AN ENERGY MODEL FOR SUSTAINABLE DECISION-MAKING IN ROAD CONSTRUCTION PROJECTS

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ABSTRACT: *Road construction operations often require considerable amounts of energy in the form of fossil fuels, thus generating substantial greenhouse gas (GHG) emissions. While fuel efficiency of the heavy construction equipment is extensively studied, limited attention is given to how the construction process can be planned in order to reduce energy use and GHG-emissions. In this study a conceptual model is proposed for the assessment of energy use and GHG-emission on-site at road construction projects. The model is applied to a road construction project to evaluate production alternatives in the early planning stages of the project. As a result the most favorable alternative in terms of energy use and GHG-emissions could be selected during the construction phase. This demonstrates the model's ability to quantify environmental effects and energy use of different production alternatives.*

KEYWORDS: Earthworks; Energy estimation; Greenhouse gas emissions.

1. INTRODUCTION AND BACKGROUND

Road construction generally requires extensive earthworks operations such as excavations, hauling, and depositing of materials as well as crushing of rock. These operations require large and energy intensive equipment and thus generate considerable amounts of greenhouse gas (GHG) emissions (Apif M, Phil 2013). (Stripple 2001) estimated that the amount of fuel needed to construct a road is about 5% of the total fuel consumption of all traffic, of 5 000 vehicles per day, using the road during its expected lifetime of 40 years. Energy efficiency, as a measure for mitigating GHG-emissions, has become one of the most important centers of attention for the Swedish Transport Administration (STA). This includes the construction processes of transportation infrastructure (Trafikverket 2012). Although the potential for reducing GHG-emissions and the use of energy in earthworks processes is high, not all important aspects have been investigated (Kim et al. 2011). In contemporary research, significant attention is given to measuring and assessing the emissions per heavy equipment (Mawlana et al. 2012, Yanowitz, McCormick & Graboski 2000, Abolhasani et al. 2008, Frey, Rasdorf & Lewis 2010). A study by (Melanta, Miller-Hooks & Avetisyan 2013) provided a comprehensive project-level estimation tool that take into account material production and the effects of absorbed CO_2 in forests and organic soils during deforestation and clearing or reforestation efforts. The performance of construction projects is mainly assessed in terms of time, costs and quality with limited attention to emissions and other environmental aspects (Gangolells et al. 2009, Kenley, Harfield 2011). These are aspects that might help reducing equipment operation time, mass hauling distances, and the number of engines used (Ahn et al. 2013). A stronger focus to reduce GHG-emissions in the project planning stage through environmental assessments of alternative designs and production methods is therefore important (Kim et al. 2011). Proposed in this study is a conceptual model for quantifying the energy use and GHG-emissions for on-site activities in road construction projects. The model is used in a case study of two planned road projects located in the city of Kiruna in Sweden. The results of the case study demonstrate the model's ability to quantify the environmental effects and energy use of different production alternatives.

1.1 Earthworks operations and estimation of energy use

Road construction projects consist of major earthmoving activities both in terms of material quantities managed and distances that the material is moved. Cutting and filling are the processes of excavating materials at cuts and depositing materials at fills along the road line. Cuts and fills might consist of different materials, which can be categorized and used for different purposes. Common cut-materials include rock, organic and inorganic soils where the rock can be used in fills to stabilize the ground conditions or can be crushed to be used as fill materials in the base course, the sub base or in asphalt or concrete surface layers. Minimizing mass hauling distances is one of the goals in the planning of earthworks activities. Different mathematical techniques such as linear programming have been proposed for minimization of mass haul distances (Easa 1988). However, there are often other important factors to consider in the planning and scheduling of earthworks activities (Askew et al. 2002). The NONROAD-model by US EPA is a comprehensive tool for estimating various emissions of large populations of vehicles and equipment (EPA 2005). The model lacks information with regard to construction project-level emissions although parts of the model are implemented in other models and tools designed for construction projects. The Inventory Model of Off-Road Equipment by California Air Resources Board is another model that estimates fuel consumption and emissions of NO_x, particulate matters and hydrocarbons from populations of equipment in California (California Air Resources Board 2011). A comprehensive tool for estimating emissions of GHG in road construction projects was proposed by (Miller-Hooks, Melanta & and Avetisyan 2010, Melanta, Miller-Hooks & Avetisyan 2013). It encompasses effects of carbon-sequestration capacity lost when woods and soils are removed as well as the effects of reforestation efforts. While being a comprehensive tool it lacks in detail especially in how the emissions from equipment is assessed or connected to project specific quantities. A more detailed but less comprehensive tool was proposed by (Apif M, Phil 2013). The method uses a multiple linear regression (MLR) method to model productivity of some simple earthworks operations based on productivity data from RSMeans. The productivity model is then used as input to model energy use and emissions.

