosphorus, and nitrogen above naturally occurring levels [22]. In addition, there are environmental impacts coming from energy use and operating machinery needed for carrying out the described quarrying activities.

2.3.1 Difficulties in opening new quarries

It is difficult to open new quarries even if a potential location is found in terms of good natural resource availability as it is possible that the area is on a nature reserve area, tensely populated, has public interest, or is already used for other purposes [19, 23]. People residing near the planned area are typically also not very keen on seeing new quarries nearby. It is feared that drinking water availability and quality will deteriorate in the area as it is not well enough considered [20]. In addition, heavy machinery must transport the excavated material and people are concerned about traffic load increases on local roads as it generates noise, dust and damages the roads [24]. Another concern is that the locals do not feel that they will gain anything positive back from the quarrying activity as a fraction of the mining rights and resource fees go to the local government and is mostly taken by the state [20].

Negative opinions from the locals are often expressed in stakeholder meetings that happen for example as a part of environmental impact assessment. The results of this assessment often heavily rely on expert knowledge as it does not consist of a strictly fixed methodology. It is because the environmental impact assessment needs to consider all impacts relevant from a local context, the particular features of the planned location and exact activities that want to be pursued [19]. This has caused problems in the practice of opening new quarries, as local residents are able to affect and hinder connected processes, often by overloading with problems that are based on emotions and not facts [24]. After all, the best measure for mitigating negative impacts from the viewpoint of locals is to not have a quarry in the first place. Local governments are typically also not interested due to risks of negative outcomes as long term impacts from the quarrying activity will be left for them to deal with and resentment from opposing locals is not wanted. The low economic gain that would be received from the quarrying activity does not outweigh the risks. Therefore, the outcome is often that approval is not given by the local government. In some cases, even the environmental impact assessment is dismissed before the analysis has been carried out.

In order to alleviate this problem, entrepreneurs expect the government to ascertain locations where quarrying is going to be allowed without any resistance [20]. This means that potential quarrying sites should be compared based on some general and comparable factors to choose optimal places. It is paramount that these factors also compare the significance of environmental and social aspects in order to meet public expectations and sustainability obligations taken by the government. After all, over half of the population believe that environmental and social impacts should be investigated in more detail than it is currently being done [25].

2.4 Oil shale waste rock generation

On average about 8 million tons of waste rock is generated annually by the oil shale industry [26]. However, this has been fluctuating in recent years due to energy reforms and environmental fees connected with the green transition. Nevertheless, most of the waste rock comes from Eesti Energia. More precisely from Estonia mine that is the biggest oil shale mine in the world. It’s underground mining area is comparable to the surface area of Tallinn. Oil shale layer present near the mine is about 70 meters deep underground and approximately 2 to 3 meters in width. In between the oil shale there are also limestone layers. Because of this, from about 1,4 tons of excavated ground only 1 ton of oil shale is produced. Rest of the material is extracted from the oil shale in the enrichment process as only high-quality oil shale is needed for energy extraction and shale oil production. This means that about 0,4 tons of waste rock is left unused per ton of oil shale output. The waste rock still contains up to 10% of oil shale which cannot be extracted and alters the limestone properties [1].

Oil shale mining process in the Estonia mine begins from drilling blast holes in the oil shale layer where explosives are placed and blasted. Material left by the blast will be transported by loader vehicles on to an extensive belt conveyor system which automates almost all of the oil shale transport from that point onward. Material placed on to the belt will go to the enrichment plant where it is crushed into smaller fractions as the original material is very irregular in size and can comprise of pieces that are over 300 mm in diameter. Sieves and wheel separator systems will then extract oil shale from limestone and oil shale will continue to go to further processing. The leftover limestone is directed to waste rock bunker where gravity sieves separate it into fractions of 0-90 mm and 90-300 mm. From the bunkers it is typically lowered onto tipper trucks where it gets transported to waste rock dump sites close to the enrichment plant.

However, some part of the leftover limestone will not go to the waste rock bunker at all, it is instead directed on to a gravel production line where it is separated to smaller fractions of 0-4 mm, 4-16 mm, 16-32 mm and 32-63 mm that are piled up next to the enrichment plant in separate rows. These fractions are more often used in construction and therefore has some market value. However, the production of smaller fractions depends on the demand and as it is generally quite low compared to how much of it is being generated, most of the waste rock ends up in the waste rock bunker and is therefore dumped as waste. In Figure 2.4 the Estonia mine refinement factory can be seen from the outside together with the colossal waste rock dumping sites next to it.

Figure 2.4 Estonia mine from top of a waste rock dump site. Own work.

Limestone waste rock that has not been transported to dump sites has mostly been used for landscaping, building smaller forest and light traffic roads [1]. Currently Eesti Energia is also constructing a foundation structure for a solar park by using waste rock as filling material. However, currently there is still over 100 million tons of waste rock in waste dump sites near the mine area. Main complications for using this material in other construction projects is due to its unsuitable technical properties. Better alternatives are continuously being searched for as waste rock is being generated in large volumes and simply dumping it to nature areas is unsustainable. The EU Waste Directive classifies waste as reused only if it substitutes other materials that would have otherwise been used for the same purpose. Rail Baltic embankment could be one option on how to reuse waste rock, as the embankment of it is a construction which is necessary with or without the presence of waste rock.

2.5 Comparison of environmental impacts

For analysing environmental impacts of different products, services, or cluster scenarios a standardized methodology called life cycle assessment is often used [27]. With this tool it is possible quantitatively measure different environmental impacts by including all life cycle stages connected to each activity measured. Using life cycle assessment in evaluating environmental impacts of construction materials has become more topical in the recent years. As companies want to lower their environmental impact, suppliers which can provide suitable materials with lowest environmental footprints are preferred. To verify construction material environmental impact, a special life cycle assessment framework called Environmental Product Declaration is often used. The outcome of the assessment is a label which shows the material impact scores of each life cycle stage. It has a fixed methodology which makes it possible to compare different products [28]. However, in academia it is more common to use more general life cycle assessment approach and define the boundaries depending on the research question.

One of such study was carried out by Saadé-Sbeih *et al.* to compare fertilizer industry waste (phosphogypsum) and conventional granulate use as a road base material [29]. Different alternative material mixtures were analysed including the use of waste rock generated from phosphogypsum mining. They found out that waste rock used together with phosphogypsum in road base has better environmental performances opposed to using conventional granulate materials, but not in all impact categories. What is remarkable from this study is that the phosphogypsum mixture alternative which has higher percentages of waste rock content in it has lower environmental impact scores compared to an alternative where waste rock is subsidized by conventional granulate. However, the baseline mixture that includes only conventional granulates had still better results from nine impact categories out of nineteen that were included in the assessment. It remains unknown what kind of results can be achieved if only waste rock is used, as this scenario was not further studied. It can be assumed that the results could be even better for waste rock as no additional processing linked with phosphogypsum and cement is needed. However, the additional use of sand which is needed in Rail Baltic embankemnt can also affect results in the opposite way.

Another comparative life cycle assessment was done in India by Suresh and Chawla [30] which analysed 1 km of railway sub ballast layer environmental impact from coal overburden aggregates and conventionally used natural aggregates. In this study, all processes starting from quarry operation until having materials at the construction site were included in the conventional alternative. For the other alternative, the mining process which generate waste rocks was not included but all other processes were assessed similarly to the conventional alternative. Their findings show that using waste rocks in railway construction significantly lowers negative effects on all impact categories analysed. For example, global warming potential impact category result was found out to be about 35% lower than the case of using conventional materials. This shows that using oil shale waste rocks might also have lower environmental impacts than the conventional alternative.

However, that assessment focused on sub ballast construction which is typically made of higher quality construction materials than the embankment. Unfortunately, it has not been proven that oil shale waste rock can be used as sub ballast layer like coal overburden aggregate. Current study at hand focuses on using waste rock to construct the embankment which does not include processes like crushing and sorting. Therefore, the results of this assessment can differ. Another important aspect is that the transport of both materials was assumed to be done by using diesel trucks and lorries, and the total transport distance was assumed to be the same for both alternatives (25 km) [30]. For using oil shale waste rock in Rail Baltic embankment this is not the case as it is possible that transport distances are much different when comparing conventional and waste rock alternatives. Waste rock must be transported from far away (Ida-Virumaa), but conventional aggregates will probably come from areas closer to the construction site, if enough volume of materials is available in nearby quarries. This can change the outcome results significantly as transportation of the materials was identified as one major contributor to most environmental impact categories analysed [30].

Another study which analysed environmental impacts linked to using recycled aggregates was done by Blengini and Garbarino in Italy [31]. They concluded that using recycled aggregates from construction sector may have about two to three times longer transport distance before the negative environmental impacts start to outweigh impacts coming from conventional material use. This is supported by a study done by Chowdhury *et al.* who studied the environmental impacts coming from using fly ash and bottom ash in road construction [32]. They found that transport distance should be less than 3 times compared to natural aggregate transport distance if lower impacts especially connected to energy use and global warming are targeted.

However, the impact equilibrium point connected to transport can differ for using oil shale waste rock than in the aforementioned studies as the connected processes are only generally similar. There has not been any previous research focused on assessing environmental impacts from using oil shale waste rock in embankment constructions using life cycle assessment methodology. As the outcome results heavily depend on details, a further examination of environmental impacts linked to using oil shale waste rock and comparing it with conventional material use in Rail Baltic embankment is necessary.

