LULEÅ UNIVERSITY OF TECHNOLOGY

DOCTORAL THESIS

MITIGATING CARBON EMISSIONS DURING THE PLANNING AND EXECUTION OF TRANSPORT INFRASTRUCTURE PROJECTS

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Luleå, May 2019

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Preface

I would like to thank all of those who have supported me during the course of my academic career. Thanks to my supervisor, Thomas Olofsson, and co-supervisors, Weizhuo Lu and Johan Larsson for helping me develop tools to manage my academic work with more creativity, confidence and rigour. Thank you to all my colleagues, both past and present, for all the support and the enjoyable moments. I would especially like to acknowledge Tim Johansson and Farshid Shadram, my closest friends and co-conspirators! Additionally, I would like to thank Hassanean Jassim and Kailun Feng together with my supervisors and co-conspirators for the great scientific collaborations, which I hope there will be more of in the future. I would also like to thank my financial sponsors Formas and SBUF, and everyone at NCC and Trafikverket who have supported my work with feedback, experience, knowledge and case study data. Thanks also to “team yellow” and all other inspirational people I met during the zero-carbon innovation competition organized by the Swedish environmental protection agency.

I would also like to thank my friends who are outside of the academic bubble, but who nonetheless have supported me. Finally yet importantly, I would like to thank my family and loved ones: Audrey, Arja-Riitta, Lennart, Lena, Leif, Ella, Elina, William, Maria and Chris. Thank you for always supporting me.

Jan Krantz
Luleå, May 2019

Abstract

International agreements to combat climate change have prompted the formulation of national emission targets, action plans, and methods for assessing and reducing greenhouse gas (GHG) emissions. Transport infrastructure accounts for roughly one third of all construction-related GHG emissions in Sweden. Consequently, a national target of reducing carbon emissions from transport infrastructure projects to net zero by 2045 has been introduced. This target is being gradually imposed on contractors in projects by the Swedish Transport Administration (STA), which uses a life cycle assessment (LCA) tool to quantify and verify carbon reductions. Most previously proposed carbon assessment methods for transport infrastructure construction disregard the complexity and constraints imposed by typical project environments, where the ability to influence carbon emissions decreases over time while the ability to assess those emissions increases. Many such methods therefore rely heavily on assumptions and industry average data, or assessments conducted after project completion. These shortcomings may limit the methods' ability to help stakeholders achieve emission reduction objectives.

Therefore, the overall purpose of this thesis was to explore carbon mitigation strategies for transport infrastructure construction with the specific aim to develop methods for assessing and reducing carbon emissions that can be applied during the planning and execution of transport infrastructure projects. The research design was based on a literature-guided exploratory approach in which new methods were developed and tested in different transport infrastructure construction settings. Each case study involved problem identification, collection of empirical data, development and testing of

methods, and evaluation and analysis of the new methods' output. The main findings of the research presented here are that:

- Bills of quantities (BOQ) can be used to create preliminary earthmoving plans that quantify project-scale carbon emissions. This provides a more comprehensive picture of the project and its processes than the BOQ itself. Such data sets are thus enriched and can support decision-making on carbon reduction measures, particularly during early planning stages when the availability of project data is limited.
- Assessment methods implementing discrete event simulation (DES) and building information modelling (BIM) can provide more project-specific data on embodied carbon emissions than would otherwise be available. DES can capture dynamic onsite processes and subtle differences between operational parameters, while BIM enables quantity take-offs from the material supply chain. This may be particularly useful in later project stages when more detailed information on construction plans and equipment specifications is available.
- The inclusion of cost and duration indicators in carbon assessment methods makes it possible to assess the economic feasibility of proposed carbon reduction measures. This necessitates analysis of the sometimes complex tradeoffs between carbon emissions, duration, and costs.

Overall, the research presented in this thesis suggests that the key to facilitating reductions in the carbon emissions of transport infrastructure projects is to reduce the gap between the ability to assess emissions and the ability to influence them. The proposed carbon assessment methods do this by enriching the data available at the different stages of a transport infrastructure project. By assessing different alternatives or scenarios throughout the project, stakeholders are given a basis for implementing superior options as the project progresses. The most important outcome of the work presented here is the integration of the proposed carbon assessment methods into the different project stages to create a comprehensive and systematic approach for facilitating the reduction of carbon emissions. The work also has implications for the STA's carbon reduction initiative, whose LCA-based carbon assessment method was unable to differentiate between some of the project alternatives that were successfully distinguished by the methods proposed in this thesis. The new methods could thus help guide the development of STA's carbon reduction scheme and assessment methods. Finally, the results presented here

have practical implications for practitioners and stakeholders involved in transport infrastructure construction. It is recommended that practitioners conduct systematic analyses of scenarios and alternatives throughout a project rather than relying on intuition or rules of thumb because the impacts of any given alternative on carbon emissions, costs, and duration can be difficult to predict and are sometimes counterintuitive. The use of assessment methods can also provide simple operational guidelines for project managers and equipment operators on issues such as hauling distances, base speeds, or fuel types that will improve project performance in terms of carbon emissions, costs and duration.

Sammanfattning

Internationella avtal för att bekämpa global uppvärmning har föranlett utvecklingen av nationella utsläppsmål, handlingsplaner och metoder för att beräkna och minska växthusgasutsläppen. Ett nationellt mål om klimatneutralitet senast 2045 har antagits för transportinfrastrukturprojekt, som idag står för cirka en tredjedel av Sveriges byggrelaterade växthusgasutsläpp. Trafikverket inför detta mål gradvis i sina projekt och har till detta utvecklat ett verktyg baserat på livscykelanalys för beräkning och verifikation av utsläppningsminskningar. Många utvecklade metoder för bedömning av växthusgasutsläpp från transportinfrastrukturbyggande bortser från begränsningar och komplexiteten i normala projektmiljöer där möjligheterna att påverka utsläppen minskar allteftersom projektet fortskrider samtidigt som möjligheterna att bedöma dessa utsläpp ökar. Analyserna bygger därför till stor del på antaganden och branschmedelvärden eller genomförs efter att projektet är utfört. Dessa brister begränsar metodernas användbarhet som beslutsstöd för att nå uppsatta utsläppsmål i planering och genomförande av projektet.

Syftet med denna avhandling var således att utforska strategier för att minska växthusgasutsläppen vid byggandet av transportinfrastruktur. Målsättningen var att utveckla metoder för bedömning och minskning av växthusgaser som kan användas vid planering och genomförande av transportinfrastrukturprojekt. En explorativ forskningsmetodik med stöd av litteraturstudier har använts där metoder har utvecklats och testats i byggprocessens olika skeden av transportinfrastruktur. De genomförda fallstudierna omfattar identifikation av

problem, insamling av empiri, utveckling och testning av metoder, samt utvärdering och analys av utdatat. Resultaten av denna forskning visar att:

- Mängdförteckningar kan användas för att skapa preliminära massförflyttningsplaner som möjliggör bättre bedömningar av växthusgasutsläpp på projektnivå. Planerna ger en tydligare helhetsbild av projektet än den som bara är baserat på mängdinformationen. Data som berikats på sådant sätt kan utgöra ett beslutsunderlag för utsläppsminskande åtgärder i tidiga planeringsskeden, när tillgången på projektdata är begränsad.
- Bedömningsmetoder baserade på diskret-händelsesimulering (DES) och byggnadsinformationsmodellering (BIM) kan generera mer projektspecifik data för bedömning av de inbyggda växthusgasutsläppen än vad som annars är möjligt. DES kan modellera dynamiska byggandeprocesser och särskilja mellan små skillnader i de operativa parametrarna, medan BIM möjliggör mängdavtagning från projektets försörjningskedja. Detta kan således vara användbart i senare projektskeden när mer detaljerad information om tillgänglig maskinpark och byggplaner finns till hands.
- Kostnads- och tidsindikatorer inkluderade i bedömningsmetoderna möjliggör att den ekonomiska rimligheten av olika utsläppsminskande åtgärder kan bedömas. Detta kräver ibland komplexa avvägningsanalyser av målfunktionerna för utsläpp, tidsåtgång och kostnader.

Totalt sett visar denna forskning att en nyckel till minskade utsläpp av växthusgaser är att minska gapet mellan möjligheten att analysera och möjligheten att påverka utsläppen i transportinfrastrukturprojekt. De föreslagna metoderna möjliggör detta genom att berika den data som finns tillgänglig i transportinfrastrukturprojektets olika faser. Genom att undersöka olika scenarier ges möjlighet att välja fördelaktiga alternativa lösningar genom projektets gång.

Avhandlingens huvudsakliga bidrag är integreringen mellan de föreslagna bedömningsmetoderna för växthusgasutsläpp och de olika projektfaserna vilket skapar ett omfattande och systematiskt tillvägagångssätt att underlätta utsläppsminskningar. Resultaten har också implikationer för Trafikverkets klimatarbete vars LCA verktyg för utsläppsbedömningar inte kunde differentiera mellan några av de projektalternativ som avhandlingens föreslagna metoder kunde särskilja mellan. De föreslagna metoderna kan därför bidra till att utveckla Trafikverkets klimatarbete och bedömningsmetoder. Slutligen, aktörer rekommenderas att systematiskt analysera olika scenarier och alternativ genom projektets gång istället för att förlita sig på praxis och tumregler, eftersom effekterna avseende utsläpp, kostnader och tidsåtgång kan vara svåra att inse och ibland till och med vara kontraintuitiva. Metoder för att bedöma växthusgasutsläpp kan också bidra till utvecklingen av enkla operativa regler och instruktioner för projektledare och maskinoperatörer gällande exempelvis transportavstånd, hastigheter eller bränsletyper, för att förbättra projektets resultat avseende växthusgasutsläpp, kostnader och tidsåtgång.

Contents

1 INTRODUCTION

This chapter presents the background, the aim and the scope of the research in this thesis. This is followed by a list of the appended papers in the thesis.

1.1 Background

Anthropogenic emissions of CO_2 and other greenhouse gases (GHGs) cause global warming, which is rapidly pushing the earth system away from its safe operating space (Steffen et al., 2015). To prevent this, the Paris agreement calls for a reduction in GHG emissions to keep global warming well below 2 °C above pre-industrial levels (Rogelj et al., 2016). To meet this target and thereby avoid the most damaging consequences of global warming, the global community must act promptly to substantially reduce GHG emissions (IPCC, 2012). At the same time, the built environment must expand to accommodate the world's growing population and rising living standards. If current construction practices are applied, this expansion is predicted to generate roughly 350 Gton of CO_2 emissions between the years 2012 and 2050 (Müller et al., 2013). This corresponds to approximately 10 years of all anthropogenic CO_2 emissions at current emission levels (Olivier et al., 2012). To reach the 2 °C target, total anthropogenic CO_2 emissions during this period must be kept below 600-1000 Gton (Müller et al., 2013). It is thus clear that the construction industry must change its practices and take a leading role in global emission reduction efforts. Consequently, researchers and policymakers concerned with environmental issues are increasingly focusing on reducing construction-related emissions of CO_2 and other GHGs (Khasreen et al., 2009). Similar trends exist in the context of transport infrastructure construction, which involves extensive earthmoving operations that often use heavy-duty diesel (HDD) equipment (Hajji and Lewis, 2013) as well as extensive use of asphalt (Hamzah et al., 2010) and concrete (Shen and Lepech, 2017). Transport infrastructure construction alone is estimated to account for roughly one third of the Swedish construction industry's total GHG emissions (IVA, 2014). Consequently, the Swedish Transport Administration (STA), which is the main public client for transport infrastructure projects in Sweden, has taken on responsibility for reducing infrastructure-related carbon emissions. The STA recently set a goal of gradually reducing carbon emissions during the delivery of their transport infrastructure projects, and of reaching net zero emissions by 2045 (Trafikverket, 2017b).

To meet these ambitious goals, methods have been developed to assess and measure carbon and GHG emissions, and to make decisions based on these measurement and assessments (Finnveden and Moberg, 2005). Some methods of this type that have been suggested for transport infrastructure construction use mathematical optimization methods to model onsite equipment usage (Avetisyan et al., 2012). Certain methods can also be used to assess project-scale emissions from construction sites (Melanta et al., 2013). Even more holistic assessment methods are those that adopt a life cycle perspective, so-called life cycle assessments (LCA), which consider the emissions (or other environmental impacts) associated with all stages in the life of a constructed product (Bilec et al., 2010). Several publications have proposed LCA-based methods or assessed GHG emissions and other impacts of entire transport infrastructure projects (Huang et al., 2015; Stripple, 2001; Stripple and Uppenberg, 2010; Treloar et al., 2004). Other studies have focused on assessing specific parts of the infrastructure, such as roads' pavement compositions (Anastasiou et al., 2015; Noshadravan et al., 2013). A related application of LCA is the environmental product declaration (EPD), which is used to communicate and advertise a product's life-cycle performance to stakeholders (Del Borghi, 2012). EPDs can be declared for unique, one-off products, such as specific bridges (International EPD System, 2015), or for products that may be used in multiple construction projects, such as asphalt (International EPD System, 2017b; International EPD System, 2018) and crushed aggregates produced at a quarry (International EPD System, 2017a). LCA methods are currently used extensively in the development and implementation of environmental policy in many countries and industry sectors (Guinée et al., 2011). For instance, the STA has developed the LCA-based tool "Klimatkalkyl", which will be used to assess the emissions of all future STA transport infrastructure projects in order to progress towards net zero carbon emissions (Trafikverket, 2018a). Klimatkalkyl is used to assess the effectiveness of GHG reduction measures and to determine whether projects achieve their stated reduction targets, and thus whether the hired contractors should receive the associated bonuses (Trafikverket, 2017b).

As the planning of a transport infrastructure project progresses, the types of decisions that are made generally change in scale: large-scale decisions about issues such as the location of the infrastructure are made in early stages, while later stages involve many smaller-scale design decisions that define design parameters in detail before construction begins (Miliutenko et al., 2014; Trafikverket, 2017a). Consequently, as shown in Figure 1, the scope for influencing a project's parameters diminishes rapidly as it progresses and increasing numbers of decisions and investments are made (Paulson, 1976). In contrast, the ability to assess project outcomes and performance in terms of construction methods (Austern et al., 2018), costs (Lu et al., 2014), or environmental emissions (Bogenstätter, 2000) increases over time as the availability and detail of project-specific information increases. As discussed by Lu et al. (2014), this mismatch in abilities to influence and assess, which is shown in Figure 1, has been widely recognized among construction management researchers. For instance, Dongier and Lovei (2006), and Kenley and Harfield (2011) noted that many proposed emissions assessment methods relating to transport infrastructure construction are based on studies conducted after the studied project had been executed, by which point the opportunity to reduce its carbon emissions had passed. It is thus difficult to obtain relevant insights into the practical implementation of such methods. Furthermore, many LCA methods rely on generic data sources based on static and industry average values (Lasvaux et al., 2015; Reap et al., 2008; Thiede et al., 2013), and do not address the challenges of the information-influence mismatch. This may be problematic for transport infrastructure projects, which often require many different materials and associated construction processes (Buyle et al., 2012). This results in a high degree of complexity and uniqueness of both the constructed product and its associated processes (Lützkendorf and Lorenz, 2006; Pushkar et al., 2005). In addition, infrastructure construction projects are generally planned and executed in temporary organizational structures that often change from one project to the next (Ortiz et al., 2009). In such environments, collecting the input data needed to assess carbon emissions can be tedious if not impossible, so many methods rely heavily on assumptions (Norris and Yost, 2001).