2. PROPOSED CONCEPTUAL MODEL

The proposed conceptual energy model, shown in Fig. 1.is designed to make sense of how the energy use and the corresponding GHG-emissions at road construction sites can be calculated or estimated.

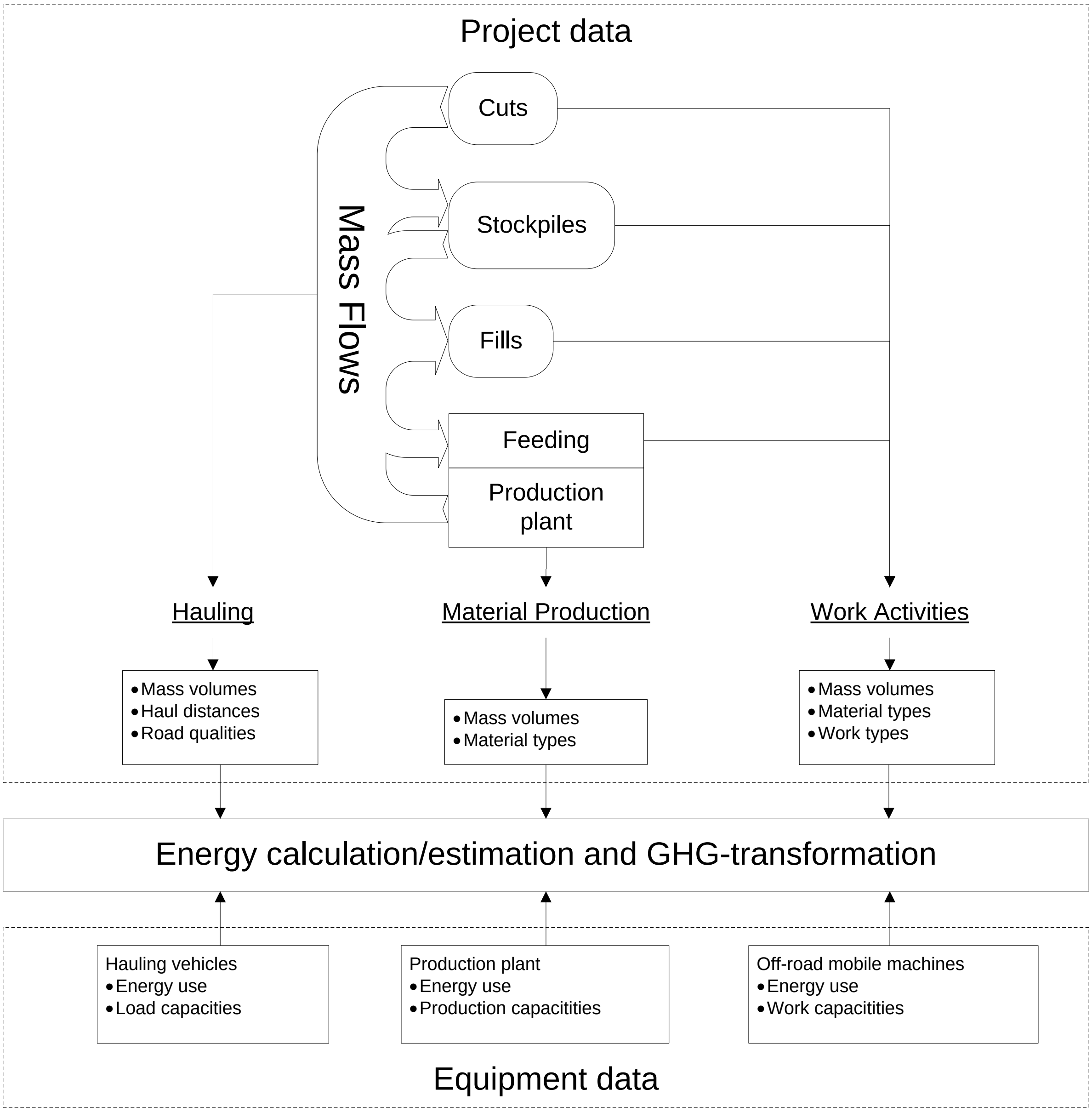

Fig. 1 The conceptual energy model.