3. METHODOLOGY

3.1 Life cycle assessment

Life cycle assessment methodology is used in this study to determine the environmental impacts which come from using oil shale waste rock and conventional material in Rail Baltic embankment, as it is currently the best-known standardized practice which makes it possible to compare environmental parameters of different construction materials. By using this methodology all relevant input processes connected to both alternative material use which contribute to different environmental problems can be summed up and quantitatively assessed. It is commonly applied in sectors linked with construction and materials. Therefore, extensive data and information about similar processes and their connections to different environmental impacts is already available for use. It alleviates the otherwise difficult task of collecting and calculating everything from scratch. In addition, credibility of the research outcomes is raised and if needed results can be compared with other materials or similar studies. Input values about processes from life cycle assessment database is supplemented by data gathered from Eesti Energia, national databases and previously made studies to describe investigated scenarios more precisely.

A full life cycle assessment considers all the stages and their impacts which are connected to the usage of construction materials in road construction. Meaning that it starts from examining the extraction of needed raw materials and ends with the dismantling and disposal of the building materials at the end-of-life stage. In-between are also stages that consist of transport and material processing, construction activities and actual use stage of the built construction. This is the so-called cradle-to-cradle approach which is mostly preferred as it gives the full picture of activities which makes up the whole environmental impact. However, it is not always necessary to involve all life cycle stages, as it depends on the problem statement and scope of the research. All stages might not be relevant as in some cases they do not have a significant contribution to the end results. It is important to explain the scope and provide explanations if some life cycle stages are left out from the study.

3.1.1 Impact categories

All data about investigated processes is summarized and converted into certain parameters that indicate impact to different globally addressed environmental impact categories. One of the most widely used impact assessment dataset in Europe called CML (baseline) is used for characterizing impact values. More specifically, the results are given in seven different impact categories that are brought out and described in Table 3.1. Ecoinvent database version 3.7.1 was used for gathering input processes connected to both alternative material use and calculating impact category values.

Table 3.1 Impact categories through which the study results are presented [33]

Impact category	Unit	Description
Ozone layer depletion - ODP steady state	kg CFC-11 eq.	Emissions of ozone depleting gases which increases carcinogenic UVB radiation
Acidification potential - average Europe	kg SO2 eq	Emissions of acid gases (NH3, Nox, Sox) that cause acid rain
Climate change - GWP100	kg CO2 eq.	Greenhouse gas emissions which cause climate change
Depletion of abiotic resources - elements, ultimate reserves	kg antimony eq.	Depletion of non-renewable minerals (excluding fossil fuels)
Depletion of abiotic resources - fossil fuels	MJ	Consumption of non-renewable fossil fuels
Eutrophication - generic	kg PO4--- eq.	Emissions of nutrients (phosphorus and nitrogen compounds) to the natural environment which leads to abnormal plant growth in ecosystems
Photochemical oxidation - high Nox	kg ethylene eq.	Emissions of toxic gases (CO, SO2, NO, volatile organic compounds) which cause smog

3.1.2 Allocation

Waste rock use with fraction 0-90 mm is investigated in this study which is classified as waste as it is otherwise dumped in nature. By-product classification would be relevant if it would be possible to immediately process this rock to comply with construction material conditions during the oil shale production [34]. However, 0-90 mm rock must additionally be mixed with building sand in order for it to be used as a construction material in Rail Baltic embankment.

Cut-off approach is used to partition waste rock from the oil shale mining and production system processes and impacts. This means that the environmental burdens which are connected to both waste rock and oil shale are attributed solely to oil shale. Only processes that are separately connected with the waste rock in order for it to be used in Rail Baltic embankment are included. As the main purpose of Estonia mine is to produce oil shale and not waste rock, it would be inappropriate to allocate it’s impacts to the waste. These environmental impacts would otherwise be double counted as they are already accounted for in the oil shale and energy generation. Same approach is used in similar studies like for example life cycle assessment done by M. Saadé-Sbeih *et al.* in 2019 for analysing the environmental impacts of using different phosphogypsum mixtures as road base material [29].

3.1.3 Process map and system boundaries

All important life cycle stages and processes that are related to constructing the railway embankment are considered. The system boundary starts from raw material extraction and ends with the material laid to the embankment site. However, not all life cycle stages are included here, as the analysis is based on a cradle-to-gate approach. Research scope is illustrated by the process map of both alternatives in Figure 3.1. All direct and indirect processes (raw materials, products and energy production, use, emissions, and wastes) connected to the stages that are inside of the system boundary are considered. Input data which is used for environmental impact assessment can be found in more detail in Appendix

1 for all included stages.

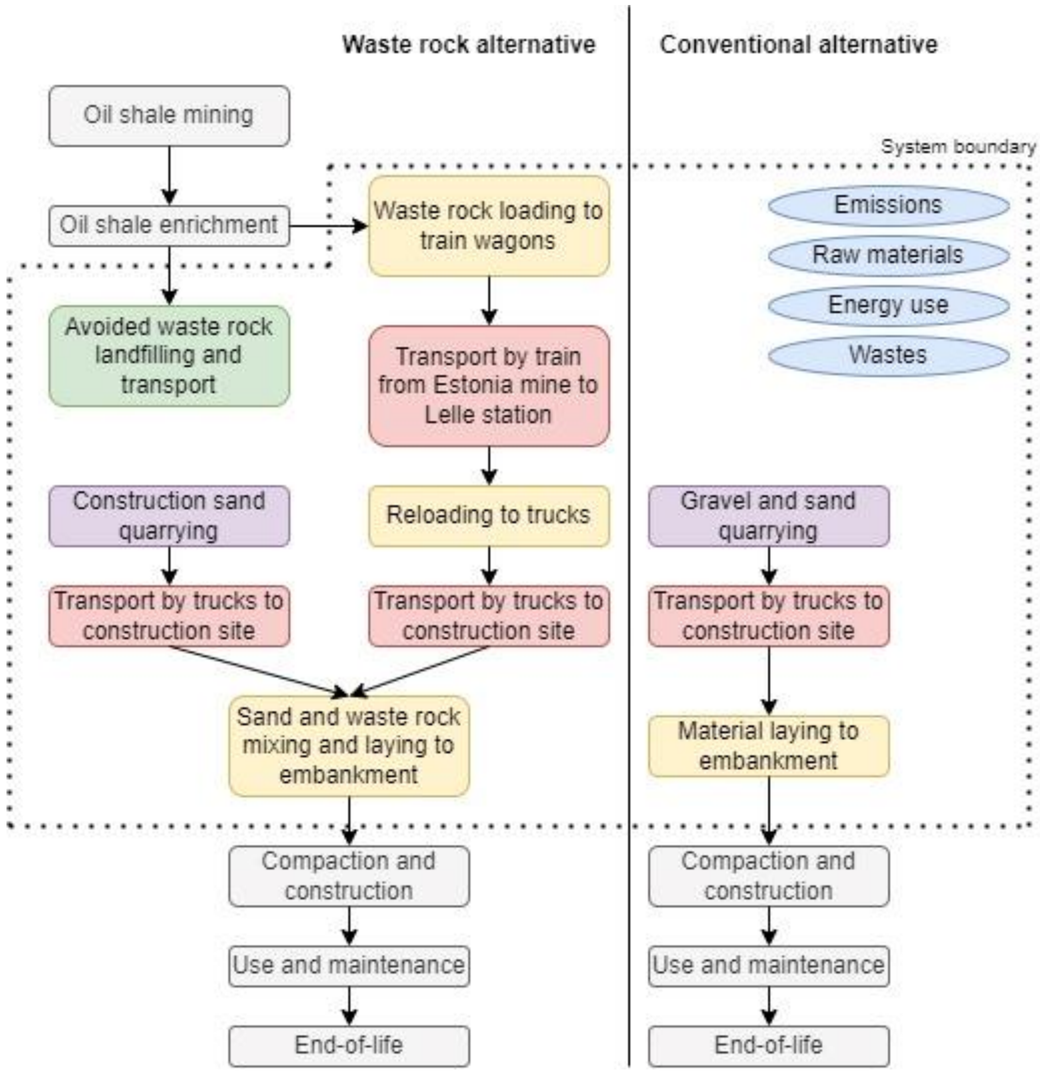

Figure 3.1 Process schemes and assessment scope of both investigated alternatives

Railway use and end of life is left out from the scope as knowledge about the differences of using either embankment material is unknown. Same mandatory construction and maintenance requirements are followed for both alternative materials. Therefore, it is assumed that the railway quality is not affected by construction material choice. In addition, both materials are inert sediments that are also found in nature and can be disposed or reused same way at the end of life. Therefore, it is assumed that these stages can be left out of the analysis, as it does not change the environmental impact results when comparing alternatives to each other.

In addition, the construction phase of the embankment is considered in a simplified manner as only the material lifting, and mixing is included. It is assumed that other construction activities like compaction of the embankment does not depend on material choice and is therefore left out of the system boundary.

3.1.4 Main parameters for scenario comparison

The main purpose of both alternative material use is to build Rail Baltic railway embankment. Therefore, the functional unit, meaning the parameter by which results are calculated and compared is chosen as a distance of one kilometre (1 km) of embankment. Reference flow, meaning the unit that indicates input flows which are needed for accomplishing the function is set as the needed material volume of one cubic meter (1 m^3). Therefore, the unit that connects function and reference flow is one kilometre per cubic meter (1 km/m^3).

3.2 Alternatives and data

Benchmark or base scenario by which the environmental impact of both alternatives is calculated and compared is the Rail Baltic preliminary design section number five that has a length of 18.6 km. This section is to be planned in Raplamaa county. More precisely, between Kehtna bourough and the administrative boundary of Pärnumaa. Chosen railway line with crossings is depicted in Figure 3.2. In order to calculate the transport distances of both alternatives, the precise centerpoint of chosen design section is used. This is research point GL08 IP109 (coordinates X=6520225; Y=546778). Spatial data and the quantities of mineral resources required for the construction of railway section is based on previously conducted research by TalTech University [2].