The characteristics of construction projects differ from those of the manufacturing industries that produce construction materials and components, which make more use of standardized and repeatable processes that allow LCA-based methods to deliver significant improvements in the environmental performance of manufactured products over time (Martínez-Rocamora et al., 2016). Suppliers of construction materials and components can declare the environmental life cycle performance of their products using EPDs

(International EPD System, 2017a; International EPD System, 2017b; International EPD System, 2018). The emission factors reported in the EPDs of products used in transport infrastructure construction could potentially be used to replace the default industry average emission factors used in Klimatkalkyl to allow assessments to be made on the basis of design choices made in the project rather than industry average figures (Trafikverket, 2017b).

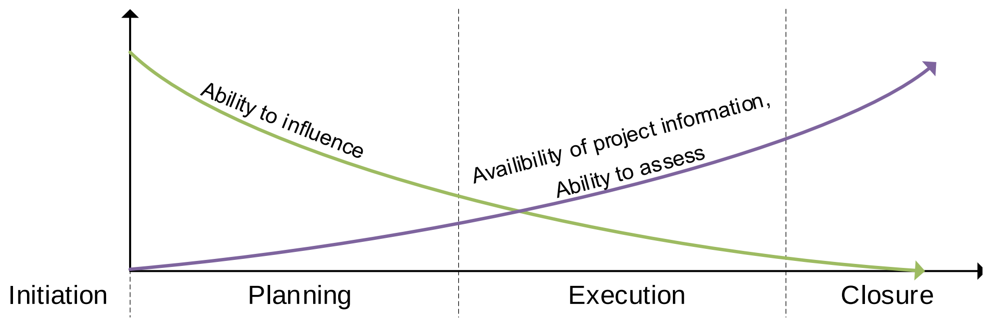

Figure 1. Schematic illustration of the scope for varying project parameters during different stages of transport infrastructure projects. Adapted after Paulson (1976).

Discrete-event simulation (DES) has been proposed as a tool that can alleviate the limitations imposed by the use of static and industry average data by simulating the dynamics of construction processes to generate project-specific data (González and Echaveguren, 2012; Li and Lei, 2010). Building information modeling (BIM) can also improve the exchange of inventory data to facilitate assessments that are more representative of specific projects (Yang et al., 2018). Integrating BIM into the design process has been shown to encourage the investment of greater effort into early planning stages, reducing the gap between ability to influence and availability of project information; this in turn can reduce total project costs (Lu et al., 2014). However, most research on how BIM can facilitate the assessment and reduction of carbon emissions has been conducted on building projects (Abanda et al., 2017; Sandberg et al., 2019; Shadram and Mukkavaara, 2018).

The aforementioned challenges and constraints of typical project environments and the practical and theoretical shortcomings of existing carbon emission assessment methods may impede efforts to achieve national carbon reduction targets in the transport infrastructure sector. A more robust and reliable strategy for reducing carbon emissions during transport infrastructure projects is therefore needed. An important challenge is to determine how best to synchronize the availability of necessary information and resources with different project stages such that effective emission reduction measures can be identified and implemented as the project evolves (Häkkinen and Belloni, 2011). Ideally, this should be done in a way that supports decision-making by industry practitioners and stakeholders throughout all the project's critical stages (Akadiri et al., 2012).

1.2 Research gap and aim

Previously proposed methods for assessing carbon emissions in transport infrastructure construction largely ignore constraints imposed by typical project environments where the ability to influence emissions decreases as the ability to assess emissions increases. Many of these methods also make extensive use of industry average data and assumptions that may be inappropriate for specific projects, or are based on assessments conducted after a project has been completed. These shortcomings limit the scope for identifying effective emission reduction measures before the closure of windows of opportunity to plan for and implement them in the project.

Therefore, the overall purpose of this thesis was to explore carbon mitigation strategies for the construction of transport infrastructure. The aim was to develop methods for assessing and reducing carbon emissions that can be applied during the planning and execution of transport infrastructure projects. Two research questions were addressed to achieve this aim. To identify the sources of carbon emissions in transport infrastructure projects and their relative importance, one requires both project-specific information and an assessment method capable of utilizing such information. This will require more individualized and project-specific ways of assessing carbon emissions. This issue defines the focus of research question 1:

RQ 1: How can the circumstances of specific projects be taken into account when assessing carbon emissions during transport infrastructure construction?

The availability of relevant information in different project stages limits the practical scope for implementing certain carbon reduction measures in a project. In particular, these constraints can dictate which methods can be used in a given project stage, situation or setting. Methods for reducing carbon emissions during transport infrastructure construction must therefore be evaluated in the light of these constraints. Research question 2 addresses this issue:

RQ 2: How can the assessed carbon emissions be mitigated during the planning and execution stages of transport infrastructure projects?

1.3 Scope

To maximize the likelihood of discovering practically useful ways of reducing carbon emissions in transport infrastructure projects, a number of decisions were made that limit and define the scope of this work. In general, the research presented here was based on conditions and settings that exist in the different planning and execution stages of a transport infrastructure project. From a life cycle perspective, this research addresses the upstream phase of transport infrastructure, with a particular focus on onsite construction processes. This was done to focus on a life cycle phase that traditional LCA-based methods generally model poorly.

The developed methods primarily address the major onsite construction processes of earthmoving and aggregate production, which can (at least in principle) use material sourced from the construction site. Vegetation removal has only a minor impact on emissions and so was not considered. Activities involving materials and components produced externally under factory-like conditions, such as paving, road marking, and installations, were also excluded because their construction phase impacts are minor. Bridge construction activities often have a major impact both onsite and during material production, and were therefore considered separately. The method used to assess carbon emissions during bridge construction is capable of accounting for impacts from the whole upstream phase, thus partly bridging the gap with traditional LCA-based methods.

Traditional functional units used in LCA-based studies, such as CO_2 emissions per m^2 or m of transport infrastructure, are not used in this thesis. Although these units enable comparisons between projects with sufficiently similar scopes, such comparisons have limited relevance in decision making because individual infrastructure construction projects all have their own unique characteristics and conditions (Barandica et al., 2013). Instead, to provide robust decision support, CO_2 (or CO_2e when specifically stated) emissions were considered on the basis of the full scope of the assessment for each alternative. This ensures that all possible alternatives or scenarios within a project or activity can be compared regardless of their character.

1.4 List of appended papers

Paper I: Krantz, J. Lu, W. Johansson, T. Olofsson, T. (2017). Analysis of alternative road construction staging approaches to reduce carbon dioxide emissions. *Journal of Cleaner Production, 143*, 980-988. As the main author, I wrote most of the paper, developed the model, and conducted the case study. The co-authors supported the process by providing feedback, ideas and research direction.

Paper II: Krantz, J. Johansson, T. (2016). Evaluating Construction-based Greenhouse Gas Emissions of Alternative Road Alignments. *Proceedings of the 2016 International Conference on Construction and Real Estate Management*, September 28-30, Edmonton, Canada. Johansson and I formulated the idea of the paper. We processed and collected data collaboratively. As the main author, I wrote the paper.

Paper III: Krantz, J. Larsson, J. Lu, W. Olofsson, T. (2015). Assessing Embodied Energy and Greenhouse Gas Emissions in Infrastructure Projects. *Buildings*, *5*(4), 1156-1170. All authors developed the idea of this paper. The model and demonstration were developed jointly with Larsson, but I wrote and compiled most of the paper.

Paper IV: Krantz, J. Feng, K. Larsson, J. Olofsson, T. (2019). 'Eco-Hauling' principles to reduce carbon emissions and the costs of earthmoving - A case study. *Journal of Cleaner Production*, *208*, 479-489. As the main author, I wrote most of the paper and conceived its central concept: Eco-Hauling. I also gathered the case study data and formulated the case study scenarios and parameters jointly with Feng. Feng developed the simulation model, conducted the simulations, and wrote subsection 4.3.1 "Model development". All co-authors supported the work by providing ideas and feedback.

Paper V: Jassim, H. **Krantz, J.** Lu, W. Olofsson, T. (2019). A model to reduce earthmoving impacts. Submitted to *Transportation Research Part D: Transport and Environment.* Jassim formulated the main idea, developed the model, conducted the simulations and calculations and wrote most of the paper. As co-author, I collected the case study data, wrote the introduction, helped refine the overall research idea, and reviewed and revised the manuscript. All co-authors provided feedback and support during the process.

1.5 Other peer-reviewed papers

Krantz, J. Lu, W. Johansson, T. Olofsson, T. (2014). An Energy Model for Sustainable Decision-Making in Road Construction Projects. *Proceedings of the 2014 International Conference on Construction Applications of Virtual Reality*, November 16-18, Sharjah, United Arab Emirates.

Larsson, J. Lu, W. **Krantz, J.** Olofsson, T. (2015). Discrete Event Simulation Analysis of Product and Process Platforms: A Bridge Construction Case Study. *Journal of Construction Engineering and Management, 142*(4).

Krantz, J. Lu, W. Shadram, F. Larsson, J. Olofsson, T. (2015). A Model for Assessing Embodied Energy and GHG Emissions in Infrastructure Projects. *Proceedings of the 2015 International Conference on Construction and Real Estate Management*, August 11-12, Luleå, Sweden.

Jassim, H. **Krantz, J.** Lu, W. Olofsson, T. (2016). A Cradle-to-Gate Framework for Optimizing Material Production in Road Construction. *Proceedings of the 2016 Congress of the International Association for Bridge and Structural Engineering*, September 21-23, Stockholm, Sweden.

Krantz, J. Johansson, T. (2016). Integrating Production Planning into Road Corridor Evaluation Using ETL. *Proceedings of the 2016 International Conference on Computing in Civil and Building Engineering*, July 6-8, Osaka, Japan.

Krantz, J. Larsson, J. (2017). Exploring the Case Study Usage in Construction Engineering and Management Research. P*roceedings of the 2017 International Conference on Construction and Real Estate Management*. November 10-12, Guangzhou, China.

Krantz, J. Johansson, T. (2018). Assessing the Energy Use and Carbon Dioxide Emissions of Maritime Infrastructure Projects. *Proceedings of the 10th International Conference in Sustainability in Energy and Buildings*. June 24-26 Gold Coast, Australia.

2 FRAME OF REFERENCE

This section begins by describing the process by which transport infrastructure is planned and built. Then follows a description of methods proposed in the literature and used in industry to assess emissions due to transport infrastructure, and ways of facilitating such assessments. The section concludes with a brief review of the literature on possible carbon emission hotspots in transport infrastructure.

2.1 Context description

New transport infrastructure is materialized via a number of planning and execution steps that are dictated by laws and regulations that establish a process to be followed during project implementation (O'Flaherty, 2001). Most countries have similar formal planning processes (Miliutenko et al., 2014). The STA, which is the main public client for transport infrastructure in Sweden, requires the following steps to be taken and milestones to be reached in its transport infrastructure projects (Trafikverket, 2017a):

1. **Analysis of needs (selection of measures):** The transportation system is analyzed for possible shortcomings. Upon identifying a shortcoming, measures that could resolve it are sought. Minor and simple measures are preferred. However, if such measures are deemed insufficient to resolve the shortcoming, a construction measure may be selected, and the formal planning process can be initiated.
2. **Location (corridor) selection:** Some projects may require an analysis of alternative locations or corridors for the planned infrastructure, based on costs, impacts on surroundings and project goals. Public consultations and

assessments of the project’s environmental impacts are also initiated at this stage.

3. **Preliminary design:** The location of the planned infrastructure is determined in detail and its connections and relationships to other components of the built environment (intersections, required changes to other infrastructure, etc.) are defined (Trafikverket, 2014). A public consultation is conducted before finalizing the preliminary design.
4. **Detailed design:** Drawings and technical descriptions for the planned infrastructure and its construction are created. This documentation must comply with the preliminary design and is the basis for executing the project. In design-build contracts, the contractor conducts the detailed design (Trafikverket, 2018b).
5. **Construction:** After completion of the detailed design, the project is ready to be executed. In a design-bid-build contract, the contractor is hired at this stage to construct the infrastructure according to drawings and other relevant documents from the detailed design. Upon completion of construction, the constructed infrastructure is ready to be delivered for use.

This progression dictates that large-scale decisions about the project are made in its early stages and smaller, more detailed decisions are made in later stages, as shown in Figure 2. Paulson (1976) noted that this causes the scope for influencing project outcomes such as costs to decrease rapidly over time. At the same time, the ability to assess project performance and outcomes increases over time (Austern et al., 2018), largely because the project’s parameters become better defined and more relevant data becomes available.

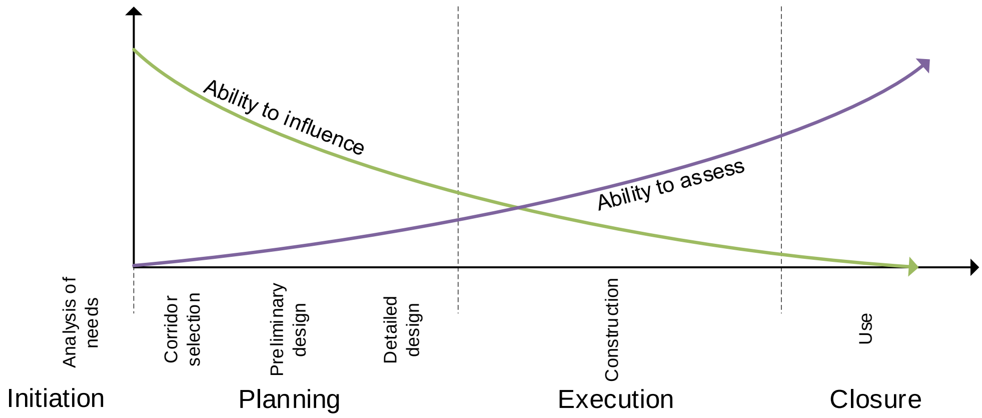

Figure 2. Schematic illustration of the ability to influence project parameters during different stages in transport infrastructure projects. Adapted after Trafikverket (2017a) and Paulson (1976).