The energy-consuming activities at the construction site are categorized into "Hauling", "Material Production" and "Work Activities". "Hauling" is the process of moving material between cuts, fills, material production sites and various stockpiles using specific hauling vehicles such as articulated haulers and dump trucks sometimes towing trailers. "Material Production" consists of large scale processing and production of materials and includes for example crushing plants, concreting plants and asphalt plants. "Work Activities" include cutting, filling, loading and loosening etc. This type of work is done using off-road mobile machines such as bulldozers, excavators, drill rigs, wheel loaders etc. Included in "Work Activities" is also shorter moving of materials that sometimes happens with wheel loaders or bulldozers. These categories are connected to some project specific quantifiable data which include hauling distances, mass volumes and material types, etc. The project data is a quantification of the tasks in the road project that are needed to make reliable calculations or estimations of the energy use associated with the road project. The equipment used for finishing these tasks has a different type of data namely the equipment data. This includes for example the load- and work capacities and the energy use of the equipment etc. This data combined with appropriate energy calculation methods are needed in order to calculate the total energy use in a road construction project.

3. CASE STUDY

To evaluate the practical applicability of the proposed model, a case study is made. The case study helps reveal some potential problems that can arise with the practical application and whether it can affect decision-making with respect to GHG-emissions and energy use. The case study consists of two new roads in Kiruna Municipality in the north of Sweden. These road projects are the "E10" and "Road 870" shown in Fig. 2.