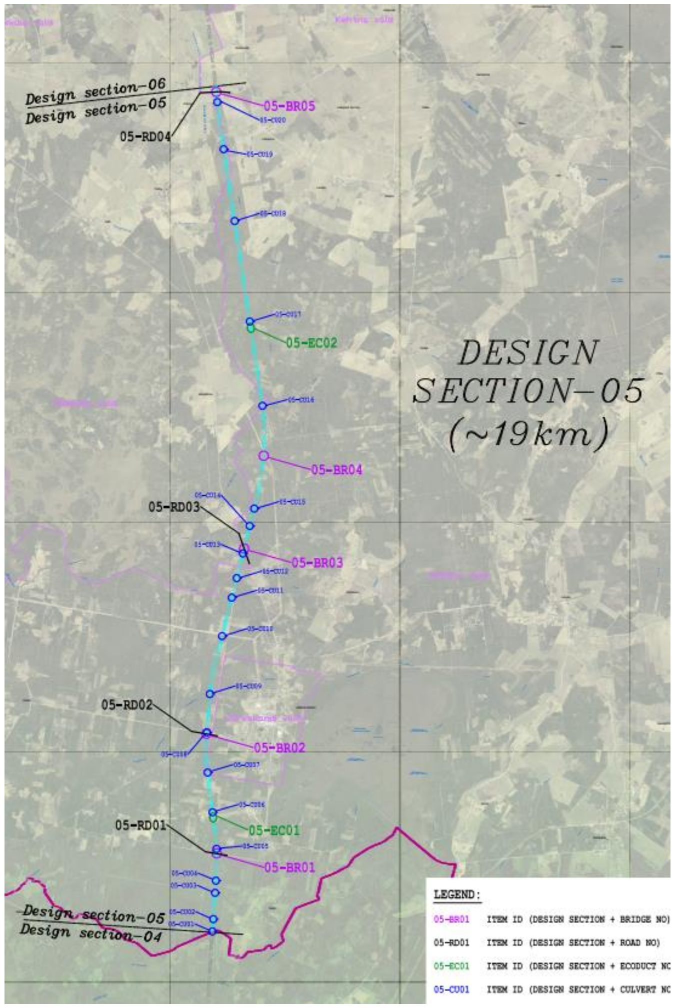

Figure 3.2 Rail Baltic preliminary design section number 5 (from Rail Baltic preliminary design documents)

3.2.1 Conventional alternative

The conventional alternative scenario consists of using filling aggregates in Rail Baltic embankment that would normally be used, including processes that are connected to it. This means that a construction solution which involves the use of materials that have at least medium (QS2) properties is focused on. The criteria for this material is that the material needs to have less than 15% of fine particles in it and it needs to have at least medium strength properties [15]. After consulting with specialists, it turned out that in Estonia sand, gravel or both would most likely be used. These materials in general comply with the given criteria and are economically most reasonable. It could also partly be higher quality limestone or dolomite, but in this case, pre-treatment is required that would include additional costs and environmental impacts and it would be more reasonable to use these materials in other projects that involve higher standards for the construction materials [1]. Therefore, higher quality construction materials are not included in this study.

Requirements for aggregates and earthworks in the preliminary design of Rail Baltic state that for building the embankment also lowest quality unsuitable (QS0) and weak (QS1) filling aggregates can be used if certain special techniques are taken [15]. Under this classification usually soils that are left over from the excavation works are considered. However, if this technique is chosen then it is necessary to surround this low-quality material with layers of material that has higher technical properties. This study does not include such alternative as at the time of conducting this research details about this alternative together with volumes and origin of needed materials was unknown.

Therefore, in this alternative it is assumed that sand and gravel is used for building Rail Baltic embankment. In national databases and documents which include information about mineral deposits this material is more precisely classified as filling gravel, filling sand, construction gravel and construction sand. A simplification is made here that all material which falls under aforementioned categories is suitable. In real life, more precise criteria for the materials would be set and therefore not all of minerals from such deposits would actually be suitable for construction. More precise technical properties and amounts of unextracted material is unfortunately unknown before it has been extracted.

Based on previously made study [2] it is estimated that 32.3 thousand m^3 of material is needed for constructing 1 km of embankment. Related processes and environmental impacts are linked by using the mentioned material volume as an input data for documented processes in the life cycle assessment database. All further details about used data, associated datasets and calculations that were included in assessing the conventional alternative are brought out in Appendix 1.

Construction material transport distance. It is assumed that the average material transport distance from surrounding quarries is 27 km. In total 25 active and 4 pending quarries were considered in calculating this distance. Active quarries that were included are brought out in Figure 3.3 (with blue dots) together with the maximum radius distance of 35 km from the railway section midpoint (in blue circle).

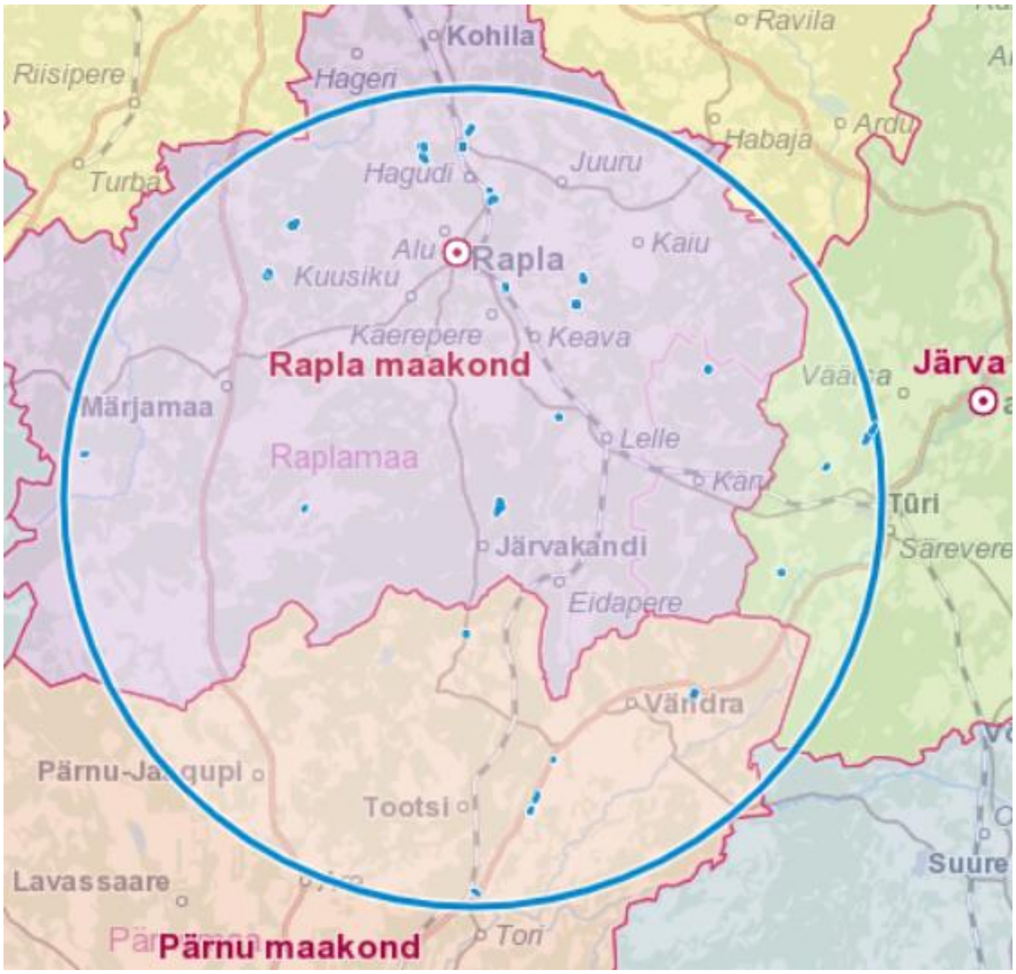

Figure 3.3 Quarry locations included in conventional alternative (from Maa-amet GIS application)

Finding the average transport distance. To calculate impacts related to transporting construction materials it is important to know the locations of where the material would come from. However, at the time of conducting this study there was not a main construction project available for the chosen railway section and therefore exact locations of where raw materials would come from was unclear. It is assumed that the material would come from quarries that are closest to the railway section midpoint. In addition, annual average production volumes of these quarries were used as there is information available about it in the national databases and documents. Therefore, it is assumed that all the annual production volumes that are extracted from these quarries will be used to build the chosen Rail Baltic railway section. In reality, this material would probably also be used in other projects and so this study focuses on the lowest environmental impacts possible coming from raw material transport if the section is built in near future within one year. If it is decided to bring this material from quarries further away, then negative environmental impacts will rise because the quantities of fuel use will also increase.

Quarries have been selected by using GIS tool of Maa-amet which allows to find quarries by location point radius and mineral resource classification (extended and spatial search for a mining allotment). Information about the annual production volumes of found quarries was taken from the register of environmental permits and registrations (KOTKAS). All information about the potential quarries is collected as of 26.04.21. Quarries with an environmental permit that expires before the beginning of year 2022 were not considered, as construction of the Rail Baltic section is unlikely to start before and the material from such mines will be used in other projects. Annual volumes of only suitable material (filling sand, filling gravel, construction sand and construction gravel) were considered.

Nearest quarries were chosen by adding together suitable material amounts starting from the closest quarry and increasing the distance radius until all volume needed for constructing the embankment was achieved. Often not only one type of material is extracted from a quarry but several, from which all might not be suitable in this alternative. But the average annual production volumes recorded in the environmental permits include all materials that can be extracted. In order to not assume that only the suitable kind of material is extracted, the total material average production volume was multiplied by the percentage of how much suitable material was in the total material reserve volume. However, if the suitable material reserve volume left was less than previously calculated then that was considered instead as it is not possible to extract it more. In such case the suitable material has already been previously extracted more than other materials and there is not much left of it.