The planning and execution of transport infrastructure projects are usually complex (Arts and Van Lamoen, 2005), which commonly leads to overruns in costs (Cantarelli et al., 2012; Flyvbjerg et al., 2003) and duration (Love et al., 2015). This can be particularly damaging because costs and duration, together with quality, are the main indicators used to assess performance in construction projects (Chan and Chan, 2004). A majority of project costs are actualized during construction but stem largely from decisions made during the early planning stages (Lu et al., 2014). Similarly, cost and schedule overruns, as well as quality problems, depend heavily on factors operating during the early stages of the project (Larsen et al., 2016). The duration of a project's execution phase correlates with cost overruns (Flyvbjerg et al., 2004). A typical project involves several different actors, and is planned and executed by organizations whose composition is temporary (Ortiz et al., 2009). Similarly, infrastructure products are assembled and constructed from several materials, building parts, and components (Buyle et al., 2012; Pushkar et al., 2005). Consequently, transport infrastructure projects are characterized by both organizational and technical complexity (Eriksson et al., 2017).

In light of the problems with overruns and the challenges posed by the overall complexity of projects, there has been a push in recent decades to develop tools and methods to improve project planning and execution, and to support good decision-making at all stages of a project (Froese, 2010). Some tools and methods have been developed to facilitate the process of assessing alternative locations or corridors for new infrastructure. For example, the STA-developed program Geokalkyl is a tool based around a geographic information system

(GIS) called ArcGIS, and is mainly used to estimate the costs, energy use, and CO_2 emissions of different alignments of planned infrastructure projects based on their required earthwork volumes (Trafikverket, 2016a). Another tool, Quantm, enables rapid automated generation of alternative alignments and facilitates comparisons between them in terms of costs and the potential for exporting the preferred alignment(s) to conventional infrastructure design tools for more detailed design work (Trimble, 2012). Location-based techniques have emerged as alternatives to traditional activity-based techniques for scheduling and planning construction projects (Kenley and Seppänen, 2009). Location-based planning is particularly useful for linear transport infrastructure projects because different construction activities can be represented as lines on a 2D-graph with the location within the transport infrastructure (the station) on one axis, and time on the other. This can be used to schedule processes, identify time-location congestion, allocate resources, and monitor the construction process (Shah, 2014).

Transport infrastructure projects often involve extensive earthworks and require large quantities of material to be hauled long distances, which is known as earthmoving or mass-hauling (Mohamed and Osama, 2003). The planning of these activities can strongly affect the project's overall success (Askew et al., 2002). It has long been understood that insofar as possible, the material needed for a project should be sourced from the construction site so as to avoid costly hauls between the site and external disposal areas or borrow pits (Mawdesley et al., 2002). However, beyond suggesting that the quantity of excavated (cut) material should equal the amount that is dumped (filled) so as to achieve mass-balance, this principle provides very little guidance on how to conduct earthmoving activities efficiently. Earthmoving can be regarded as an allocation problem where the objective is to find the shortest or cheapest set of hauls between cuts, fills, borrow pits, disposal areas, and other project locations to complete the work (Shahram et al., 2007). This problem can be solved using linear programming where the objective function is the total hauling costs, which is subject to constraints that ensure that the cut and fill work represent the actual cut and fill amounts available at different locations (Son et al., 2005). Both location-based scheduling techniques and linear programming-based earthmoving optimization procedures have been incorporated into construction planning software tools such as DynaRoad (Shah and Dawood, 2011).

2.2 Emissions assessments for transport infrastructure

Emission reduction agreements, such as the Paris agreement (Rogelj et al., 2016) are increasingly being translated into more manageable goals at national levels. For instance, the STA has introduced a goal of delivering transport infrastructure with net zero carbon emissions by 2045 (Trafikverket, 2019). Such goals require methods to enable measurement or assessment of emissions, both to verify possible reductions and to facilitate the decision-making required to achieve them. Bueno et al. (2015) argue that providing decision support based on carbon and sustainability assessments should be the primary objective of assessment methods for transport infrastructure projects. The use of assessment methods during project planning can reduce emissions by helping planners make better decisions (Treloar et al., 2004). These reductions can be achieved by systematically assessing a set of project alternatives, such as alternative materials or equipment types (Fernández-Sánchez et al., 2015). A number of different assessment methods have been proposed, some of which are reviewed below.

2.2.1 Life cycle assessment (LCA) based methods

Many emissions assessment methods used in transport infrastructure projects adopt a life cycle perspective in which the product's environmental burdens are evaluated over either its entire life cycle or selected parts of the life cycle (Buyle et al., 2013). The formal LCA framework is specified in the ISO 14040 standard, which defines LCA as the "compilation and evaluation of the inputs and outputs and the potential environmental impact of a product system throughout its life cycle" (International Standardization Organization, 2006). The four steps required to create an LCA are (Rebitzer et al., 2004):

1. **Goal and scope definition**: Establish the study's goals, define system boundaries and functional units.
2. **Inventory analysis**: Collect data for assessment based on the defined system boundaries.
3. **Impact assessment**: Calculate contributions to different environmental impact categories.
4. **Interpretation of results**: Evaluate the quality of inventory and assessment results in relation to the goal, and make recommendations based on (for example) identified hotspots.

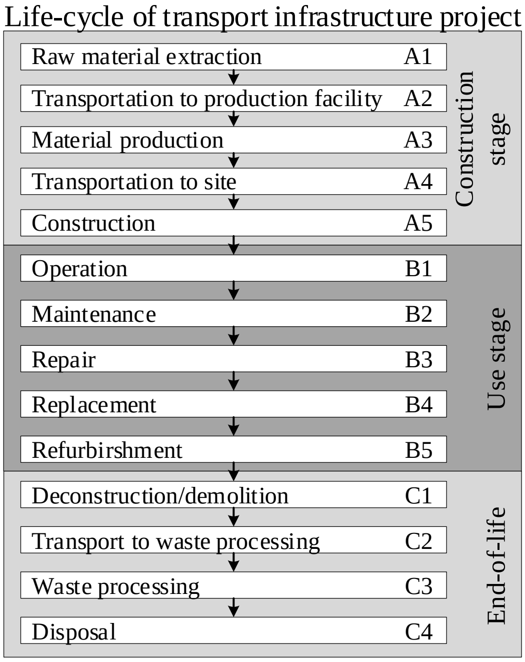

Figure 3. Life-cycle stages of a transport infrastructure project. Adapted after Strömberg (2017) and the International EPD System (2012) and (2013).

The LCA framework has been adapted for several product categories and industries including several relevant to construction (Lasvaux et al., 2015). LCAs for transportation infrastructure and other construction products address the life-cycle stages listed in Figure 3 (International EPD System, 2012; International EPD System, 2013). This type of adaption ensures that similar procedures and scopes are used, which enables comparisons between different products in the same category (Strömberg, 2017). Suppliers of construction products can enable such comparisons, or otherwise communicate the life-cycle performance of their product(s), by producing an environmental product declaration (EPD), which must be verified by a third party (Del Borghi, 2012). To be accepted, the EPD must disclose which of the life cycle stages (modules A1-A5, B1-B5, and C1-C4) listed in Figure 3 are covered by the declaration (Strömberg, 2017).

LCAs have been conducted on the scale of full transport infrastructure projects. For instance, Stripple (2001) conducted a pilot study involving a detailed inventory analysis for road construction, covering most of the major materials and processes that were used. Stripple and Uppenberg (2010) also conducted an LCA study on a major railway construction project, including its anticipated train traffic. The study forecasted that the transfer of freight transportation from road to the railway would fully mitigate the carbon emissions due to the railway's construction after approximately 13 years' operation. Huang et al. (2015) conducted an LCA for a road tunnel project, excluding the impact of road traffic and end-of-life treatment. Their study indicated that the tunnel's construction, maintenance, and operation would generate substantial carbon emissions, and the authors advised the project stakeholders to take these emissions into account from the very beginning of the planning process. Anastasiou et al. (2015) presented a comparative LCA of alternative concrete road pavements for an expected 40 year life span. Pavements containing fly ash were shown to enable considerable reductions of GHG emissions, and replacing limestone aggregates with steel slag reduced emissions if the hauling distance from the aggregate source was short. Noshadravan et al. (2013) compared the LCA performance of a concrete pavement to a hot-mix asphalt pavement, accounting for the impact of pavement roughness on the fuel economy of vehicles using the road. The assessment used Monte Carlo simulations to address uncertainty in the pavement roughness predictions and found that the median GHG emissions for the asphalt design were higher but the concrete pavement exhibited higher variation in predicted GHG emissions.

LCA methods have faced criticism for potentially lacking accuracy due to poor data quality (Ross et al., 2002), which is often due to the difficulty of acquiring sufficiently representative data (Wang et al., 2011). Conventional LCA methods also cannot account for the dynamic interactions between resources and activities that occur at construction sites (Thiede et al., 2013). Furthermore, the effects of temporal relations and spatial aspects are often ignored in favor of using industry average data (Reap et al., 2008). Nevertheless, LCAs provide a comprehensive picture of life-cycle impacts, can reveal impact hotspots (Miliutenko, 2016), and provide valuable decision support during the course of projects (Huang et al., 2015; Treloar et al., 2004).

2.2.2 Other methods of assessing emissions

While the LCA framework provides an important foundation for assessing carbon and other emissions in transport infrastructure projects, several assessment methods have been proposed that do not follow the LCA procedures and often only cover a limited part of the transport infrastructure life cycle. These methods can provide new perspectives or more detailed assessments within their scope. Melanta et al. (2013) proposed a method for assessing carbon emissions of transport infrastructure that accounts for the carbon sequestration potential gained or lost by deforestation and reforestation efforts. Barandica et al. (2013) developed a method for assessing GHG emissions in road projects, accounting for all life cycle stages other than end-of-life. The developed method was used by Fernández-Sánchez et al. (2015) to assess several alternative equipment and material usage scenarios, in a study that emphasized the importance of systematic assessments to support emission mitigation efforts. Hanson and Noland (2015) assessed a road reconstruction project, focusing on carbon emissions associated with the traffic disruption caused by the construction activities. They concluded that measures to minimize this disruption could efficiently reduce the project's overall carbon emissions.

Some assessment methods target onsite activities in transport infrastructure projects. Kim et al. (2012) developed a method to quantify the carbon emission sources at road construction sites based on the final design documents, such as BOQs and unit price data. The study assessed 24 case projects to provide an overview of their emissions, revealing that the carbon emissions per lane-km differed by almost a factor of five between the least and most polluting projects. Hajji and Lewis (2013) developed a multi-linear regression model for predicting the productivity rate and carbon emissions of excavators in different operational situations. Avetisyan et al. (2012) created a mixed integer program to optimize equipment selections on the basis of carbon emissions and costs given certain operational parameters. Measurements of actual emissions at the equipment level can be used to verify the results of assessments and develop improved assessment methods. Engine and chassis dynamometers are widely used for emissions measurements in lab environments (Babbitt and Moskwa, 1999; Yanowitz et al., 2000). Portable emissions monitoring systems (PEMS) can be used to measure emissions under more realistic field conditions, and have been used in a number of studies (Abolhasani et al., 2008; Frey et al., 2010; Rasdorf et al., 2010). Measurements of this type have been used to define emission factors to be used in regional or national emission inventories such as MOVES (EPA, 2015) and OFFROAD (California Air Resources Board, 2011).

2.2.3 Assessment facilitation with planning and modeling tools

The emergence of information and communication technology (ICT) tools has given the construction industry opportunities to facilitate most aspects of planning and execution of projects (Walker and Peansupap, 2005). The claimed benefits of adopting these technologies include higher levels of project success (i.e. lower costs and durations) as well as soft benefits relating to communication, organizations, and team management (Barlish and Sullivan, 2012; Yang et al., 2018).

Several studies have addressed the use of ICT to facilitate the assessment of carbon emissions and other environmental impacts in transport infrastructure projects. The optimization of earthmoving activities using planning software such as DynaRoad has been proposed to enable realistic measurements and assessments of environmental impacts in linear transport infrastructure projects (Kenley et al., 2011). However, at present they are primarily used to manage resources, production, and costs in projects (DynaRoad, 2015).

Simulation methods, such as DES, offer new opportunities to better capture the dynamic nature of the construction environment (Martinez, 2010). This has also enabled improved assessments of carbon emissions and other environmental impacts due to transport infrastructure construction. González and Echaveguren (2012) developed a DES-based method to assess fugitive and exhaust emissions under different equipment scenarios in the earthworks processes of a road project. Similarly, Li and Lei (2010) demonstrated a DES-based method for assessing carbon emissions under different equipment scenarios in the earthworks processes of a building project. Because of its ability to evaluate different scenarios, particularly relating to equipment choices and other operational parameters, DES can be a powerful decision support tool. However, despite its potential benefits, DES has yet to find mainstream usage in the construction industry (AbouRizk et al., 2011).

BIM technology is used to create a digital representation of a construction project that contains information on the building or infrastructure such as its geometry, spatial data, properties, cost estimates, and the quantities of materials and components needed for its construction (Azhar, 2011). This information can be used in assessments of carbon emissions and other environmental impacts of construction projects (Ernstrom, 2006). For instance, the quantity takeoffs from a BIM provide a project-specific BOQ enabling more representative assessments of a project’s carbon emissions (Yang et al., 2018). BIM integration using automated information exchange systems could also reduce or eliminate the need to manually input information into environmental impact tools such as programs for performing LCA (Russell-Smith and Lepech, 2011) or building energy performance simulations (Pinheiro et al., 2018). Most studies linking BIM with assessments of carbon emissions and other environmental impacts have been conducted on building projects (Abanda et al., 2017; Sandberg et al., 2019; Shadram and Mukkavaara, 2018). However, transport infrastructure projects also often use BIM (Chong et al., 2016), and could thus benefit from similar approaches.

2.2.4 Carbon emission hotspots and reduction measures

The methods and tools reviewed above can be used to assess carbon emissions. However, actual reductions of carbon emissions occur only when normal designs and construction practices are replaced with measures that have lower carbon impacts. This section reviews some notable studies that have highlighted potential carbon mitigation hotspots and measures.