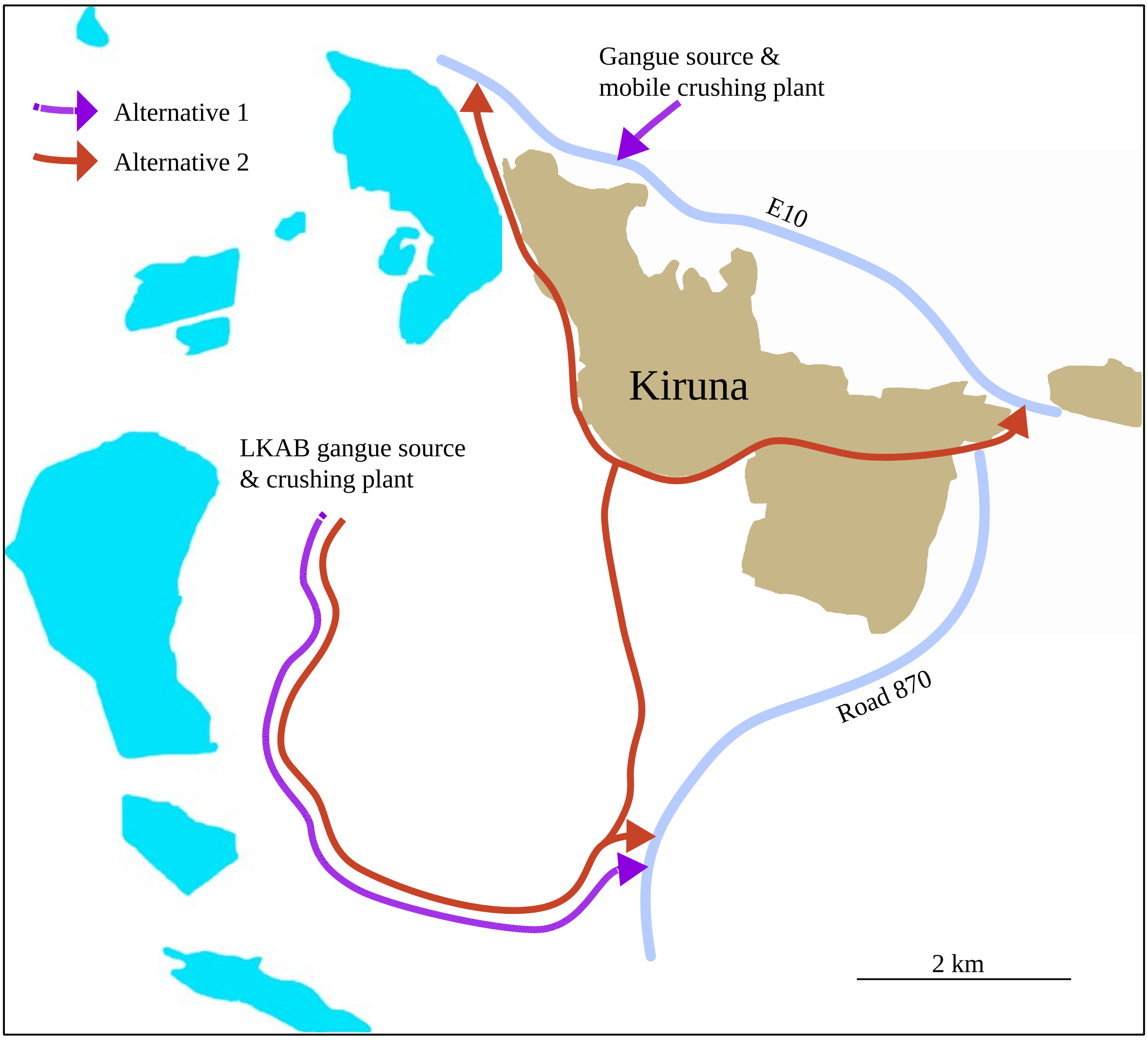

Fig. 2 The hauling routes for the crushed aggregates in each alternative.

The case study was made in the planning stage of the road projects when corridors had been decided and the road locations were being decided in detail. The STA, who were the client in the projects, wanted to compare two production alternatives from an energy perspective. In “Alternative 1” some of the crushed aggregates used in the road were intended to be produced locally near the road line. While in “Alternative 2” all the crushed aggregates were produced by the mining company LKAB in the city. Table. 1 shows a detailed comparison of the alternatives studied in this case study.

Table. 1 Overview of the alternatives in the case study

	Alternative 1	Alternative 2
”E10”		
Cut & Fill	handled in road line	handled in road line
Excess earth cut	not accounted for	not accounted for
Rock cut	crushed and used in road line	hauled to nearby disposal area
Subbase	produced from rock cut and nearby gaunge source	rovided by LKAB
Base course	produced from rock cut and nearby gaunge source	provided by LKAB
Energy source for crushing	diesel driven electric generator	electricity from the grid
”Road 870"		
Cut & Fill	handled in road line	handled in road line
Excess earth cut	not accounted for	not accounted for
Rock cut	none	none
Subbase	provided by LKAB	provided by LKAB
base course	provided by LKAB	provided by LKAB
Energy source for crushing	electricity from the grid	electricity from the grid

The STA expected that producing the crushed aggregates near the road line as it is done in Alternative 1 would require shorter hauls and therefore lower energy use and emissions of GHG instead of having the LKAB provide the material which is common practice in Kiruna. In the case study the construction of the subgrade, sub base and base course layers were considered. This included the mass hauls, crushing of aggregates and acquisition and disposal of some material off-site.

4. DATA COLLECTION, ASSUMPTIONS, AND CALCULATIONS

Because of the scale of the road projects the acquisition of data has been extensive. Also, since the projects were at an early planning stage, not all of the necessary data has been available. Therefore, some assumptions and manual preprocessing of unrefined data have been necessary to complete the study. Beside a detailed description of the different alternatives the STA contributed with a map, a bill of quantities, some details of the work activities included in the projects and other project specific information. This data had to be preprocessed in the mass-haul planning software DynaRoad to create a mass-haul plan which essentially provides information of hauling distances, types and quantities of materials hauled, worked and produced. The DynaRoad software implements linear programming methods to minimize the hauling distances. To account for swelling or shrinking of material the common mass states of Bank Cubic Meters (BCM), Loose Cubic Meters (LCM), and Compacted Cubic Meters, were used. The correction factors of the applicable materials in the case study are as follows:

Material	BCM	LCM	CCM	Tonnes
Rock	1	-	1.45	2.7
Earth	1	1.2	-	2
Subbase	-	-	1	2.15
Base Course	-	-	1	2.25

Hauling of earth is calculated based on the load capacity in terms of volume while other materials are based on their mass and this is assumed to be true for both trucks and articulated haulers. The STA provided information about the likely equipment that would be used during the construction of the road. Based on this information some data about load capacities, work capacities, power rating, and other necessary data was found. If data about certain machines could not be found, some equivalent machines were assumed instead. A total of four different energy calculation formulas were used. “Hauling” was divided between two formulas, one distance-based for trucks and trailers and one time-based for articulated haulers. "Material production” in the form of crushing of aggregates uses an elementary relationship while the “Work activities” with off-road mobile machines uses a formula based on the rated power, average load factor, the brake-specific fuel consumption and the activity of the machine. Additional details of this case study can be found in (Krantz 2013).