The used GIS tool does not include potential quarries that will be opened in the near future, but their produce could also be used in constructing the embankment and these quarries could be closer. Therefore, information about those quarries were separately collected from pending environmental permits. Suitable material volumes which are present in those pending quarries and are nearer, were considered by substituting previously found furthest active quarry volumes with those volumes, shortening the transport distance. However, for quarries with pending environmental permits information about average production volumes was not available and therefore total volumes of mineral resources that potentially could be extracted (stated in the pending permit) was considered instead. Those volumes were divided by the pending environmental permit period of validity (years) to identify the approximate average annual material production volume.

Location coordinates of all gathered suitable quarries were collected from the database to find transport distances by vehicle roads to the railway section midpoint by using Google Maps software. The distance of every suitable quarry was then multiplied by their annual suitable material volume and divided by all material volume needed for constructing the railway section. After which the distance results of all quarries were summed to find the total average transport distance.

Other relevant data. Regarding impact coming from transport, it is also important to know parameters of the vehicles which carry material from quarries to the construction site. Consulting with logistic companies it turned out that material transport would most likely be done by using saddle trucks (type N3) which have a load capacity of 22 m^3. It is assumed that the emission standard of these trucks is EURO 4 as it is the average standard that these type of trucks in Estonia have, according to the national Transport Administration statistics of vehicles (based on the average vehicle age).

Based on the same data previously gathered about suitable quarries, it is assumed that from the whole material volume needed to construct 1 km of embankment (32.3 thousand m^3), 19.68 thousand m^3 of gravel and 12.6 m^3 of sand is used. This means that considering gravel average density of 1.4 t/m^3 and sand average density of 1.3 t/m^3, the assumed input transport amount per functional unit is 1.3 Mt*km (to have a more precise input parameter, the number has been divided by 0.9 – this is the actual truck load capacity of these trucks divided by the truck capacity in reference process used from the life cycle database).

It is also assumed that material arrived to the construction point will be lifted and laid on the site by using machine Sennebogen-817 which has a grab that fits 500 liters. Based on a visual assessment it is assumed that the machine lifts this amount twice in one minute and therefore the expected working time of one machine is approximately 32 thousand minutes according to one functional unit.

3.2.2 Waste rock alternative

This alternative evaluates the environmental impact that would happen if examined railway section embankment will be built using waste rock with fraction of 0-90 mm. It originates from Estonia mine as a residue waste that comes from oil shale extraction and enrichment processes. It can only be used in Rail Baltic embankment if 30% of quartz sand is added to the amount of waste rock and mixed [2]. The sand cannot be of sediment rock origin and must classify under standard EVS-EN 1342 as fine or not fractioned filling material, meaning that the maximum grain diameter must be 8 mm or lower and have a content of fine particles classified as f5 or UF5 [2]. After consulting with specialists, it was found out that most likely the material which would best fit with these parameters is construction sand. All construction sand might not be suitable but more precise parameters and amounts about unexcavated materials was unknown. Therefore, all construction sand is assumed to be suitable (a similar simplification like in the other alternative). Based on the previously made study [2] it is assumed that for constructing 1 km of embankment, 9.683 thousand m^3 of construction sand and 32,3 thousand m^3 of waste rock is needed. All further details about used data, associated datasets and calculations that was included in the assessing the waste rock alternative are brought out in Appendix 1.

Parameters connected to sand transport. Suitable quarries from where construction sand will come from to be mixed with waste rock is found by the same method described in Section 3.2.1. The only difference is that suitable mineral type is narrowed down to only construction sand. In total 14 active and 4 pending closest quarries were considered in the calculation of average sand transport distance which was found out to be 38 km. By assuming that the needed sand volume is 9.683 thousand m^3 and sand density is 1.3 t/m^3, the total input parameter that characterises transport is 0.534 Mt*km. Transport type is assumed to be the same as for conventional alternative and it is also divided by factor 0.9 (more detailed explanation in Section 3.2.1). In Figure 3.4 active quarries that were considered (marked by blue dots) and the maximum distance from the railway section midpoint (blue circle) which is 41 km is depicted.

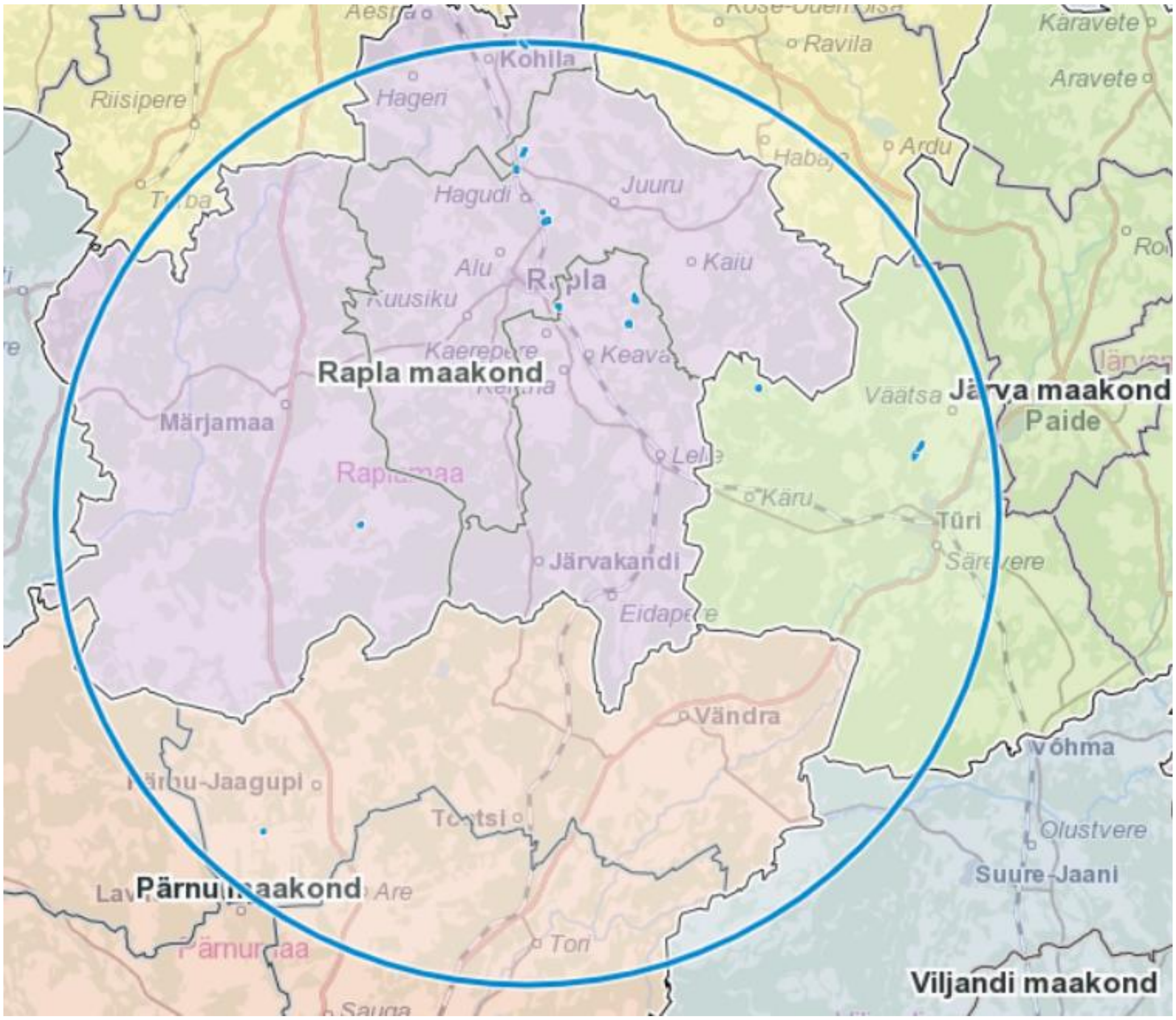

Figure 3.4 Quarry locations included in waste rock alternative for construction sand (from Maa-amet GIS application)

Parameters connected to waste rock transport. Waste rock environmental impact assessment begins from the material loading on to a train car. Stages that come before it like mining and enrichment which are connected to oil shale are not included. Reason for this is already discussed under allocation (section 3.1.2). After loading the material onto a diesel engine train, it will go to Lelle freight station which is the closest station to the examined railway section midpoint. Transport from Estonia mine must before reaching the destination, go through Jõhvi and Ülemiste freight stations. Based on the data received from Eesti Energia, the total one-way distance is about 250 km (21 km to Jõhvi, from there 156 km to Ülemiste and from there 73 km to Lelle). No reloading of the material happens in intermediate stations. Taking into account that 32.27 thousand m^3 of waste rock is needed, waste rock density is 1.3 t/m^3 and 250 km is the distance, then the parameter that describes transport of waste rock per functional unit by train is 5.7 Mt*km. Because the used original input process from database was based on hilly landscape area and Estonia has a rather flat landscape that causes less fuel use, the input parameter was corrected to match more precise fuel use data gained from Eesti Energia. The factor for which result was multiplied with was 0.54. This factor was found by taking diesel consumption data from Eesti Energia (60t) and dividing it by input parameter original diesel consumption data (112t).