An LCA study conducted by Noland and Hanson (2015) on a highway project indicated that carbon emissions attributed to the production of materials used during construction and maintenance accounted for the majority of the highway's life-cycle emissions. Similar results were obtained in another LCA-based study of a highway project by Cass and Mukherjee (2011), who found that material production is the main source of emissions during the construction stage. Reducing the carbon emissions of the materials used in a project could thus strongly affect its overall emissions. For instance, Rubio et al (2013) discovered that asphalt mixed at a lower temperature (known as half-warm mix asphalt) could reduce carbon emissions by almost 60% if used instead of traditional hot mix asphalts. Likewise, replacing some traditionally used crushed limestone with steel slag in concrete pavements can cut the carbon emissions of pavements by over 50% (Anastasiou et al., 2015).

While the studies of Noland and Hanson (2015) and Cass and Mukherjee (2011) concluded that the carbon emissions from equipment used at the construction site were comparatively low, an analysis of four case studies on road projects in Spain conducted by Barandica et al. (2013) found that off-road equipment was the main contributor to GHG emissions, accounting for 60-85% of the total for the construction stage. This difference is at least partly attributable to differences in the studies' scopes, the natures of the studied cases, and the methods used to assess emissions. Kim et al. (2012) specifically examined onsite equipment use in a series of case projects and discovered that over 90% of the carbon emissions due to onsite equipment were attributable to earthworks and earthmoving equipment, while equipment for paving, utility, and other works accounted for the remainder. The study also concluded that improving equipment productivity could substantially reduce carbon emissions. Jassim et al. (2018) found that equipment utilization rates correlate strongly with equipment carbon emissions, and that increasing utilization rates can reduce emissions. Abbasian-Hosseini (2016) studied the potential for reducing emissions from earthmoving equipment by turning the engine off while idling. However, it was concluded that the loss of productivity due to restarting the engine would probably completely negate the achievable emission reductions.

The fuel and energy types used by equipment have also been investigated in search of ways to reduce carbon emissions in transport infrastructure construction. Fossil diesel remains the most commonly used fuel for heavy equipment (Hajji and Lewis, 2013). However, alternative fuels that require little or no engine adaptation are gaining ground. Replacing fossil diesel with liquefied natural gas (LNG), which is another fossil fuel, can reduce life cycle GHG emissions by roughly 10% according to a European study (Arteconi et al., 2010). Similarly, a study conducted in Greece by Nanaki and Koroneos (2012) found that replacing fossil diesel with biodiesel derived from rapeseed oil could reduce life-cycle GHG emissions by roughly 75%. The use of hydrogenated vegetable oil (HVO) derived from Malaysian palm oil and German rapeseed oil also reduced emissions (relative to a fossil diesel baseline) by about 55% and 25% respectively (Arvidsson et al., 2011). More recent data suggest that the use of HVO in Sweden could reduce GHG emissions by around 85% relative to fossil diesel based on an LCA perspective (Energimyndigheten, 2016). The high torque demand of heavy equipment makes its electrification particularly attractive (Lajunen et al., 2018). Electrified powertrains are inherently more energy efficient than those based on combustion engines, and generate no emissions during operation (Palencia et al., 2015). However, from a life-cycle perspective, the GHG emissions of electric motors can be significant, depending on the composition of the electrical grid. For instance, the US generates a significant proportion of its electricity from fossil fuels. Consequently, the GHG emissions of electric heavy trucks in the US are only moderately lower than the diesel baseline (Sen et al., 2017).

3 SCIENTIFIC APPROACH

This section describes the methods used to address the purpose of this thesis. It also provides a brief description of the research process and the main activities conducted to fulfill the research.

3.1 Research design

Delivering carbon neutral transport infrastructure within the next few decades (see for instance Trafikverket (2017b)) will require a radical shift in the construction industry driven by substantial advances in knowledge, methods, and technology. However, efforts in this area are at a relatively early stage, and there is a lack of established formal research methods. Consequently, the research presented in this thesis is exploratory; discoveries made along the way strongly influenced later choices of research directions. Exploratory research is known to be useful in early stages of inquiry into a research topic, particularly when extensive further discoveries and advances are expected (Yin, 2013).

Construction engineering and management (CEM) is very much an applied field of research; accordingly, the research presented in this thesis was conducted in association with actors in the construction industry. As a result, the findings presented here do not only contribute to the development of CEM knowledge; they have also been used to address immediate practical problems in construction. The association with the construction industry made it possible to gather empirical data on real-world projects by conducting case studies. Case research was the primary research method used in this work; the case studies involved:

- Gathering empirical data on the case.
- Developing a conceptual model, framework or method.

- Demonstrating the model, framework or method, often within the scope of the same case.

A review of case studies in CEM found this structure to be common in studies proposing conceptual models, frameworks, and methods (Krantz and Larsson, 2017). Although there is, at least loosely, a logical progression from one activity to the next, it was not strictly followed in the actual conduct of the studies. This is somewhat inevitable because discoveries made in the course of a case study cannot be planned for in advance but may influence the conduct of subsequent activities (Dubois and Gadde, 2002).

3.2 Research process

The elements underpinning the research presented in this thesis, and their temporal and logical relationships, are illustrated schematically in Figure 4. The research was conducted in the scope of three case studies (see Table 1), each of which contributed to the development of the proposed methods and the appended papers. Cases 1 and 2 were the basis of my licentiate thesis (Krantz, 2017) and addressed the potential for reducing transport infrastructure projects' carbon emissions during the planning process. The advent of the STA's carbon reduction target, which is being imposed on contractors (Trafikverket, 2019), made it necessary to address the contractor's perspective and the project execution stage. Therefore, Case 3 was conducted in association with a contractor in a project during the construction phase. In this case study, the concept of Eco-Driving was studied as a way of reducing carbon emissions in earthmoving. The PSED method was developed within the scope of this case to provide a comprehensive approach for allocating earthmoving equipment.

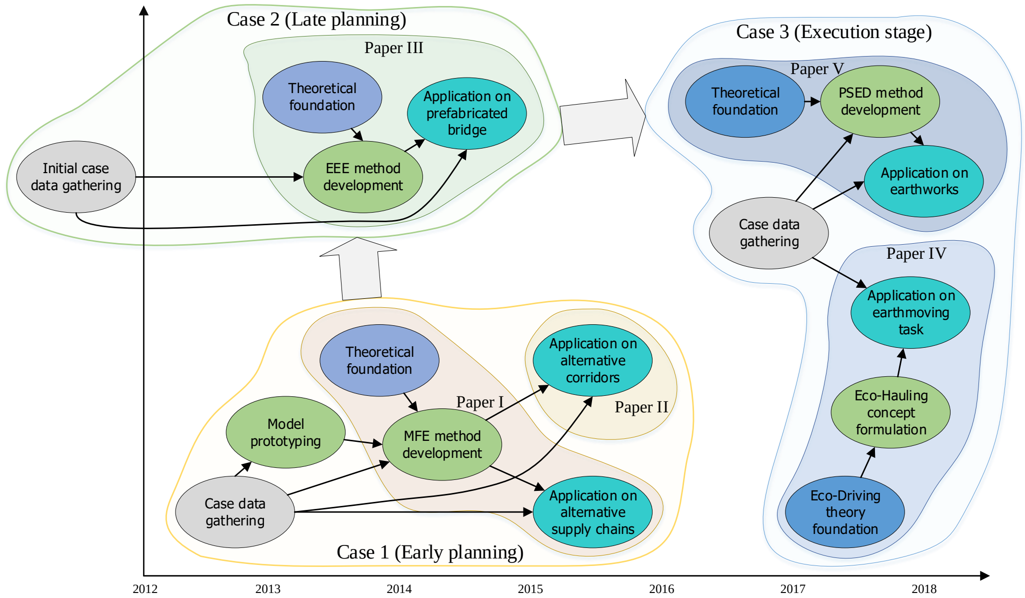

Figure 4. Outline of the research process underlying this thesis, including conducted case studies, research activities and appended papers.

The summary of the case studies presented in Table 1 shows how each of them contributed to this thesis. The case studies were not conducted using any guidance derived from the LCA framework. However, this framework was useful for describing some core elements of the case studies, such as their goals and scopes, the life-cycle stages that were addressed, the (functional) unit under consideration, and the associated inventory data. The life-cycle stages assessed are based on those shown in Figure 3. Additional information on each case study is provided in the following sections.

Table 1. Summary of the case studies conducted in the scope of this thesis.

Case study	**Case 1**	**Case 2**	**Case 3**
Description	Two road projects constituting a bypass around a city.	A semi-prefabricated bridge concept.	Expansion of road through renovation and new construction.
Contribution to papers	Paper I and Paper II	Paper III	Paper IV and Paper V
Contribution to carbon assessment methods	MFE	EEE	Eco-Hauling and PSED
Goal	Comparative assessments of alternatives.	Assessment of superstructure.	Comparative assessments of scenarios.
Scope of assessments	Earthworks, earthmoving, aggregate production.	Bridge superstructure.	Earthworks (only excavation, loading and spreading), earthmoving.
Life-cycle stages assessed	Modules A3-A5	Modules A1-A5	Module A5
Unit	CO_2 emissions per alternative	CO_2e emissions and energy use for superstructure	CO_2 emissions, cost and duration per scenario
Data collection	- Interviews - Archival records, - Documentation	- Site observations, - Interviews, - Archival records - Documentation	- Site observations, - Interviews, - Archival records - Documentation
Inventory data types	- Material quantities - Productivity - equipment energy use - Project locations - Digital terrain model - Project map	- Material quantities - Productivity - Activity durations - Equipment energy use - Construction recipes - Drawings	- Earthmoving plan - Time-location schedule - Available equipment - Drawings - Project map - Geological data

3.2.1 Case 1

Case 1 was studied to explore how carbon emissions could be assessed and reduced during the early planning stages of two transport infrastructure projects. The case encompasses the relocation of two existing roads in the north of Sweden. Data gathering was conducted in 2012 and 2013, when both projects were in the early stages of their planning. The projects were initially considered to be interrelated, and were to be executed at roughly the same time. However, in 2013, the starting date for one of them had been postponed and its exact new location remained undetermined. Consequently, while one project was opened to traffic in 2015, the remaining road is planned to open in 2020.

The gathered data included a BOQ for both projects, project maps, digital terrain models (DTMs) of the project locations, and project-specific details regarding e.g., access roads, borrow pits, disposal areas, planned crushing plant locations, and available equipment. Basic equipment data, such as power ratings and bucket/load capacities were based on generic or commonly used equipment, and were collected from equipment specification sheets. Energy use and carbon emissions for work activities using off-road mobile equipment were calculated based on the load factors reported by Persson and Kindblom (1999) and the EPA (2010), and brake-specific fuel consumption values from Lindgren (2007). The energy use for hauling with articulated haulers was estimated using a method presented in the Caterpillar Performance Handbook (Caterpillar Inc., 2012). Data relating to aggregate production and hauling with trucks were obtained using simple calculations and information obtained by personal communication.

Most of the data were obtained from documentation, archival records, personal communications, and unstructured interviews with project managers at the STA, consultants, previous contractors, and experts. The gathered data were selected on the basis of their potential to help in developing and validating the proposed carbon assessment method that would be applied in the case.

The case study was initially intended to focus on carbon assessment. However, when examining alternative supply chains during the early stages of the planning process, it became apparent that considerable method development would be needed to perform a meaningful assessment. In particular, the developed carbon assessment methods would have to be able to differentiate adequately between the possible supply chains in terms of their different construction processes. Therefore, the study’s focus expanded to encompass method development. This led to an initial prototype method, which was developed further into the current MFE method (see Paper I) to enable more systematic use across different project contexts. Paper II demonstrates an application of the MFE in a different context, where it was used to assess the carbon emissions of three alternative road corridors. Case 1 is discussed in Papers I and II, and in a conference paper (Krantz et al., 2014).

3.2.2 Case 2

The experience gained while developing and testing the MFE in Case 1 prompted an effort to expand the scope of carbon assessments in transport infrastructure beyond the earliest planning stages. Case 2 provided an opportunity to do this by examining more detailed project data relating to a bridge concept developed by a major Swedish construction company. The concept is scalable and implements a high level of industrialized construction by using prefabrication. The bulk of the data for this case study were gathered by Johan Larsson during 2010 at a site where the bridge concept was being implemented. These data included interviews, site observations, archival records and documentation (Larsson, 2016). The site observations included observations of the bridge's construction and assembly, which facilitated understanding of the work activities, their durations, and task dependencies. Complementary interviews with the manager for the bridge concept and the site manager further increased the understanding of the bridge's product and process aspects. The gathered documents and archival records include drawings, calculations and schedules for the construction process. Equipment and material data were gathered from contractors, suppliers, and EPDs, while energy use data for onsite equipment were collected from equipment specifications and the literature (Olsson, 2012).

Initially, the case was studied to gain a deeper understanding of the on-site construction processes, and more generally to investigate the development and use of industrialized construction. For the purposes of this thesis, the data gathered in Case 2 were considered in more general terms, with the bridge concept being included in a new project during later planning stages due to the level of detail of the data on the process and product. The MFE method was unable to make use of all this data to model the construction process, so a new method was needed. As a result, the EEE method was developed (see Paper III). This method can use material energy data and data on variable construction processes to both assess carbon emissions due to the upstream phase and capture dynamic onsite construction processes. Case 2 was also used to demonstrate the EEE method by considering an implementation of the bridge concept and its superstructure at a hypothetical location. In addition to Paper III, the semi-prefabricated bridge case is discussed in a journal publication (Larsson et al., 2016) and conference articles (Larsson and Simonsson, 2012; Larsson et al., 2014).

3.2.3 Case 3

Case 3 was studied to explore the potential for carbon reduction during the execution stage of transport infrastructure projects. The case consists of a road project in southern Sweden, which is being executed between 2017 and 2019, i.e., during the period when the case study was conducted. The existing road is being upgraded to an alternating 2+1 lane road, partly through construction in virgin land and partly within its current route. The project's general contractor was my main point of contact and source of data relating to the case. The bulk of the data gathering was conducted during the early stages of the project's execution in spring 2017. Additional complementary data were gathered during 2018. Site observations and interviews with project managers were conducted to gain a deeper understanding of the project. Archival records and documentation examined in the study included data on material properties, geological data, drawings, a location-based project schedule, and a record of the equipment used. Data on equipment productivity were gathered from Zhang et al. (2014) and data on equipment fuel consumption was gathered from Rylander et al. (2014) and Abbasian-Hosseini et al. (2016).