4.1 Hauling with trucks and trailers

To account for the fuel consumption of hauling by trucks with trailers Eq. (1) is used. Trucks with trailers are used for hauls that part of the way use public roads. The independent variables in the equation are the hauling distances, load capacities of the trucks, total masses, and the fuel use per km of the trucks (Nätverket för Transporter och Miljön (NTM) 2006).

$$F_{truck} = \sum_i (L_t / L_c * 2 * T_d * F_c)_i \qquad \begin{cases} i = \text{all truck configurations in the project} \\ F_{truck} = \text{total fuel use of trucks} \\ L_t = \text{masses hauled} \\ L_c = \text{load capacity of vehicle} \\ T_d = \text{hauling distance} \\ F_c = \text{fuel consumptionof vehicle} \end{cases} \qquad (1)$$

Furthermore a correction factor of 1.44 was used to account for the extra fuel use of the truck at the instances when they run on dirt roads (Abelson 1973). The truck type assumed was a 3-axle truck with a 4-axle trailer with a load capacity of 30.8 m^3 or 40 tonnes and fuel consumption of 0.58 liters / km.

4.2 Hauling using articulated haulers

Articulated haulers aren't allowed on public roads and thereby can only be used within the road lines that are built and the road connection to the LKAB area from "Road 870". The fuel consumption from articulated haulers is calculated with Eq. (2). The equation is based on hauling time which is dependent on the hauling distances as is also the case in Eq. (1).

$$F_{hauler} = \sum_i (L_t / L_c * C_t * F_c)_i \qquad \begin{cases} i = \text{all articulated hauler configurations in the project} \\ F_{hauler} = \text{total fuel use of articulated haulers} \\ L_t = \text{masses hauled} \\ L_c = \text{load capacity of vehicle} \\ C_t = \text{cycle time} \\ F_c = \text{fuel consumption of vehicle} \end{cases} \qquad (2)$$

The calculation method is explained in the Caterpillar Performance Handbook (Caterpillar Inc. 2012). A Volvo A40, with a load capacity of 22.2 m^3 or 36 tonnes, was assumed as the type of articulated hauler used, but to be able to calculate the cycle times and fuel use, a Caterpillar 740 Tier 3 was assumed as an equivalent vehicle to the A40. The following assumptions regarding the cycle times were made: loading time = 2.5 min; dumping time = 0.5 min; full loaded speed = 20 km/h; empty speed = 28 km/h. The fuel consumption of the vehicle is assumed to be 20 l/h.

4.3 Material production with crushing plants

The only type of material production accounted for in this study is the production of base course and sub base through crushing. Eq. (3) shows the basic relationship used for the energy use of crushing.

$$E_{crushing} = \sum_i (E_c * M_t)_i \qquad \begin{cases} i = \text{all crushing configurations in the project} \\ E_{crushing} = \text{total electricity use of crushing} \\ E_t = \text{electricity consumption of crushing plant} \\ L_c = \text{masses crushed} \end{cases} \qquad (3)$$

The crushing plant assumed is based on the use of a Sandvik HJ3800 crusher with an estimated electricity consumption of 5.54 kWh/t of produced end material. This includes the fact that different fractions need to be crushed several times the number of times the material needs to pass the crusher is assumed to be 2.675. The electricity sources of the crushing plants are either the electric grid or a diesel driven electric generator depending on when which is applicable. The diesel driven electric generator is assumed to have an efficiency of 38% in its generation of electricity.

4.4 Work activities with off-road mobile machines

To calculate the fuel use of the off-road mobile machines Eq. (4) is used.

$$F_{offroad} = \sum_i (A * P * L_f * B_e)_i \qquad \begin{cases} i = \text{all articulated hauler configurations in the project} \\ F_{offroad} = \text{total fuel use of off-road mobile machines} \\ A = \text{activity of the machine} \\ P = \text{rated power of the machine} \\ L_d = \text{average load factor} \\ B_e = \text{brake-specific fuel consumption} \end{cases} \tag{4}$$

The rated power (P) of the machine is a straightforward once a machine is selected. The L_f for excavator activities is based on research by Persson and Kindblom (Persson, Kindblom 1999) while the remaining load factors come from (EPA 2010). The B_e-values are based on work by Lindgren (Lindgren 2007) and are a function of the rated power. The activity is a function of the capacity of the machine performing a specific task which is partly assumed and partly read from capacity diagrams. Activity (A) is also a function of the quantity of masses worked or the surface area worked which is predominantly the case when compacting or leveling. In Table. 2 the mass quantity based activities can be seen, note that the brake-specific fuel consumption (B_e) is 0.254 kg/kWh for all of these machines.