In Lelle freight station waste rock is reloaded onto trucks (same technology and input parameters as described under conventional alternative (section 3.2.1). From there the transport distance is 20.5 km to the examined section midpoint and so the indicator that describes waste rock transport by truck is 0.96 Mt*km per functional unit (the same truck is used as described in conventional alternative). It is assumed that waste rock and sand mixing will happen at the same place as embankment construction to consider the minimum possible impact as in the other alternative. Therefore, no other transport of the material is needed.

Parameters connected to mixing sand and waste rock. Already made waste rock suitability analysis brings out that the mixing of waste rock and sand can be done in several ways [2]:

- On the construction site by using excavator;
- Putting sand and waste rock in turn on to trucks that transport it to the construction site;
- Building the embankment by first laying waste rock layer, then adding sand and compacting the material;
- Using a filling material mixing unit.

The latter option is thought to be the most secure way of ensuring homogeneity of the materials. However, in this study it is assumed that the first option is chosen as it does not need the use of any additional heavy machinery and is therefore possibly with the least environmental impact. After consulting with specialists, it also turned out that for using the third option, it is necessary to lay the materials in very thin layers and is therefore not as efficient. Second option is excluded because in that case sand would first need to be brought to the freight station where waste rock is unloaded, and it would unnecessarily increase transport distances. It is basically the same option as the first one with the only difference being that mixing happens in a truck and not onsite.

Therefore, it is assumed that waste rock is mixed with sand onsite, next to the embankment construction area. Same excavator as described in conventional alternative (Sennebogen-817) is used for carrying out this process. This means that in order to mix sand and waste rock, both materials will be in turns lifted and laid to a mixing area (excavator takes one load of waste rock, then one load of sand and so on). The mixed material is then lifted and laid to the construction site. If it would directly be laid on the construction site without putting it to the mixing site first, then the needed level of homogeneity would not be ensured. This means that material must be lifted twice as much compared to the conventional alternative. Considering the same machine operation specification (1000 litres of material per minute) and material amounts (in total 42 thousand m^3), the machine work time is about 1400 hours in total per km of railway.

Positive impacts considered. In this alternative negative impacts which are prevented by not dumping waste rock near Estonia mine as it will be transported to building Rail Baltic embankment is considered. More precisely, it is analysed based on information gathered from Eesti Energia that how much transport distance was prevented and how much land area would be not occupied by waste rock as dumping sites. Dumper trucks emission standard is assumed to be EURO 3 with a carrying capacity of 35 m^3. It is considered that distance to the dumping site is 3.2 km. Therefore, considering that per functional unit it takes 32.27 thousand m^3 of waste rock with density of 1.3 t/m^3, the avoided transport is about 77.7 kt*km. In order to have a more precise input, the result were first multiplied by a factor of 1.7, which was found by taking more precise truck capacity and dividing it with the average capacity used in the dataset. In addition, it is assumed that one metric ton of waste rock takes about 0.26 square meters of land.

3.3 Limitations and assumptions

This study considers a certain assumptions that are thoroughly explained in the previous chapter. Processes and parameters can differ, depending on the main project, time, actual construction company preferences, resource availability etc. As at the time of conducting this study there was not a main project about the examined Rail Baltic railway section or no real construction works or contracts have been done yet to take as a benchmark, other best information available was used (mainly the preliminary design documents, other studies, environmental permits, calculations from Eesti Energia, and general efficiency and cost indications). Simplifications have been made in places where relevant information was missing, by taking a general estimate (like for example quarry choice, distance, material amounts, lifting technology). In addition, datasets used in the calculations only roughly estimate background processes (based on previously made similar analyses and measurements not actual measurements). To make this information more accurate, multipliers were used if a more precise indicator was known. These resembled the ratio of real data to data in the dataset. When possible, input parameters were also completely substituted with the actual data known (information collected from Eesti Energia).

In addition, the focus of the study was to find out minimal environmental impacts that would happen in both alternatives. If other measures are taken, then the negative impact can increase. Usually, reserve, or spare material amounts are also calculated in projects to ensure material availability if unpredicted additional material losses happen. However, no spare material amounts were taken into account in this study. The amounts of needed material in the embankment are also precisely unknown as different opinions exist until the actual main project is compiled. Material amounts were based on previously made study [2]. It can be possible that the needed volumes are actually lower but even then, results of this study should be roughly same when comparing the two alternatives, as it would probably impact both equally.

Life cycle assessment methodology in essence measures environmental impact through globally important parameters and fails to consider some local impacts or undervalues them. But these can also have substantial impact to ecosystems, like for example when opening new quarries, the surrounding area will heavily be impacted by noise, reshaping of nature etc. It also does not consider exact region-based differences (based on regional average) and therefore impact relevance that can differ. In addition, social impacts which are also very important to consider, especially when opening new quarries. To not completely leave this part out, general results about land transformation and occupation are given in the next chapter. The impact to local ecosystems and people can vary based on the quarry location and surrounding context, therefore these impacts are not analysed further as exact information about it is unknown in parameters that can be measured in similar nature to the life cycle assessment approach.

3.3.1 Land transformation and occupation

To assess environmental impact in addition to life cycle assessment results, information about land transformation and occupation is brought out separately in this section. This is done in order to emphasize the very different impact results discussed alternatives have to land use which is important when talking about local impacts that the used life cycle assessment method does not focus on. Data relevant to land use has been gathered from environmental permits of the same suitable quarries discussed earlier (in chapter 3.2.1). For all quarries considered where construction material would come from, data has been collected about permit validity period, quarry service area, total allowed resource extraction capacities and resource capacities that would potentially go to building Rail Baltic embankment.

In order to find out how much land would be transformed, a percentage has been found that indicates how much material from the total allowed extraction volume would go to building Rail Baltic embankment. This has been then multiplied with the total quarry service area. To obtain an overall result that includes all suitable quarries, results have been summed. This shows how much land will theoretically have to be transformed to a quarry in order to extract the needed materials for one km of railway embankment. For the conventional alternative it has been found that 1.24 ha and for waste rock alternative 0.37 ha of land is transformed to a quarry area. In addition, the waste rock alternative would avoid 1,09 ha of land being transformed to a waste rock dump site. This means that waste rock alternative avoids in total 0.72 ha of natural land being technogenically transformed per km of railway built.

In addition, land occupation has roughly been calculated which also takes into account the time of how long needed quarries would minimally affect the surrounding nature. In order to evaluate this, land area transformed to a quarry area has been multiplied with the time that it takes to extract needed materials from quarries to construct the railway embankment. This time has been found by taking total permit validity period (in years) and multiplying it to the ratio of resource capacities that would go to construct railway embankment from total allowed extraction capacities. Total permit validity period shows the time of how long a quarry is allowed to be operated and therefore after that time the quarry area could potentially start to recover back towards a naturally existing ecosystem. However, this expects that right after the permit ends, all quarrying activity would cease, and land would be recultivated. The time that is needed for recultivation activities and for the area to recover to its natural condition has not been taken into account. Therefore, the actual time that land is occupied and affected by the quarrying activity is higher. For conventional alternative this land occupation indicator is 0.54 hectare-year and for waste rock alternative 0.1 hectare-year. Avoided land occupation from dumping waste rock has not been considered in this calculation.

4. RESULTS

In Table 4.1 both alternative results are presented in all seven assessed impact categories that indicate the impact which would happen from such construction material choice if 1 km of Rail Baltic railway embankment is built. Across all impact categories the waste rock alternative has higher results which means that from an environmental impact point of view the conventional alternative turned out to be superior by having the lowest environmental impact in all measured indicators. In Figure 4.1 these results are brought out from the viewpoint of how much conventional alternative results make up from waste rock alternative results. It can be seen that the impact category in which conventional alternative is most favourable is in eutrophication category. The category in which both alternative impacts are closest to each other is in photochemical oxidation category, very closely followed by depletion of abiotic resources category. When considering the average percentage from all categories it can be said that conventional material use results in approximately 57% of environmental impacts from the waste rock alternative.

Table 4.1 Both alternative results in all measured impact categories

Impact category	Unit	Conventional alternative	Waste rock alternative
Ozone layer depletion - ODP steady state	kg CFC-11 eq.	0,068	0,13
Acidification potential - average Europe	kg SO2 eq	2 400	4 400
Climate change - GWP100	kg CO2 eq.	430 000	810 000
Depletion of abiotic resources - elements, ultimate reserves	kg antimony eq.	0,015	0,021
Depletion of abiotic resources - fossil fuels	MJ	5 800 000	11 000 000
Eutrophication - generic	kg PO4--- eq.	460	1100
Photochemical oxidation - high Nox	kg ethylene eq.	110	150

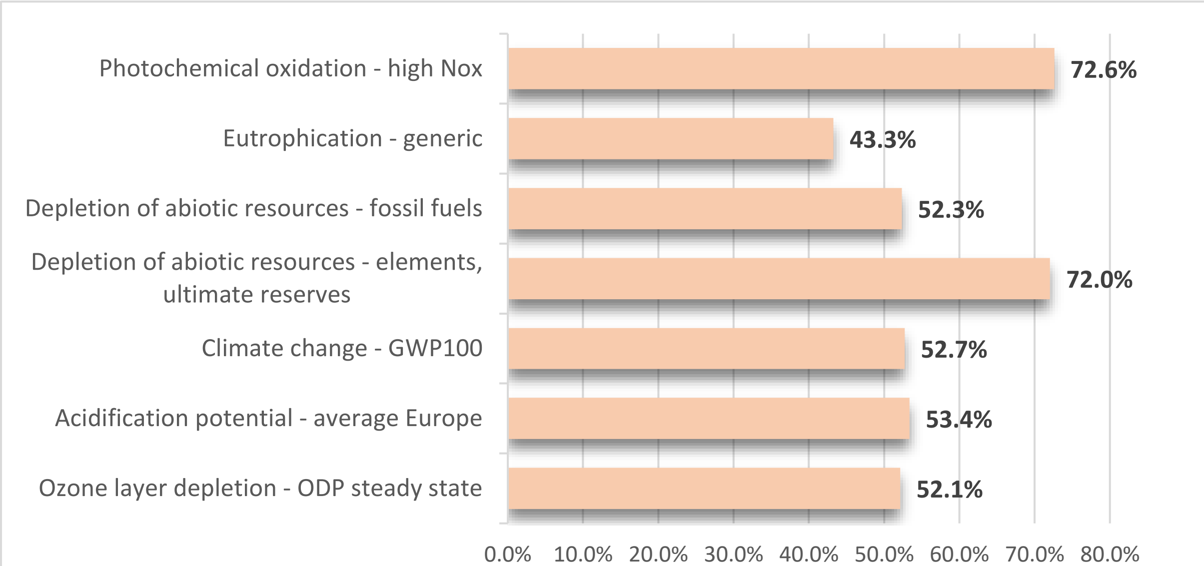

Figure 4.1 Share of conventional alternative *results from waste rock alternative*