This case study was selected because it offered a suitable context for developing carbon assessment methods for contractors. Furthermore, the contractor undertaking the project had created an earthmoving plan using DynaRoad. Consequently, the sources, possible intermediate stockpile locations, and final destinations of all materials moved in the project were recorded. The case data were useful for demonstrating the Eco-Hauling method developed in Paper IV because these detailed earthmoving plans and the lists of available equipment made it possible to capture nuanced differences between different combinations of Eco-Hauling parameters. Material properties, geological data, drawings, equipment data, and hauling distances from the earthmoving plan were also used to demonstrate the PSED method proposed in Paper V.

3.3 Research quality

To contribute meaningfully to the body of knowledge in a field, research must be rigorous and of high quality (Fellows and Liu, 2015). Several measures were taken during the work presented in this thesis to ensure that it satisfied these requirements.

Reliability of research refers to the ability for other researchers to repeat the research procedures used and obtain the same results (Yin, 2013). Case-based research, such as that presented here, is conducted in a specific time frame and a specific real-life context (Dubois and Gadde, 2002). It therefore cannot be replicated in the same way as experiments. Replicability and reliability in case-based research are instead ensured by thoroughly documenting the procedures that were followed (Yin, 2013). Therefore, the data gathered from the case studies, the assumptions made, and the procedures used to generate the results presented in this thesis are all comprehensively documented. This documentation can be found in the appended papers and used to conduct similar studies and verify that similar results are obtained, for instance in comparisons between alternatives. Comparisons based on simulations with DES engines, such as those reported in Papers III-IV, can vary due to their dependence on probability distributions. Possible biases in the results of such simulations were mitigated by performing enough simulation runs to ensure stability of the results.

The external validity of a study relates to the extent to which one can generalize from its results (Fellows and Liu, 2015). Case-based research has been criticized for lacking generalizability; it is often impractical to study enough cases to provide statistically significant results, and even if enough cases are studied, they must be sampled randomly to avoid bias in the results. The cases presented in this thesis do not rely on statistical generalization; instead, the generalizations that can be made are theoretical. This means that the scope of the generalizations are determined by the contexts and settings in which the findings or theories are applicable (Tsang, 2014). The new carbon assessment methods presented in this thesis are applicable and useful in certain project situations, but not others. The assessment results (i.e. the carbon emissions of specific processes or project components) cannot be generalized to other projects, but can offer insights into potential hotspots and the use of the assessment methods. Using multiple sources of evidence is another way of increasing the validity of research (Yin, 2013). The validity of the case studies presented here is thus increased by their basis in data sources including documentation, archival records, observations, and interviews.

4 SUMMARY OF FINDINGS

This section summarizes the main findings of the research presented in this thesis in terms of the proposed methods and issues significant to their usefulness for assessing and reducing the carbon emissions of transport infrastructure projects. The methods' technical features, inputs, and outputs, are discussed, along with the practical results obtained by applying them in case studies.

4.1 Mass flow emissions (MFE) method

The MFE method, outlined in Figure 5, was developed to quantify the carbon emissions of project alternatives based on the mass flow, i.e. the transport of materials in the project. The method is based on four steps:

1. Identify project alternatives and gather project quantities and equipment data

Alternatives suitable for assessment are those that generate different mass flows, for instance due to differences in design, material sources, supply chains, or alignment. Project quantities can be obtained from a bill of quantities (BOQ) and include cut and fill volumes of soil, aggregate, and pavement materials. Equipment data are connected to the work processes required for the construction stage and depend on the materials and components of the designs. Generic data based on industry average values or data from commonly used equipment may be used if the actual equipment to be used in the project is unknown.

2. Create optimized mass haul plan

A mass haul (earthmoving) plan ensures that all constituent material quantities of the final design, and all materials that must be disposed of from the project, have a source, destination, and a possible intermediate location. Hauling distances can be optimized by using planning tools capable of mass haul optimization.

3. Select calculation models and calculate energy use
The energy use of each alternative is assessed based on the mass haul plan and equipment data for *work activities*, *aggregate production*, and *mass hauls*. *Work activities* include cutting, filling, loading, and compacting; their energy use depends primarily on the surface areas and quantities of material involved. *Aggregate production* involves transforming loosened rock into aggregates by performing various crushing steps using crushing machines. *Mass hauls* include all transportation of materials; their energy use depends on the quantities of material (in terms of mass or volume) to be hauled and the hauling distances.

4. Transform energy use to carbon dioxide emissions
The total energy use in terms of fuel and electricity is transformed into CO_2 emissions. Fuel combustion generates CO_2 emissions directly; the exact amount depends on the fuel type. Emissions related to electricity use are estimated based on the energy mix of the region or country where the electricity is generated.

MFE can be used to model mass flows using limited and/or preliminary data such as a project BOQ, generic equipment specifications, and possible locations of borrow pits, crushing plants, and disposal areas. Consequently, it is suitable for use in early project planning stages, when more detailed and definitive project information has yet to be defined. This was demonstrated in Case 1, in the studies on alternative supply chains described in Paper I, and the analysis of alternative alignments presented in Paper II.

Paper I describes the assessment of two alternative supply chains using the MFE method during the preliminary design stage before a contractor became involved. One alternative used loosened rock from a stockpile adjacent to the construction site for aggregate production, while the other depended on crushed aggregates from an external supplier. The earthmoving plans for each alternative were created with the DynaRoad software package. The client's project managers anticipated that the shorter overall hauling distances resulting from the use of nearby rock for aggregate production would produce lower CO_2 emissions. However, it was deemed impractical to establish a mobile crushing plant using grid electricity, so a mobile crushing plant would have to rely on electricity produced by diesel generators, which are less efficient and generate considerably higher CO_2 emissions than the average for electricity sourced from the Swedish grid. Consequently, the alternative involving longer hauling distances and crushed aggregates produced by an external supplier generated considerably lower CO_2 emissions than the alternative relying on the mobile crushing plant. It thus appears that aggregate production with mobile crushing facilities using diesel generators is a hotspot that can profoundly affect a project's overall carbon emissions.

This case study also illustrates the benefits of assessing project alternatives at an early stage. The project managers found the result of the MFE assessments to be counterintuitive, and the less favorable alternative would probably have been selected if the alternative had not been assessed. Transport infrastructure projects have many complex interdependencies, so systematic comparisons and assessments of realistic alternatives and scenarios to support decision-making cannot be replaced by rules of thumb, experience, or intuition. Paper I illustrates the importance of such assessments in the early planning stages of transport infrastructure projects.

Paper II describes the use of the MFE-model to study the potential for reducing carbon emissions by varying the alignment of the planned project, which can be likened to the corridor selection stage of the planning process. Case 1 was used as a source of background data to develop three hypothetical alignments that served as the alternatives in the study. These alignments were modeled in a digital terrain model of the case study area using a design tool for early planning stages called Quantm. The BOQ for each alignment was then exported from Quantm to DynaRoad, where an earthmoving plan for each scenario was created. The results presented in Paper II show that the MFE method can be used to estimate the carbon emissions of earthmoving processes for different alignment options. Note that the assessment in paper II did not include the road bridges for the different options.

The results presented in Papers I and II show that MFE can be used to assess the carbon emissions of major earthmoving processes very early in the design and planning stages of infrastructure construction projects – even during the selection of corridors. This is primarily due to its ability to capture the responses of construction processes (and their carbon emissions) to differences in supply chains, material types, quantities, and their distribution along alignments. Assessing realistic project alternatives in early planning stages is important to reduce the risk of ill-informed decision-making that causes viable measures for reducing carbon emissions to be overlooked.

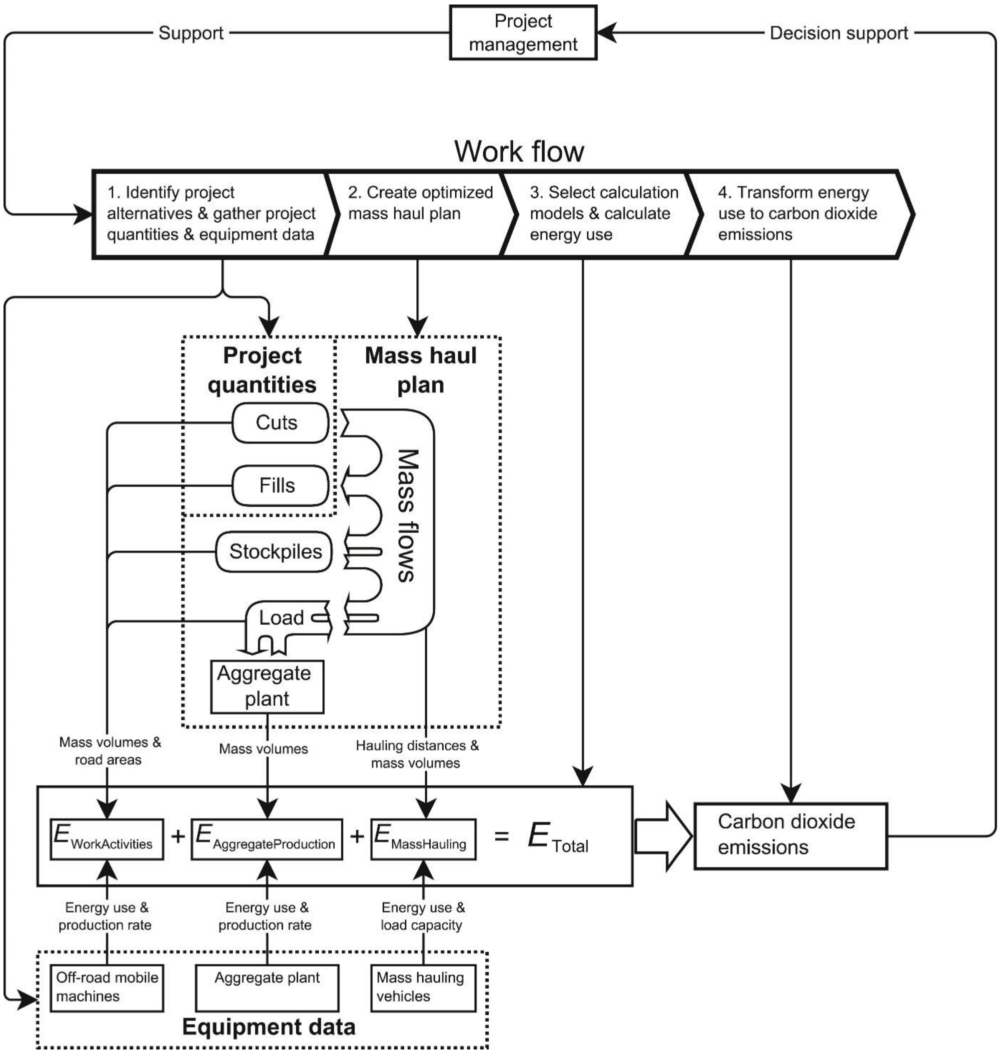

Figure 5. Outline of the MFE method and its implementation.

4.2 Embodied energy and emissions (EEE) method

The EEE method, illustrated in Figure 6 was developed to assess the energy use and carbon emissions of offsite material production, transportation to the site, and onsite construction processes in transport infrastructure projects. This approach generates more comprehensive assessments, akin to those provided by LCA methods. The EEE method is implemented in a project by performing the following three steps:

1. Design process
Customer requirements, regulations, and standards dictate the product design, which is represented in a BIM. The product’s material types and quantities are extracted from the BIM and imported into a relational database for use in a data-driven simulation of the construction process.

2. Process simulation
An agent-based DES model is parameterized using project data including material quantities, construction recipes and schedules, and productivity data for the construction equipment and workers. The process simulation is conducted to model the onsite construction processes.

3. Energy and carbon assessment
The carbon emissions from the onsite construction process are calculated based on the durations of activities and the energy use of equipment used according to the process simulation. The carbon emissions due to transport of materials and components to the construction site are calculated based on the hauling distance from suppliers, load capacities of transportation vehicles, and the quantity of materials transported to the site. Carbon emissions due to the production of those materials are estimated based on the quantity of materials produced, and on EPDs when they are available.

The EEE method is useful for choosing between possible alternatives once sufficient project information becomes available – specifically, information on available equipment, product design, construction processes and recipes, and possible suppliers. Such information often becomes available in later planning stages when the detailed design is produced. Paper III describes the application of the EEE method in the planning of the superstructure of the prefabricated bridge examined in Case 2. This bridge is a standardized prefabricated concrete beam bridge whose concrete cover and edge beams were cast on-site. The location of the construction site and the suppliers of material and prefabricated components material were hypothetical.

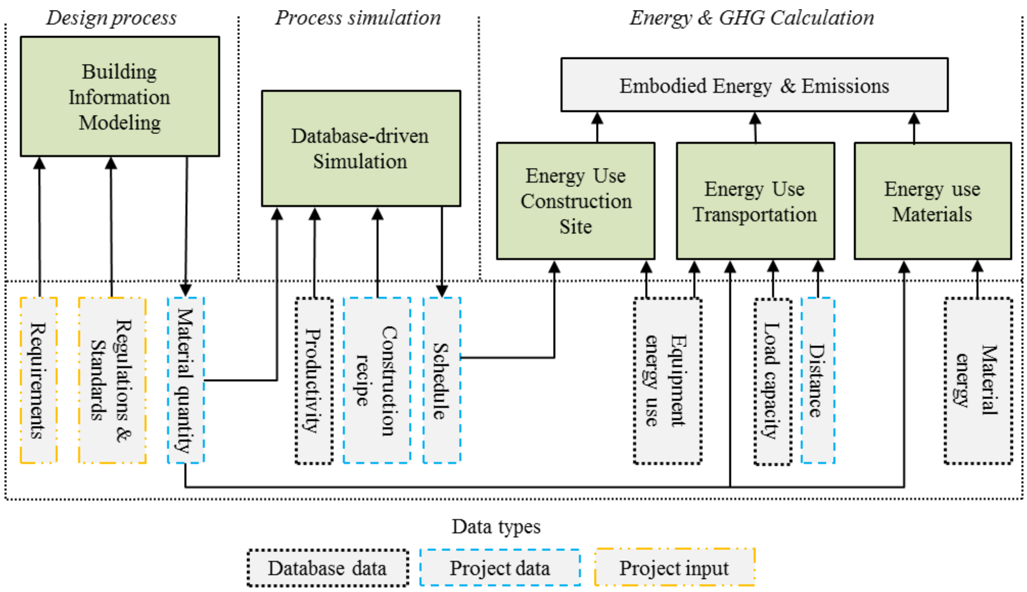

Figure 6. Outline of the EEE method.