Table. 2 Description of the mass-based activities with their corresponding machines.

Machine	L_f	P (kW)	Capacity (BCM/h)	Description
Excavator 45 tons	0.40	250	175	Loosening earth cuts and loading to hauling vehicle
Bulldozer CAT D7	0.58	175	150	Recieving loosened earth and spreading to fill
Drill Rig Sandvik DX780	0.43	151	100	Loosening rock cut
Excavator 45 tons	0.40	250	130	Loading loosened rock to hauling vehicle
Bulldozer CAT D7	0.58	175	150	Recieving rock and spreading it at a rock fill
Loader CAT 980	0.48	260	250	Loading loosened rock to crushing plant
Loader CAT 980	0.48	260	250	Loading crushed aggregates to hauling vehicle
Bulldozer CAT D7	0.58	175	150	Recieving subbase and spreading it

The surface based activities and their corresponding machines can be seen in Table. 3. The total road length in the project is 16.96 km and its estimated that in the road roller needs 18 trips or 9 round trips on the roads to compact each layer. The motor grader is assumed to need 9 trips in total or 4.5 round trips to level the base course.

Table. 3. Description of the surface-based activities with their corresponding machines.

Machine	L_f	P (kW)	B_e	Speed (m/h)	# trips	Description
Road Roller	0.59	110	0.26	500	18	Compacting earth fills
Road Roller	0.59	110	0.26	500	18	Compacting subbase
Road Roller	0.59	110	0.26	500	18	Compacting base course
Motor Grader	0.59	159	0.254	5000	9	Leveling base course

4.5 Transformation to GHG-emissions

The energy use gives rise to GHG-emissions in the form of CO_2 depending on the type of energy used. In the studied road projects the energy types are fuel (diesel) and electricity. To account for the CO_2-emissions caused by electricity consumption the average Swedish emissions are assumed and equals to 0.02 kg CO_2/kWh (Svensk Energi 2014). The diesel combustion is assumed to cause emissions of 3.22 kg CO_2 per kg diesel combusted.

5. RESULTS

Alternative 2, where all crushed aggregates are provided by the LKAB, has considerably longer hauling distances compared to Alternative 1, where some of the crushed aggregates are produced from nearby gangue. Although the hauling distances in Alternative 2 are 142% longer than in Alternative 1, the corresponding diesel use is only 69% higher. The crushing of materials in Alternative 2 uses 144% more electricity than in Alternative 1, but Alternative 1 has considerable diesel consumption as a result of the crushing next to the road which runs with a diesel driven electric generator. For the work activities both alternatives require the same amount of diesel since the work activities are the same for each alternative. For the entire project, Alternative 1 requires 63% more diesel than Alternative 2. However, Alternative 2 uses 144% more electricity than Alternative 1. The total CO_2-emissions, based on both the diesel- and electricity consumption, is 59% higher in Alternative 1 than in Alternative 2.

Table. 4 Summary of the results from the case study.

	Unit	Alternative 1	Alternative 2
Hauling			
average distance	(m)	3 664	8 851
masses hauled	(t)	1 753 171	1 753 171
diesel use	(kg)	290 955	491 573
Material production			
masses crushed	(t)	1 100 393	1 100 393
diesel use	(kg)	803 980	
electricity use	(kWh)	2 494 210	6 093 151
Work Activities			
diesel use	(kg)	459 714	459 714
Total			
diesel use	(kg)	1 554 649	951 288
electricity use	(kWh)	2 494 210	6 093 151
CO_2-emissions	(kg)	5 055 855	3 185 010

6. DISCUSSION AND CONCLUSIONS

The conceptual energy model turned out to be useful as a decision-making tool as the most favorable alternative in the case study was identified and implemented later in the road project. Implementing the model at an early planning stage in the road construction project can offer both challenges and opportunities. The challenge is to acquire reliable data since not all data has been produced at such an early stage. However since the case study involves the comparison of certain alternatives one might suspect that many of the inaccuracies cancel out. The opportunities therefore seem extra strong when the tool is used for comparisons between alternatives in the early planning stages as large scale changes are easier to implement. This study has both a theoretical and a practical contribution. The theoretical contribution is the conceptual energy model which is helpful for getting an understanding of how the energy use in a road construction project can be understood and the main types of data needed to calculate the energy use. The practical contribution is the application of the model to real road projects. This helps reveal a method of how the conceptual energy model practically can be implemented and the constructor in this case used the findings to adapt their production method.

7. Acknowledgements

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