In general, the reason for such outcome is due to the much longer distance that waste rock has to be transported as opposed to conventionally used gravel and sand. In addition, waste rock must be moved more because of reloading it to different transport systems and additional mixing that is not needed for using conventional materials. Waste rock alternative is also larger in volume (30%) due to additional construction sand need, and this is an important parameter which raises impacts coming from transportation as more materials need to be moved around. When choosing conventional materials for embankment construction, it needs to be about four times moved less around from one transport carrier to another and the total transport distance is about ten times lower. Filling material is low quality and inert natural resource that does not cause high environmental impact compared to perhaps other higher quality resources which need more processing. Extracting less filling materials does not compensate much higher transport need that comes with using waste rock as it is heavy and moving it around takes a lot of energy.

4.1 Conventional alternative

In Table 4.2 different processes which make up to the conventional alternative are brought out together with a heatmap which shows the percentages of how much different processes contributed to the assessed environmental impact categories. In Figure 4.2 the average results across all impact categories are visualised for each separate process stage. As might be expected, the highest impact proportion comes from quarrying the material, followed by transporting and lifting. Ironically most of the quarrying impact results in acidification, climate change and photochemical oxidation impact categories comes from the use of electricity which is largely produced from oil shale. Eutrophication category results are high primarily because of diesel fuel use.

Table 4.2 Conventional alternative process heatmap that shows process contributions to impact categories

Impact category	Process		
	Quarrying	Transport	Material lifting
Ozone layer depletion - ODP steady state	44%	36%	20%
Acidification potential - average Europe	65%	24%	11%
Climate change - GWP100	51%	31%	18%
Depletion of abiotic resources - elements, ultimate reserves	52%	43%	5%
Depletion of abiotic resources - fossil fuels	46%	35%	19%
Eutrophication - generic	60%	28%	12%
Photochemical oxidation - high Nox	74%	16%	10%

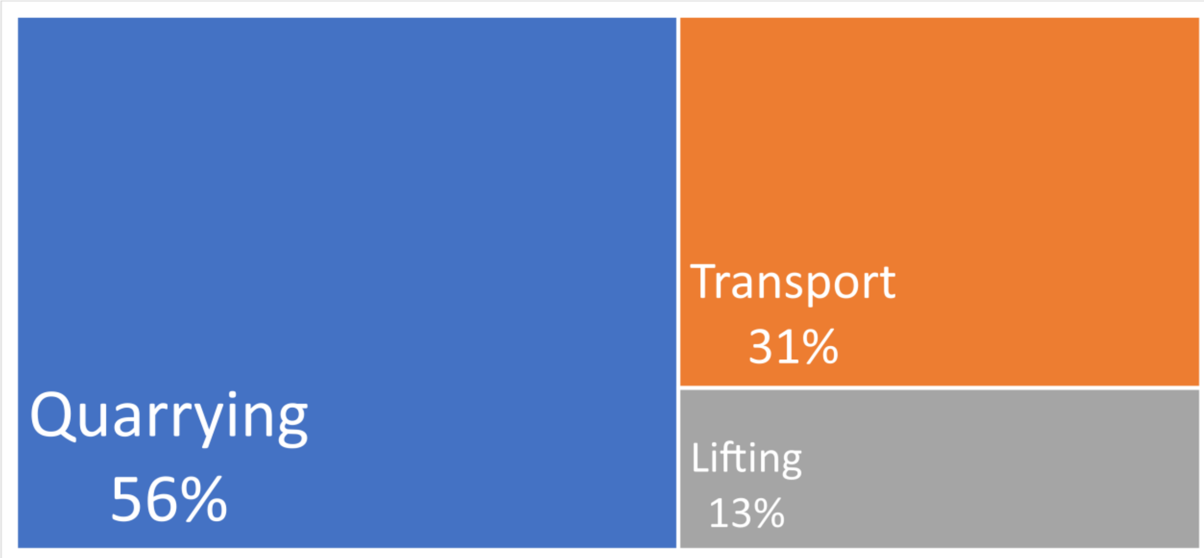

Figure 4.2 Average percentages of conventional alternative processes across all impact categories

4.2 Waste rock alternative

In waste rock alternative there are more processes which are needed to be done. These can all be seen in Table 4.3 as a heatmap together with contribution to the total results in all assessed impact categories. Most impact in all impact categories comes from train transport. This is mainly due to diesel fuel use. In addition, processes related to waste rock reloading and lifting have a significant contribute to the total results. All of these processes combined even exceed impact coming from train transport in ozone layer depletion and depletion of abiotic resources impact categories. Impacts coming from construction sand quarrying is generally marginal, making only about 10% from the total impact. In Figure 4.3 average results across all impact categories are visualised for each separate process stage.

Table 4.3 Waste rock alternative processes impact contribution to whole impact results

*Table **Tõrge! Rakendage vahekaardi Avaleht kaudu käsk 0 tekstile, mida soovite siin kuvada.**.1*

Category	Process						
	Sand quarrying	Sand transport	Waste rock loading onto train wagons	Transport by train	Waste rock re-loading	Waste rock transport by truck	Mixing and lifting to con-struction site
Ozone layer depletion - ODP steady state	7%	8%	2%	35%	10%	12%	27%
Acidification potential - average Europe	10%	5%	3%	55%	6%	7%	15%
Climate change - GWP100	8%	6%	2%	39%	10%	11%	25%
Depletion of abiotic re-sources - elements, ul-timate reserves	11%	13%	1%	42%	3%	23%	9%
Depletion of abiotic re-sources - fossil fuels	7%	7%	2%	37%	10%	12%	26%
Eutrophication - generic	8%	5%	3%	60%	5%	7%	14%
Photochemical oxida-tion - high Nox	16%	5%	2%	46%	7%	7%	18%

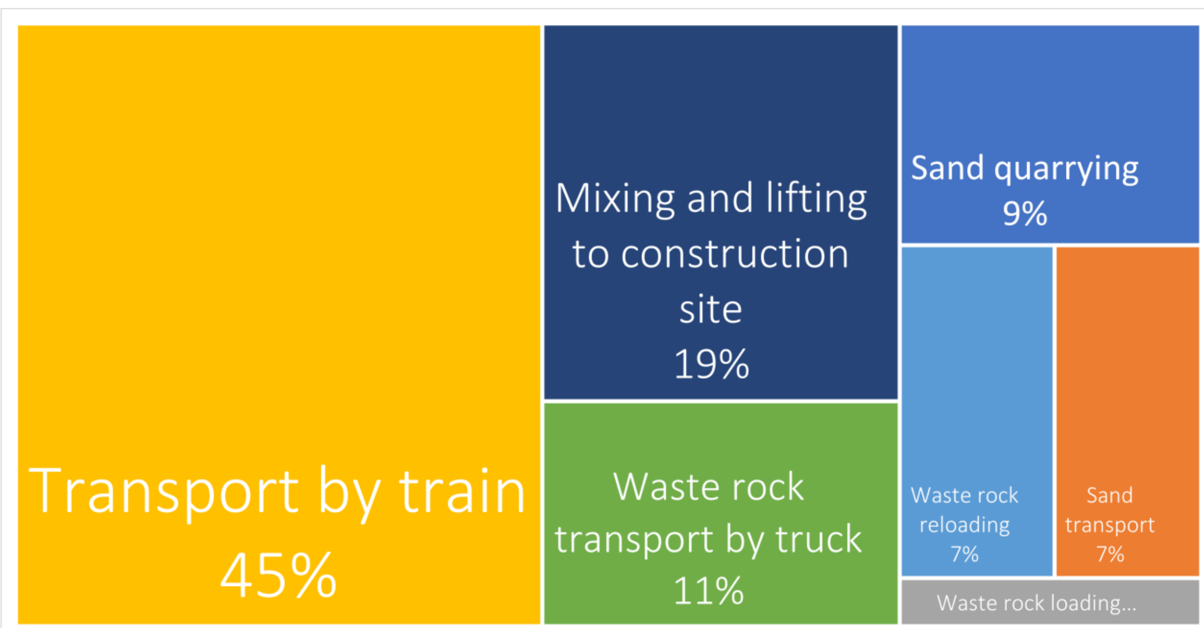

Figure 4.3 Average contribution of waste rock alternative processes across all impact categories

4.3 Waste rock optimal transport distance

Maximum transport distances from which point onward waste rock alternative environmental impact exceeds the conventional alternative are calculated for each impact category. Rail transport and related reloading processes in waste rock alternative are left out from this calculation. This means that only transport by trucks is considered. Data about suitable quarry distances and other relevant information is kept the same. For conventional alternative all input processes and data remained the same. In Figure 4.4 these maximum distances are shown. Like in the previous results when looking only at the photochemical oxidation impact category, then it is possible to transport waste rock furthest before it starts to exceed impact coming from conventional alternative. The shortest transport distance is possible when looking at the ozone layer depletion impact category and not the eutrophication category as train transport has not been included here. When considering all impact categories then the average maximum transport distance of waste rock is 41 km before waste rock alternative starts to exceed the conventional alternative environmental impacts.