The findings of Paper III show that the EEE-model enables project-specific assessments of GHG emissions that capture the uncertainty of construction processes on-site. This is enabled by a BIM-supported design process, which facilitates the extraction of data on materials and components (and their quantities) for the assessment of carbon emissions due to material production. Also essential is access to data on the locations of suppliers and the construction site, and knowledge of the construction processes to be used; the former is needed to assess carbon emissions due to transportation to the site, and the latter to assess carbon emissions due to onsite construction works, which in combination can be used to model the carbon emissions of the entire upstream phase. The DES simulation of the construction process also enables assessments of project dynamics and uncertainties by modelling the interdependencies between activities, materials, and equipment at the construction site. Probability distributions are used to account for variation in the productivity of different equipment and activities in order to capture the uncertainties in the construction process. The relational database facilitated the development of the simulation engine and the environmental assessments by providing data on emission factors, equipment load capacities, productivity, and energy use. The simulation engine reads the database to configure the simulation using project-specific values. Such database-driven simulation engines can facilitate the development of automated simulations and assessments of scheduled construction processes provided that the necessary input data are available. The bridge in the case study was particularly suitable for analysis because it is based on a concept developed by the contractor that has a high degree of standardization in its product design and related construction processes. The high degree of standardization and the possibility of knowledge feedback reduced the need for assumptions. The data gathered in this case were rich, including both EPDs and site observations from previous constructions of similar bridges.

The case study results relating to carbon emissions and energy use are shown in Figure 7. The onsite carbon emissions differ by about 30% from the minimum to the maximum value based on the distributions used in the simulation. Although this difference is considerable, material production is the main carbon emission hotspot. This is largely a consequence of all materials being produced offsite, with a high proportion of them being prefabricated components of reinforced concrete.

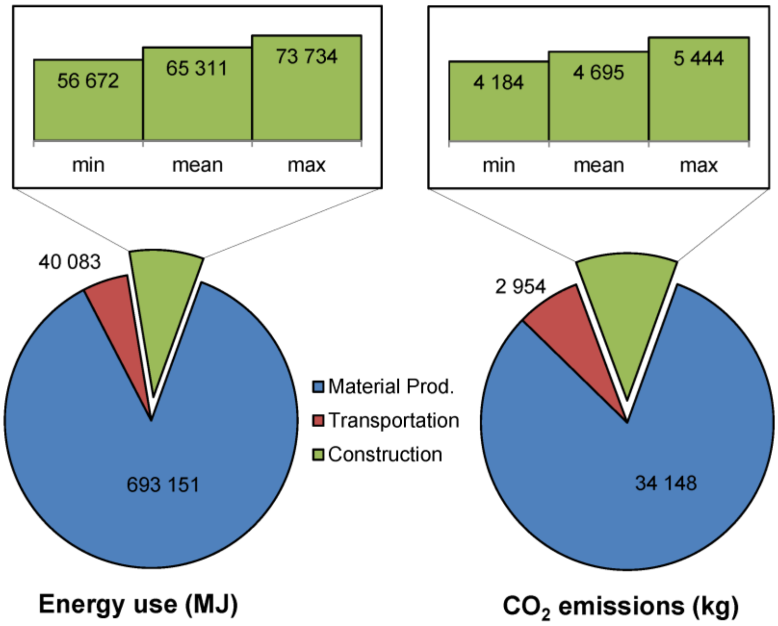

Figure 7. The energy use and carbon emissions of the upstream processes required to construct the bridge superstructure.

4.3 Eco-Hauling

Eco-Hauling was proposed in Paper IV as an extension of Eco-Driving for use in earthmoving processes. Eco-Driving is a comprehensive set of practical methods and decisions at strategic, tactical, and operational levels that private car owners/drivers can implement to reduce fuel consumption, CO_2 emissions, and costs. There are similarities between articulated haulers in earthmoving and cars in traffic, which suggests that Eco-Driving principles, if adapted to earthmoving, could generate similar benefits. The Eco-Driving concept was therefore extended into the earthmoving realm to create the Eco-Hauling concept. The concept is adapted for use by contractors conducting earthmoving operations, and consists of decisions to be made at the strategic (company), tactical (project and task), and operational (equipment operator behavior) levels, as shown in Table 2. It is therefore something to be used in the later stages of projects, primarily the project execution stage. Unlike the other methods proposed in this thesis, Eco-Hauling is a collection of practical measures and decisions that can be implemented at different levels rather than an assessment method. However, since the proposed actions have yet to be tested in a real project, a DES model was developed to evaluate the impact of adopting the Eco-Hauling principles listed in Table 2. The simulation made it possible to determine how the principles interacted with each other to identify the combinations with the greatest impact on the CO_2 emissions. In addition, the effects of Eco-Hauling on costs and duration were evaluated because these variables strongly affect the viability of proposed CO_2 reduction measures.

The use of Eco-Hauling principles was evaluated by simulating an earthmoving task performed in Case 3. The main project data used in these simulations included a list of available equipment and a detailed earthmoving plan developed in DynaRoad, which outlined the scheduled progress of the earthmoving task. Additional equipment data on variables such as load capacities, productivity, average fuel use, and fuel use at different speeds was gathered from the scientific literature. For more details on the implementation of Eco-Hauling, see Paper IV.

Table 2. Characteristics and possible decisions to be made at specific decision levels in Eco-Driving and Eco-Hauling.

Eco-Driving	Eco-Hauling
General characteristics - For individual drivers. - Reduces costs, fuel use, and CO_2 emissions at vehicle level.	General characteristics - For earthmoving contractors and equipment operators. - Reduces costs, fuel use, and CO_2 emissions at fleet level. - Maintains or increases productivity.
Strategic (long-term decision level) - Acquire energy-optimal vehicle. - Regular vehicle maintenance. - Install energy-optimal navigation system.	*Strategic* (company level) - Acquire fuel/productivity-optimal equipment fleet. - Regular equipment maintenance.
Tactical (trip level) - Optimal route choice (eco-routing). - Eliminate excess load from the vehicle.	*Tactical* (project and task level) - Optimize equipment assignments. - Optimize earthmoving (mass-haul) plan. - Determine optimal speed for equipment in earthmoving task. - Select fuel types.
Operational (driver behavior level) - Use fuel-optimal speed. - Anticipate upcoming obstacles to maintain even speeds. - Use high gears while cruising. - Minimize throttle.	*Operational* (equipment operator behavior level) - Anticipate upcoming obstacles to maintain even speeds. - Use the determined optimal speed.

Several findings were drawn from the analysis of the Eco-Hauling simulation. Eco-Hauling solutions inevitably require a tradeoff between CO_2 emissions, costs, and task duration, as shown in Figure 8. The combinations that implement the initial earthmoving plan using three haulers running at a 25 km/h base speed yield the lowest CO_2 emissions, but cannot compete with the best performing combinations with respect to cost and duration. Some combinations produce counterintuitive outcomes. A base speed of 25 km/h, which is optimal for individual haulers in terms of fuel use per distance travelled, can be suboptimal once CO_2 emissions, costs, and the overall duration of the earthmoving process are considered. Conversely, a base speed of 31 km/h is far from optimal in terms of the fuel used per distance travelled. However, for the complete earthmoving task, a base speed of 31 km/h together with the use of 3 haulers and the alternative earthmoving plan is a particularly competitive option with respect to all three objectives (CO_2 emissions, costs, and duration). They outperform alternatives with 4 haulers operating at a 25 km/h base speed with respect to CO_2 emissions and costs, and those with 3 haulers and a base speed of 25 km/h with respect to costs and duration.

Consequently, a base speed of 31 km/h with 3 haulers using the alternative earthmoving plan could be a particularly competitive combination for reducing CO_2 emissions if the task is constrained in terms of costs and maximum allowed duration. The alternative earthmoving plan, which was designed to keep hauling distances more uniform over time than they are in the initial earthmoving plan, exhibited additional complexities. The results for the full set of studied scenarios showed that the alternative earthmoving plan yields consistently higher CO_2 emissions than the original. However, the alternative plan also produces consistently lower durations and costs, which is why some of the three hauler-scenarios can compete with four hauler-scenarios in terms of duration while performing better with respect to costs and CO_2 emissions. These results illustrate the complex interactions between the parameters and highlight the need to systematically assess interactions between equipment configurations, base speeds, and earthmoving plans.

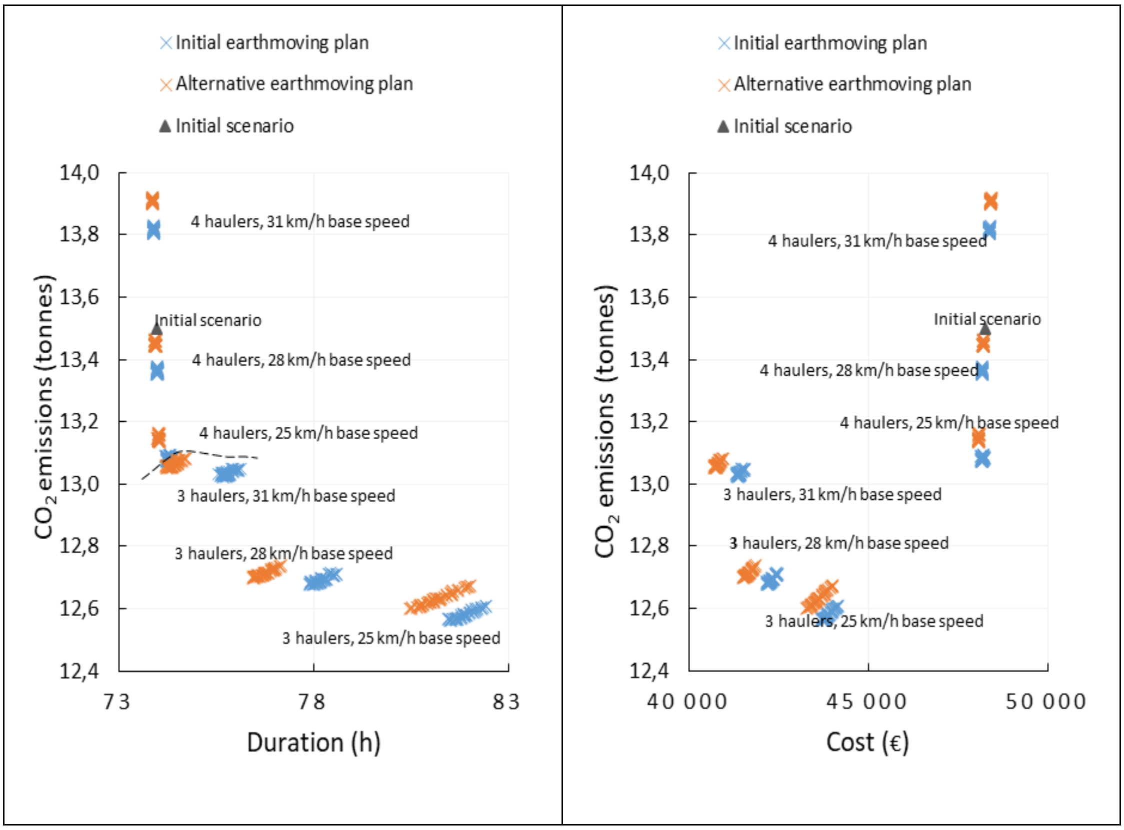

Figure 8. The results of all studied combinations of Eco-Hauling scenarios (except those using HVO) with respect to CO_2 emissions, duration, and costs.

The results in Paper IV also revealed that replacing diesel with a less polluting alternative fuel, hydrogenated vegetable oil (HVO), created a carbon mitigation hotspot. This does not necessitate any replacement of equipment or engines. It also does not interact with other decisions because it has no effect on the earthmoving operations, and thus does not require the same type of systematic assessment as for the other parameters. The DES model was also used to estimate the utilization rates of different equipment types. This showed that the combinations that performed best in terms of costs, duration and CO_2 emissions were those that maintained well-balanced and comparatively high utilization rates for excavators and haulers. Measures that improve equipment utilization rates could thus act as proxies that deliver the benefits of Eco-Hauling without necessarily having to assess tradeoffs between costs, duration, and carbon emissions.

4.4 Planning, simulation, estimation and decision making (PSED) method

The PSED method, illustrated in Figure 9, was proposed in Paper V to facilitate the optimal allocation of earthmoving equipment configurations on a project scale in terms of CO_2 emissions, costs and duration. This method uses material quantity, geotechnical, and topographic data to create an optimized earthmoving plan based on hauling distances. The resulting plan divides the earthmoving process into smaller sections, referred to as stations, consisting of excavation areas (cuts) from which excavated material is hauled to dumping sites (fills). The method also requires input data on the productivity, costs, and emissions of the equipment available for use in the earthmoving processes, which is used to define a number of possible equipment configurations. The earthmoving process is then simulated using DES successively across all stations using all possible equipment configurations. Finally, the CO_2 emissions, costs and duration for each equipment configuration are estimated across all stations. These estimates were used to compare three different approaches for equipment allocation with respect to the trade-off between CO_2 emissions, costs and duration for the configurations chosen using each approach and possible project constraints. The PSED method was demonstrated in Case 3, which comprised three earthmoving zones selected from a 17 km long road construction project in southern Sweden containing a cut volume of around 151 000 m^3.