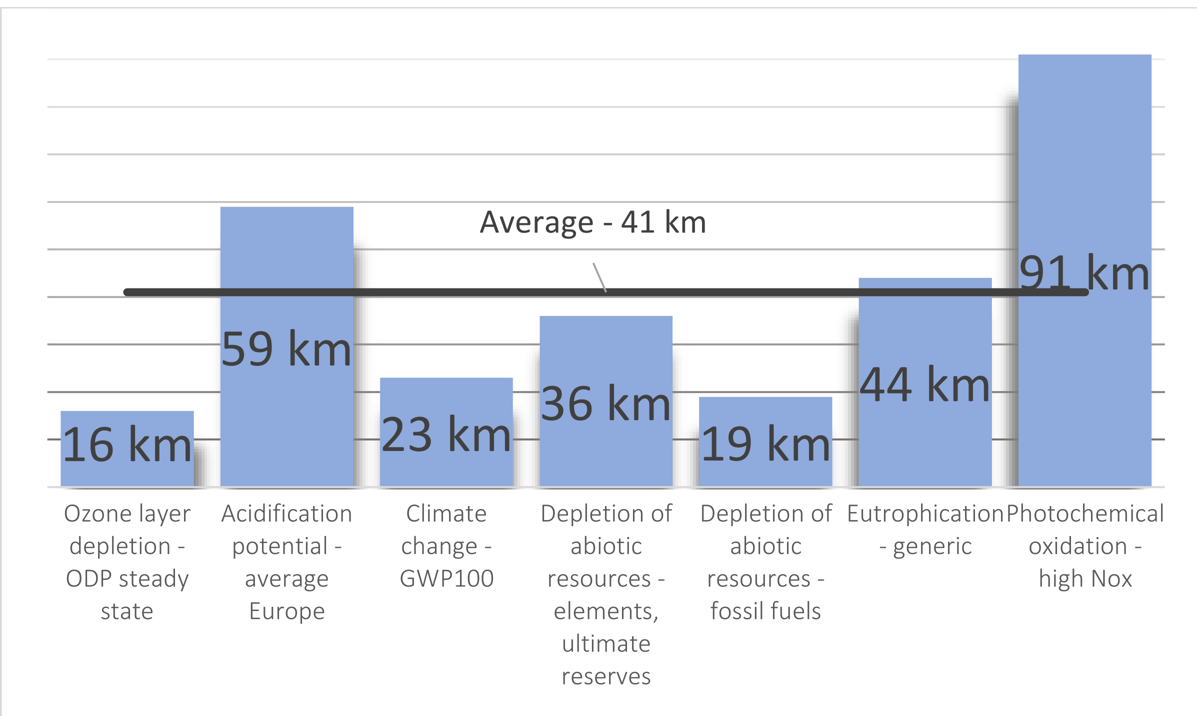

Figure 4.4 Maximum distance waste rock can be transported by trucks before it starts to exceed conventional alternative results

4.4 Uncertainty assessment

Monte Carlo simulation was used for conducting uncertainty assessment. This consists of a method where a program randomly selects and changes input data within the uncertainty limits of input data and then recalculates the output result values. For both alternatives and every impact category, 300 random iterations were done in each simulation. 5% and 95% quantiles are shown in Table 4.4 for each impact category and alternative. This means that with 90% certainty the impact category result is in between the calculated quantiles. In Figure 4.5 one of such simulation results are illustrated as an example of photochemical oxidation impact category.

Table 4.4 Quantile values identified with the Monte Carlo simulation

Table ***Tõrge! Rakendage vahekaardi Avaleht kaudu käsk 0 tekstile, mida soovite siin kuvada.***.2

Impact category	Conventional alternative 0.05 quantile	Conventional alternative 0.95 quantile	Waste rock alternative 0.05 quantile	Waste rock alternative 0.95 quantile
Ozone layer depletion - ODP steady state	0,047	0,17	0,087	0,34
Acidification potential - average Europe	2 100	3 300	4 300	5 300
Climate change - GWP100	390 000	540 000	790 000	940 000
Depletion of abiotic resources - elements, ultimate reserves	0,013	0,03	0,019	0,36
Depletion of abiotic resources - fossil fuels	5 300 000	7 200 000	11 000 000	13 000 000
Eutrophication - generic	420	720	1 000	1 500
Photochemical oxidation - high Nox	93	178	150	200

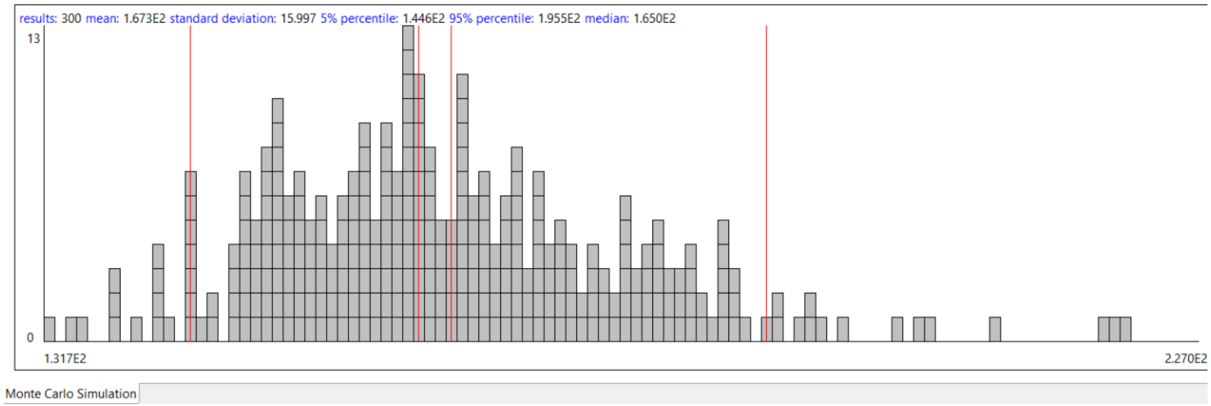

Figure 4.5 Example of Monte Carlo simulation results for photochemical oxidation – high Nox impact category

4.5 Discussion

Results of the life cycle assessment of both alternative materials show that the use of conventional materials (sand and gravel) has lower environmental impacts linked to it than the use of oil shale waste rock for constructing Rail Baltic embankment. It is important to note that the waste rock alternative did not turn out to have lower environmental impacts in any of the seven impact categories assessed, which is the opposite of the set research hypothesis.

However, the results would be the opposite in all assessed impact categories and prefer waste rock use if differences in transport distances would be evened for both alternatives. Similar conclusion was also made by Shuresh and Chawla [30] who compared environmental impacts of using waste rocks from coal mining with conventional aggregates in railroad sub ballast construction. Their baseline scenario had same transport distances for both alternatives and that is one major reason why the waste rock alternative turned out to be superior.

For the conventional alternative, the total material transport distance is 27 km but waste rock needs to be transported in total about 267 km to get to the Rail Baltic construction site. It is almost 10 times the difference in distance, and this does not include the additional transport of sand which is needed for mixing the waste rock and which comes from 38 km away. So, in the waste rock alternative, in addition to longer distances, 30% of more materials also need to be transported which adds additional environmental impacts compared to the conventional material use. Previous similar studies done by Blengini and Garbarino [31], and Chowdhury *et al.* [32] stated that transport distances for recycled aggregates can be at maximum about 2 to 3 times more than conventional materials before the negative impacts from transport start to outweigh positive effects from not needing to extract new raw materials. Therefore, it is not surprising that using oil shale waste rock in Rail Baltic does also not have better environmental impact results as transport distances exceed conventional material transport distances at least ten times and not three.

In addition, it is important to point out that transport equilibrium point where environmental impact results start to be equal with the conventional aggregate use, is for oil shale waste rock about 1.5 when considering the average of all environmental impact category results and not 2 or 3 as in the previously mentioned studies. This is mainly because for using waste rock some natural aggregates must still be used (construction sand) which increases total transport loads and includes material extraction impacts. Also, for using oil shale waste rock in Rail Baltic embankment, more processes like mixing and additional reloading between different transport systems needs to be done which all adds to the environmental impact of waste rock alternative and therefore decreases the optimal transport distance compared to the conventional alternative.

5. CONCLUSIONS AND RECOMMENDATIONS

When considering that Rail Baltic embankment will be built in the centre point of design section number 5 in Raplamaa then the optimal material from environmental impact perspective is conventional material and not waste rock. Therefore, in such circumstances, using conventional materials for constructing Rail Baltic railway embankment is recommended. Constructing 1 km of embankment by using waste rock as construction material will result in:

- Higher ozone depletive substance emissions - 0.13 kg CFC-11 eq. is emitted which is about 190% compared to conventional alternative;
- Increased acidification - 4 400 kg of SO2 eq. will be released to the nature which is about 180% compared to conventional alternative;
- Higher greenhouse emissions – 810 000 kg of CO2 eq. is emitted which is about 190% compared to conventional alternative;
- Depletion of more abiotic resources – 0.021 kg of antimony eq. is used which is about 140% compared to conventional alternative;
- Depletion of more fossil fuels – 11 million MJ worth of fossil fuels will be used which is about 190% compared to conventional alternative;
- Increased eutrophication by releasing 1 100 kg of PO4—eq. substances to the environment which is about 240% compared to conventional alternative;
- Higher photochemical oxidation by releasing 150 kg of ethylene eq. substances to the environment which is about 140% compared to conventional alternative;

On average across all impact categories 56% of conventional alternative environmental impacts is linked to quarrying activities and the rest to transporting and lifting procedures. For the waste rock alternative 56% of environmental impacts are connected to transporting waste rock by diesel trains and trucks, 28% from lifting, reloading and mixing procedures. The remaining 16% comes from sand quarrying and transport that is needed in addition to waste rock.