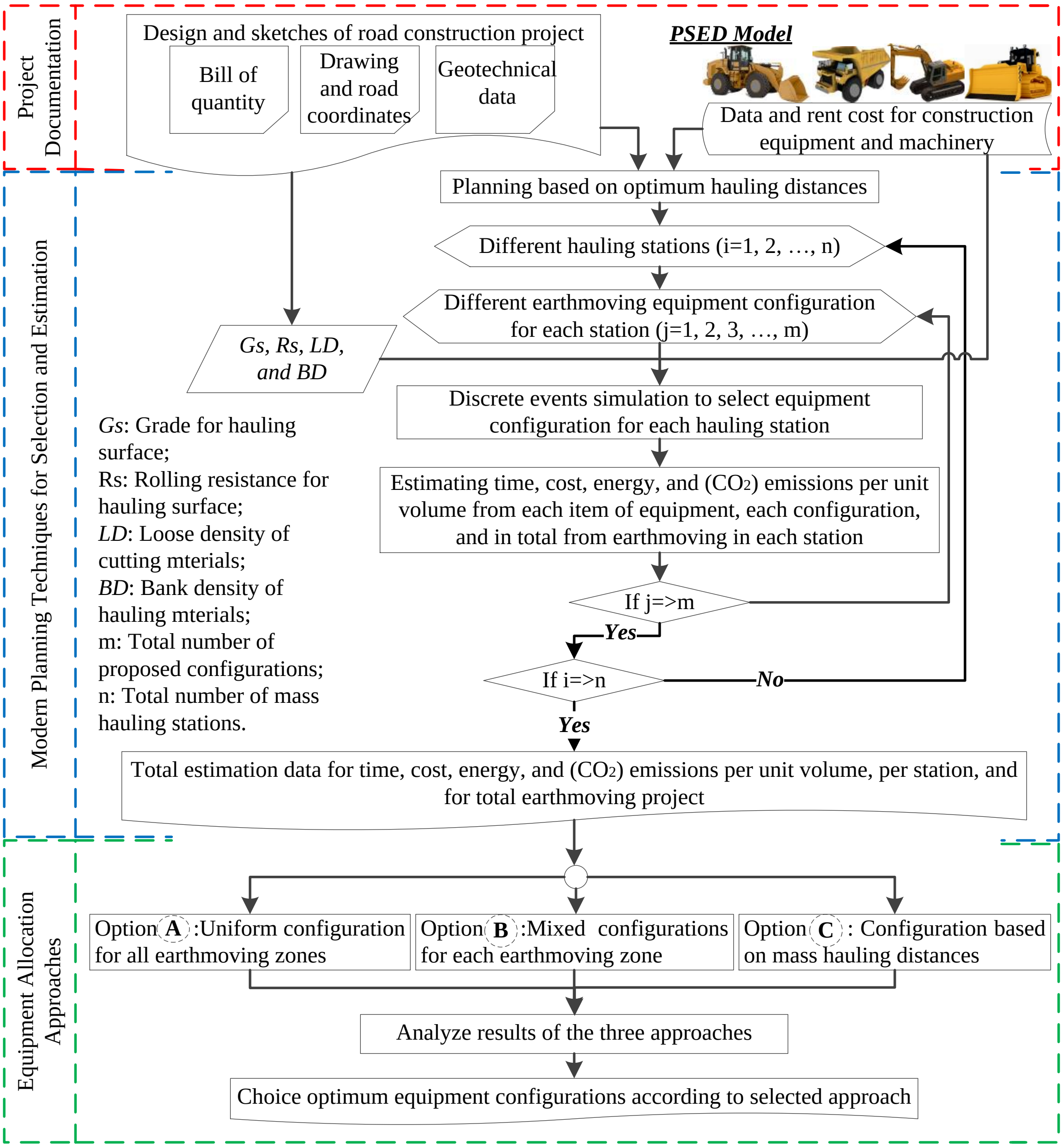

Figure 9. Outline of the Planning, Simulation, Estimation, and Decision making (PSED) model and its implementation.

The findings from the case study demonstrated the strong effect of equipment configuration on carbon emissions, costs, and duration. The simplest allocation approach, (A), one configuration is selected for all earthmoving zones with respect to the three objectives. The second approach, (B), used mixed configurations, selecting one optimal configuration for each zone. Approach (C), where equipment configurations were allocated based on the hauling distance from the earthmoving station to the dump site, provided the best performance in terms of CO_2 emissions and costs, but yielded a higher duration than Approach (A). Thus, a potentially successful way of allocating equipment configurations is to identify hauling distance tipping points where one configuration outperforms the others. In the studied case, one tipping point at hauling distances of 1.5 km was identified, resulting in two equipment configurations being used – one for hauling distances >1.5 km and another for distances <1.5 km.

In addition, the utilization rates of the equipment in each configuration were studied. The best performing configuration based on allocation approach (A) maintained similar truck and hauler utilization rates while generating higher loader and bulldozer utilization rates than the other studied configurations. Similar tendencies in the balance of utilization rates between trucks and excavators were observed for the best performing configurations at earthmoving stations with hauling distances >1.5 km and <1.5 km. A clearer picture emerged when considering a measure of the weighted utilization rates for the entire configurations, i.e. the utility rate. The equipment configurations delivering the best overall performance in terms of CO_2 emissions, costs, and duration at hauling distances >1.5 km and <1.5 km also had the highest utility rates under those conditions. This demonstrates that utilization rates and utility rates are important factors in reducing CO_2 emissions. In addition, high and balanced utilization and utility rates yielded favorable results with respect to cost and duration, which suggests that these factors may be key to successfully addressing the tradeoffs between all objectives when selecting earthmoving equipment configurations.

5 COMPARISON OF ASSESSMENTS TO THE SWEDISH CARBON REDUCTION INITATIVE

In response to the target stipulated in the Swedish climate act, the STA requires that government-funded transport infrastructure projects achieve net zero carbon emissions by 2045 at the latest (Trafikverket, 2018b). The gradual implementation of these requirements in transport infrastructure construction projects (see Figure 10) has led to them becoming integral parts of the project planning and execution process (Trafikverket, 2017c). Upon initiating a project, the STA sets a CO_2e emission baseline, which is used to determine a reasonable total emission reduction level. This baseline can be modified if major deviations in the initial conditions are discovered during the project. During project planning, hired consultants are encouraged to identify possible carbon reduction measures, some of which are included in the design. The contractors are responsible for implementing any additional measures needed to reach the project's total reduction target during construction. In design-build contracts, the contractor is responsible for meeting the carbon reduction targets by identifying and implementing measures related to the project's design and construction phase. A climate declaration is made to determine the project's total CO_2e emissions when the construction phase ends. Contractors who exceed the project's carbon reduction targets are eligible for a bonus while those who miss the target may be penalized by losing eligibility for other performance-based bonuses (Trafikverket, 2019).

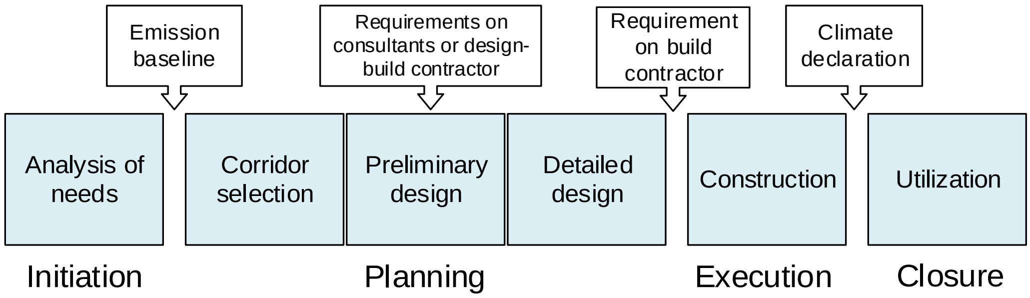

Figure 10. The implementation of the STAs carbon reduction requirements for transport infrastructure projects.

A web-based LCA tool called *Klimatkalkyl* in Swedish, developed by STA (Trafikverket, 2018a) is used to quantify baseline CO_2e emissions and reasonable reduction levels, record reduction measures implemented in the design and construction phases, and complete the climate declaration. Users (i.e. project managers, consultants and contractors) can input project data into Klimatkalkyl and link them to emission factors for the transport infrastructure, its constituent components and materials, and the resources used during construction. The emission factors, expressed in terms of CO_2e emissions per functional unit of the infrastructure, building part, materials, or resources, are multiplied by the project quantities to assess the project's emissions. In early stages of planning, when information on project-specific quantities is limited, emission factors based on generic measures of the planned infrastructure as a whole can be used. As more project-specific information becomes available, generic emission factors, can be replaced with industry average emission factors for the constituent building parts and materials to provide a more accurate assessment. Other emission factors can only be used if they are verified by an EPD. Like other LCA-based methods, Klimatkalkyl normally uses industry average values for emission factors. However, this approach has been criticized for giving results that are insufficiently representative of individual projects (Shadram et al., 2016). A comparison of the methods presented in this thesis to Klimatkalkyl could thus provide insight into how carbon emissions assessments can provide feedback on the impact of emissions reduction reductions measures in transport infrastructure projects. Therefore, the following sections compare the results of Klimatkalkyl assessments to (i) assessments of alternative corridors (Figure 11) and supply chains (Figure 12) performed using the MFE method, and (ii) the impact of the Eco-Hauling method in a number of scenarios representing different combinations of Eco-Hauling parameters that were chosen at random for illustrative purposes (Figure 13).

5.1 The MFE method compared to Klimatkalkyl

The emissions predicted in the assessments of the various alternative corridors are shown in Figure 11 (the material types and quantities for each alternative were taken from Paper II). The materials considered were base course, earth cut, earth fill, and possible surpluses or deficits. In addition, alternatives 2 and 3 both included a bridge. Unlike MFE, Klimatkalkyl can estimate the bridge's contribution to emissions; these contributions are included in the comparison to illustrate Klimatkalkyl's capabilities. Klimatkalkyl estimates the emissions associated with each of the material types listed above but breaks its estimates down based on the (standard) equipment types that are used and other resources that may be required. To enable comparisons with the MFE results, the Klimatkalkyl estimates were aggregated to match the categories used by the MFE method.

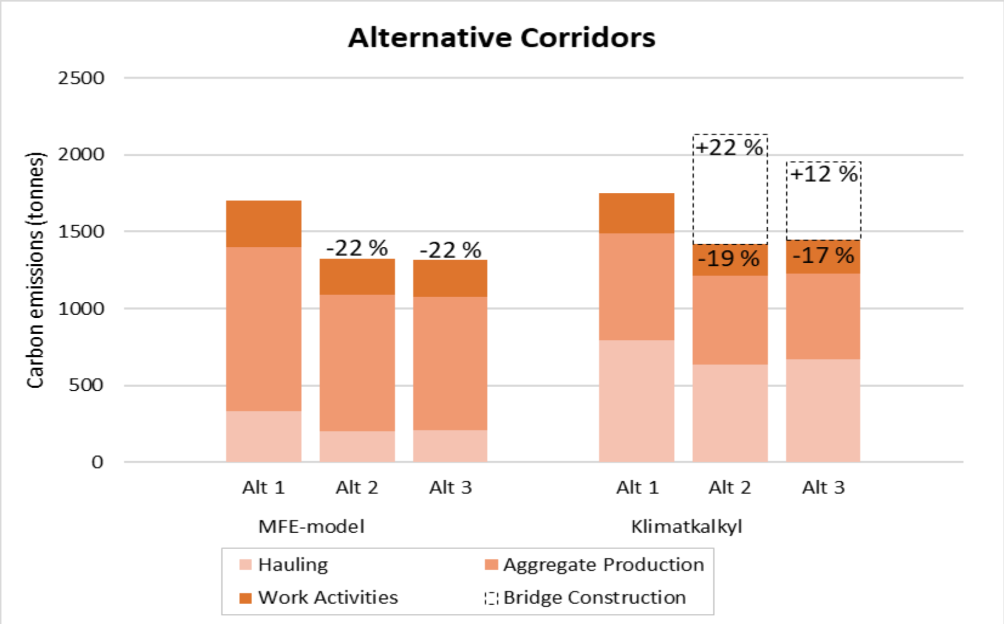

Figure 11. Carbon emissions for three alternative corridors as predicted by MFE assessments and Klimatkalkyl.

The results presented in Figure 11 show that both methods produce similar estimated emission levels. The results obtained with the two methods are within 10% of each other for all of the studied alternatives, and within 3% for Alternative 1. A similar procedure was used to compare MFE and Klimatkalkyl based on assessments of two alternative supply chains, as shown in Figure 12. The material types and quantities specified in Klimatkalkyl were obtained from Paper I. The same materials were used in both alternative supply chains, so only one set of quantities was needed. To differentiate between the supply chain alternatives, the emission factor for aggregate production had to be manually changed from diesel to grid electricity in Klimatkalkyl when assessing alternative 2. The difference in hauling distances between the two alternatives could not be assessed using Klimatkalkyl.

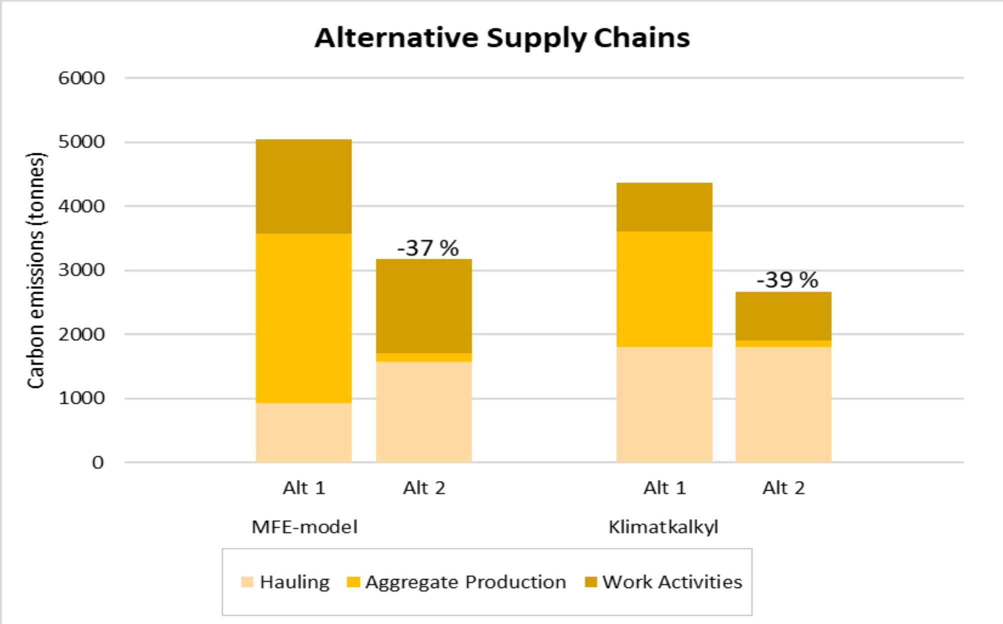

Figure 12. Predicted carbon emissions for two supply chain configurations generated using the MFE-model and Klimatkalkyl.

The results presented in Figure 12 again show clear agreement between the two methods, albeit to a lesser degree than in the previous case. This similarity of the results obtained using the two methods is probably a coincidence given the differences in their assessment procedures. For example, MFE estimates CO_2 levels whereas Klimatkalkyl uses the broader CO_2e measure to assess emissions. The two methods also calculate emissions in different ways: Klimatkalkyl does it based on the quantities of different material types used in the project, multiplied by an industry average emission factor for the material type in question, whereas MFE uses specific calculation methods for each emission category. However, the two models' results for individual emission categories differ considerably more than their predicted overall emissions for the two alternatives. The results show that when compared to Klimatkalkyl, the MFE method underestimates the emissions due to hauling activities but overestimates those due to Work Activities and Aggregate production. These differences are due to differences in calculation methods, the emission factors used in each model, and the ways in which different aspects of the construction process are captured. For instance, hauling distances within the projects cannot be specified at all in Klimatkalkyl because they are implicitly included in the industry average emission factor. Consequently, Klimatkalkyl was unable to model the differences in CO_2e emissions between the two alternative supply chains in the hauling category (see Figure 12). The hauling-based CO_2e emissions captured by Klimatkalkyl for the alternative corridors (see Figure 11) only differ because of differences in the material quantities. When applied to the alternative supply chains, the MFE method indicated that hauling in Alternative 2 generated about 600 tonnes more CO_2 (an increase of over 60%) than Alternative 1. This difference corresponds to roughly 15% of the total CO_2 emissions included in the analysis, which Klimatkalkyl is unable to account for.