Therefore, waste rock alternative has higher environmental impact mainly due to transporting the waste rock. If waste rock would not have to be loaded on to train wagons and would instead be put straight on to trucks and the transport distance to construction site is not over 41 km more than conventional material transport distance, then on average across all impact categories the environmental impact would be less than conventional alternative. This shows that waste rock still has some advantage over the conventional material, but transport plays a crucial role. To support waste rock use from environmental perspective, it is important to first-hand focus on solving impact problems linked to transporting it. Better alternatives for transporting the material need to be found to increase optimal transport distances. For example, shifting from diesel fuel use to using renewable or non-fossil fuel energy.

Local impacts that come from using both construction materials were not included in the assessment. However, it was found that waste rock alternative avoids about 0.72 ha of natural land being transformed to waste rock dump sites per km of railway built but conventional alternative on the other hand transforms 1.24 ha of natural land into a quarry site. These impacts should be further analysed and included to have a more comprehensive assessment and comparison of the alternatives.

SUMMARY

Sustainable use of raw materials is becoming increasingly important when constructing huge infrastructure projects like Rail Baltic, as finding suitable sites for extracting raw materials has become increasingly difficult. It has been discussed that one option to alleviate the need for opening new quarries, waste rocks from oil shale industry can be used for constructing Rail Baltic railroad embankment. Consensus is that using this waste has also lower environmental impacts and policies describe this activity as environmentally sustainable. However, both conventional material use and the use of oil shale waste rock have an impact on the environment and the magnitude of it depends on the context and connected activities. For using conventional materials, resources must be extracted but for using waste rock this is not needed. However, transporting materials also has a significant contribution to the overall environmental impacts and should therefore be considered. Any actual analysis of comparing which material use would result in lower environmental impacts for constructing Rail Baltic railroad embankment had not been done before.

This research focused on conducting this environmental impact assessment by using life cycle assessment approach to calculate results that come from constructing 1 km of railroad embankment in the centre point of design section 5 (Rapla). All relevant processes from raw material extraction up to laying the material on the construction site were included. For the waste rock alternative, it is important to note that only the use fraction size 0-90 mm was assessed which needs to be mixed with sand to be suitable. Also impacts connected to oil shale use were excluded from the study scope. Environmental impacts of both alternatives were analysed by using seven impact categories from CML (baseline) dataset. For gathering input data, a potential scenario was generated for both alternatives to find out the transport distances of raw materials. This means that the results show only a certain scenario and in real life impacts will differ if any deviation of described scenarios would happen, which is likely as information about the construction details was lacking. Minimal possible environmental impact approach was considered.

Research results show that using conventional material has lower environmental impact compared to using oil shale waste rock in all impact categories. This means that the hypothesis is refuted, as using waste rock in constructing Rail Baltic embankment does not

result in lower environmental impacts. Using conventional material on average (across all impact categories included) results in 57% of environmental impact that would come when waste rock alternative would be chosen. Waste rock alternative has higher impact scores mainly due to transport and therefore this stage was further analysed to find out in which case the use of waste rock could still be preferrable from an environmental point of view. In order to do that, transport by train was completely excluded and recalculations were made by changing truck transport distance until an equal result with the conventional alternative was determined. It was found out that on average (across all impact categories included) waste rock transport distance can be up to 41 km longer than distance for transporting conventional materials. If waste rock needs to come from further away than the environmental impact results begin to exceed conventional alternative results.

It is important to note that this research did not include local impacts to the surrounding environment as life cycle assessment methodology uses global parameters. In future assessments this impact area should also be considered to have a more comprehensive approach in determining which material choice has lower environmental impacts. For example, with conventional material natural land area transformed is much larger compared to waste rock alternative and environmental impacts linked to it are underestimated in this research. In addition, future studies should also include assessment of social impacts as it is a major aspect of sustainability. It can be assumed that similarly to differences in land use, waste rock alternative is also superior in social impact categories.

KOKKUVÕTE

Toormaterjalide jätkusuutlik kasutamine on muutumas üha olulisemaks, eriti kui planeeritakse suuri infrastruktuuri projekte nagu Rail Baltic. Seda põhjusel, et uute sobivate maardlate leidmine toormaterjalide kaevandamiseks on muutunud järjest raskemaks. Ühe võimalusena, mis uute maardlate avamist leevendab, on välja pakutud kasutada põlevkivi tööstuses tekkivat aherainet Rail Baltic raudteetrassi muldkeha ehitamisel. Esineb arusaam, et nimetatud jäätme kasutamisega kaasnevad väiksemad keskkonnamõjud ning poliitikad kirjeldavad seda kui keskkonnasäästlikku tegevust. Siiski mõlema, nii konventsionaalse kui põlevkivi aheraine kasutamisel on keskkonnamõju, ning selle suurus sõltub kontekstist ja seotud tegevustest. Konventsionaalsete materjalide kasutamisega on vajalik nende kaevandamine, aga aheraine puhul see puudub. Siiski kaasneb materjalide transpordiga samuti olulisi keskkonnamõjusid ja seetõttu tuleb seda arvesse võtta. Ühtegi tegelikku analüüsi, mis võrdleks kumma materjali kasutusega kaasneks väiksem keskkonnamõju Rail Baltic muldkeha ehitamisel, polnud varem tehtud.

See uurimistöö keskendus selle keskkonnamõju analüüsi teostamisele kasutades olelusringi hindamise metoodikat, et arvutada tulemus 1 km raudtee muldkeha ehitamise kohta, võttes arvesse disain lõigu number 5 keskkohta (Rapla). Kõik asjakohased protsessid alates toormaterjalide kaevandamisega kuni materjali laotamisega ehituskohta võeti arvesse. Oluline tähelepanek on, et aheraine alternatiivi puhul hinnati üksnes võimalust kasutada 0-90 mm fraktsiooni, mida on vaja liivaga segata, et see oleks sobilik. Lisaks on kõik põlevkivi kasutamisega kaasnevad mõjud uuringu ulatusest välja jäetud. Mõlema alternatiivi keskkonnamõju hindamiseks kasutati seitset mõjukategooriat CML (baseline) andmestikust. Sisendandmete korjeks loodi potentsiaalne stsenaarium mõlema alternatiivi kohta, et leida toormaterjali transpordivahemaad. See tähendab, et tulemused näitavad ainult kindlalt stsenaariumi ja tegelikus elus tulemused võivad erineda, kui on tehtud kõrvalekaldeid antud töös kirjeldatud stsenaariumitest, mis on tõenäoline kuna informatsioon ehitustegevuse detailide kohta oli töö tegemise hetkel puudulik. Arvestati vähima võimaliku keskkonnamõjuga.

Uuringu tulemused näitavad, et konventsionaalse materjali kasutamisest tuleneb väiksem keskkonnamõju kõikides mõjukategooriates kui aheraine kasutamisel. See tähendab, et hüpotees sai ümber lükatud, kuna aheraine kasutamine Rail Baltic muldkeha ehitamisel ei oma väiksemaid keskkonnamõjusid. Konventsionaalse materjali kasutamine on keskmiselt (üle kõikide arvesse võetud mõjukategooriate) 57% keskkonnamõjust, mis kaasneks, kui valitaks aheraine alternatiivi. Aheraine alternatiiv omab kõrgemaid mõjukategooriate tulemusi peamiselt transpordi tõttu ja seega seda etappi analüüsiti täpsemalt edasi, et tuvastada, millises olukorras oleks aheraine kasutamine siiski eelistatav keskkonna seisukohast. Selleks võeti analüüsist täielikult välja raudteetranspordi vedu ja teostati ümberarvutused muutes veoste transpordivahemaid seni, kuni tuvastati olukord, kus tulemused on võrdsed konventsionaalse alternatiivi tulemustega. Uuringu käigus leiti, et keskmiselt (üle kõigi arvesse võetud mõjukategooriate) saab aheraine transpordivahemaa olla kuni 41 km pikem kui konventsionaalse materjali transport. Kui aheraine peab tulema kaugemalt, siis keskkonnamõju kategooriate tulemused hakkavad ületama konventsionaalse alternatiivi tulemusi.

Oluline tähelepanek on, et see uurimistöö ei võtnud arvesse kohalikke mõjusid ümbritsevale keskkonnale, kuna olelusringi analüüsi metoodika arvestab globaalseid parameetreid. Järgmised hindamised peaksid seda mõju ka arvestama, et saavutada ulatuslikum lähenemine selgitamaks, milline materjali valik omab väiksemaid keskkonnamõjusid. Näiteks, konventsionaalse materjali puhul on muudetav loodusliku ala palju suurem võrreldes aheraine alternatiiviga ja sellega seonduvad keskkonnamõjud on alahinnatud. Lisaks peaksid järgmised uuringud samuti hindama sotsiaalseid mõjusid, kuna see on oluline jätkusuutlikkuse osa. Võib oletada, et sarnaselt maakasutuse erinevustele, on aheraine alternatiiv parem valik samuti sotsiaalsete mõjukategooriate vaatest.

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Appendix 1

Used data, Ecoinvent datasets, calculations and results attached as a separate excel file.