5.2 The Eco-Hauling method compared to Klimatkalkyl

Selected scenarios from the Eco-hauling study were assessed using Klimatkalkyl (see Figure 13). These scenarios represent different combinations of Eco-Hauling parameters, i.e. numbers of haulers, earthmoving plans, base speeds, and speed adaptions due to obstacles between cut and fill. The cut and fill quantities for the earthmoving task in Paper IV were used as inputs for Klimatkalkyl. This task did not include any operations involving receiving equipment at the fill. Therefore, the emission factor for the excavator at the fill was set to zero in Klimatkalkyl to ensure a representative comparison. Klimatkalkyl cannot differentiate between the Eco-hauling scenarios because its assessments are based only on the quantities of cut and fill materials, and do not account for any of the Eco-Hauling parameters addressed in Paper IV (see Figure 10). Consequently, it produced identical results for all of the scenarios. Additionally, the results obtained using the two methods differ markedly with respect to both total emission levels and the emission source categories addressed, i.e., the hauling and the excavator at the cut. This shows that the current version of Klimatkalkyl is poorly equipped to assess alternatives in the construction process. The differences in the results obtained using the two assessment methods only reflect differences in the way they operate. The comparison also shows that the method used in the Eco-Hauling paper can be used to mitigate carbon emissions by selecting optimal combinations of operational parameters; assessments performed using Klimatkalkyl would not be suitable for this purpose.

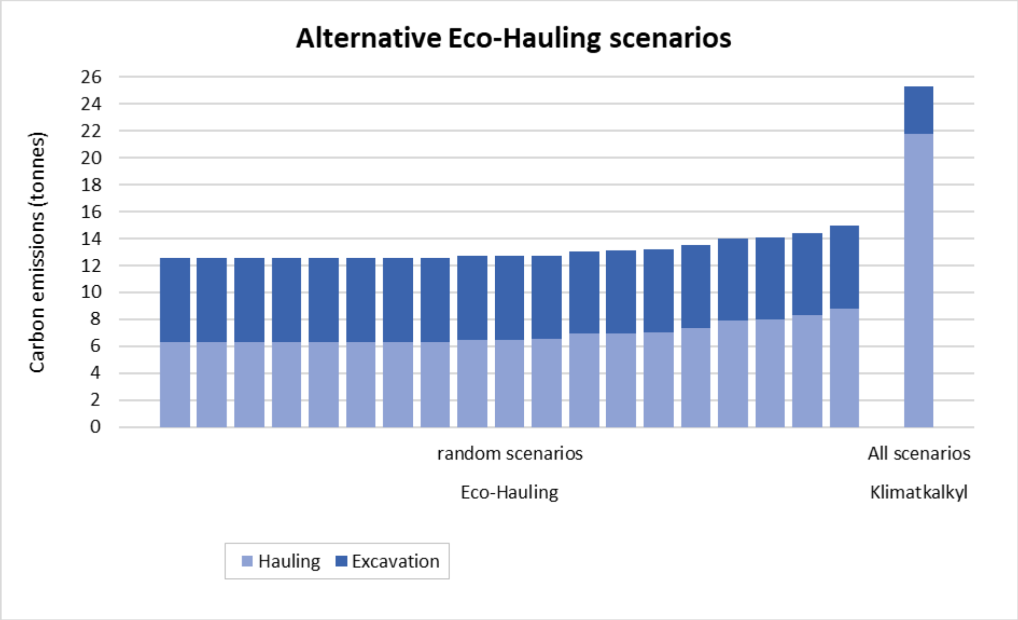

Figure 13. Predicted carbon emissions for a number of randomly chosen scenarios generated using the Eco-Hauling method and Klimatkalkyl.

6 DISCUSSION

This chapter discusses the findings of the thesis in relation to existing scientific literature and national initiatives aimed at reducing carbon emissions in transport infrastructure construction.

This work set out to propose methods for assessing and reducing carbon emissions that could be applied during the planning and execution of transport infrastructure projects. Four carbon assessment methods adapted to different stages of construction projects were proposed. These methods facilitate the reduction of carbon emissions by increasing stakeholders' ability to assess carbon emissions during the different stages of a transport infrastructure project, as shown in Figure 14.

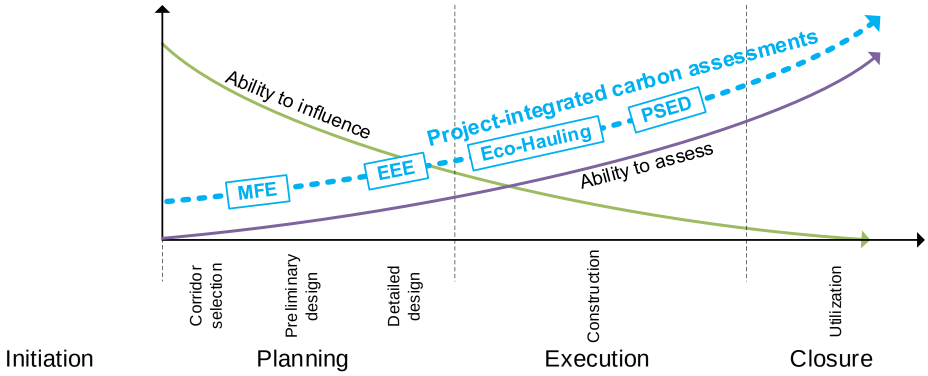

Figure 14. Overview of the project stages in which the proposed carbon assessment methods are most useful and the overall benefits they provide.

6.1 Reducing emissions during project planning

If substantial reductions of carbon emissions in transport infrastructure projects are to be achieved, assessment efforts must begin early in the planning process (Akadiri et al., 2012). A particularly useful approach for identifying possible carbon reduction measures is to assess and compare alternatives to a baseline or common practice scenario (Fernández-Sánchez et al., 2015). While there is considerable potential to influence and reduce emissions in the early stages of planning, the limited availability of relevant information in these stages makes it difficult to perform accurate assessments and make informed decisions (Häkkinen and Belloni, 2011). Assessment methods that can make better use of the limited information available in the early stages of planning could thus enable significant reductions of carbon emissions during project execution. Miliutenko (2016) identified BOQ as useful sources of information for assessing carbon emissions in the early stages of project planning. BOQ provide project-specific information on material types and their quantities, and the scale of the work required. The MFE method presented in Paper I shows that BOQs can be used as a basis for modeling a project's mass flows, using planning software such as DynaRoad to assess the carbon emissions of different project alternatives. The enrichment of BOQs in this way produces a more comprehensive picture of the project that accounts for dependencies between work activities and materials by tracing masses from their sources to intermediate locations and their final destinations. The difference between BOQ assessments using MFE and assessments using Klimatkalkyl is that MFE uses planned mass flows and information on project-specific equipment if available, whereas Klimatkalkyl is based on industry average data for hauling and work activities (see section 5.1). This difference was clearly illustrated by using MFE and Klimatkalkyl to asses two different supply chain alternatives for a project (see Figure 12): MFE captured differences in carbon emissions due to the different hauling activities for the two alternatives, but Klimatkalkyl was unable to do this because it only models hauling activities implicitly using industry average emission factors based on the project's material quantities, and does not account for project-specific hauling distances. The MFE method is thus more suitable than Klimatkalkyl for identifying opportunities to reduce carbon emissions in early planning stages.

The impact that single decisions in early planning stages can have on carbon emissions was demonstrated by comparing alternative corridors in Paper II and alternative supply chains in Paper I. In these cases, the carbon emissions for the alternatives with the lowest emissions were 19% and 37% lower, respectively, than those for the alternatives with the highest emissions. The ability to achieve emission reductions of this magnitude clearly demonstrates the importance of decisions during early planning stages for reducing carbon emissions, which is consistent with the results of earlier studies (Huang et al., 2015). While the STA promotes the use of Klimatkalkyl for planning and decision support, it does not require planners to achieve any particular carbon reductions during the planning stage (Trafikverket, 2016b). The achievable emission reductions depend entirely on the conditions of the project, the available alternative configurations, and the scope of the assessment. The findings presented in this thesis indicate that decisions made during the early planning stages can strongly influence the scope for mitigating carbon emissions. The most important carbon mitigation hotspot identified in the case of the alternative supply chains examined in Paper I was the use of diesel-powered generators for aggregate production; replacing these generators with grid electricity caused a sharp reduction in emissions. This illustrates the importance of identifying hotspots as a project progresses; Miliutenko (2016) has argued that hotspot identification is the main benefit of emissions assessment methods. Other researchers have similarly highlighted the impact of early planning stage decisions on project outcomes (Austern et al., 2018; Bogenstätter, 2000; Lu et al., 2014; Paulson, 1976).

While MFE captures mass flows and thereby provides project-specific assessments of construction processes, its assessments are based on static systems and so do not account for the inherent dynamics of the construction environment. These dynamics depend strongly on the equipment configurations, their characteristics, and their interactions. However, these factors are largely unknown in the early stages of a project, before contractors are involved. Better opportunities to model the dynamic construction environment emerge in the detailed design stage, when drawings and production specifications become available. If the contractor is responsible for the design, as in design-build contracts, additional knowledge relevant to the project is available, such as the equipment available for use, the work activities to implement, and possible material suppliers. Such knowledge can be used to evaluate the dynamics and variation at the construction site, and to perform carbon emissions assessments of upstream material and component supply processes, as demonstrated by the use of the EEE method in Paper III. However, such assessments require detailed information on the construction process as well as the ability to use that information. DES can use information of this type to model on-site construction processes. The DES engine models dependencies between equipment, materials and activities to ensure that construction processes are realistically simulated. Additionally, the use of probability distributions instead of fixed values for productivity or material deliveries makes it possible to capture dynamic effects stemming from variation in construction processes. Previous reports have accordingly highlighted the role of DES in enabling more project-specific environmental assessments (González and Echaveguren, 2012; Li and Lei, 2010). The work presented in Paper III suggests that DES can help overcome the limitations of traditional LCA-based methods, which have been criticized for being static and relying excessively on industry average data (Lasvaux et al., 2015; Reap et al., 2008; Thiede et al., 2013). The BIM component of the EEE method enabled automation and the use of project-specific BOQ. Data on the quantities of materials and components to be used in a project are essential for simulating on-site construction processes because they influence the duration of different activities. Quantity data are also important for assessing carbon emissions due to transportation of construction materials from suppliers to the site, as well as the carbon emissions due to the energy used in producing the materials. In ideal cases, this data can be obtained from the EPDs for the supplier's materials and components. These findings emphasize the benefits of using BIM in supporting more project-specific carbon assessments, in keeping with the conclusions of Yang et al. (2018).

6.2 Reducing emissions during project execution

Additional work was conducted to evaluate the potential for reducing carbon emissions during project execution, after the planning process has ended and the product/design parameters of the planned infrastructure have been determined. While the potential for reductions is greatest in the planning stage, the findings relating to Eco-Hauling presented in Paper IV and the PSED method presented in Paper V indicate that considerable emission reductions can also be achieved during project execution by optimizing construction activities and the equipment used to realize the planned infrastructure. The methods discussed in these papers offer ways of achieving such reductions cost-efficiently and in a time-saving manner by facilitating assessments of the tradeoff between carbon emissions, costs, and duration.

The execution-stage work presented in this thesis builds on previous studies examining the scope for influencing a project's parameters while it is being executed (Austern et al., 2018; Bogenstätter, 2000; Lu et al., 2014; MacLeamy, 2004; Paulson, 1976). The results obtained when implementing Eco-Hauling and PSED suggest that emission reduction efforts should be made integral to the management of project execution and not just seen as something only relevant during the planning phase. In other words, both the product and the process are important for mitigating carbon emissions in transport infrastructure projects.

Carbon emissions during the execution of construction activities can be reduced by selecting suitable combinations of Eco-Hauling parameters, including equipment configurations, fuel types, base speeds, and earthmoving plans. The replacement of fossil diesel with HVO as the fuel of choice for construction machines is arguably the most important carbon mitigation hotspot accessible to contractors in most situations because it requires no special equipment or modification of equipment engines. The other parameters influence one-another and their impact depends on the characteristics of the earthmoving task. Consequently, systematic methods are needed to assess their effects on the construction process. DES can be used to model many combinations of parameters and to provide decision support with regard to these combinations. While the results obtained by modeling various parameter combinations in Papers IV and V may appear to be largely project-specific with little general applicability, some aspects of these results display patterns suggesting the possibility of extracting more general rules. Such rules, if identified and sufficiently understood, could serve as simple operational guidelines that could be implemented more generally in projects without requiring additional assessment using the proposed methods. One such rule was extracted from the PSED analysis reported in Paper V, which identified hauling distance tipping points that determine which equipment configuration to use for hauling distances within specific intervals. These tipping points depend on the characteristics of the equipment configurations that are assessed. However, once identified for a given set of equipment configurations, they can provide simple guidelines to be used by site managers and equipment operators during project execution.

Section 5.2 (Figure 13) showed that Klimatkalkyl could not differentiate between the studied operational parameter combinations (except for changing fuel type). If carbon reductions achieved by varying these parameters cannot be captured with Klimatkalkyl, they also cannot be accounted for in the STA's carbon reduction scheme, which is used to determine whether a contractor has met a project's carbon reduction target and is thus eligible for a bonus. This may reduce the incentive for contractors to use Eco-Hauling to minimize carbon emissions. However, both Eco-Hauling and PSED assessments include integrated evaluations of costs and duration, which could incentivize and facilitate their use by contractors. If emissions reduction is placed in competition with cost and duration, it is unlikely to be seen as a primary objective (Chan and Chan, 2004), particularly in the absence of financial incentives such as bonuses. Therefore, a tradeoff between the objectives is necessary. The target values respond differently depending on which parameters are changed, and by how much. Therefore, the choice of parameter settings will depend on the project conditions and the stakeholders involved. Jassim et al. (2018) identified the equipment utilization rate as an important determinant of environmental impacts. The work in Papers IV and V confirms this conclusion, and shows that increasing and balancing the utilization rates of construction equipment can have strongly beneficial effects on emissions, costs, and project duration.

6.3 Facilitating emission reductions at the strategic level

This thesis has focused on ways of reducing carbon emissions during the planning and execution of transport infrastructure projects. However, Jacobsson and Linderoth (2010) noticed that permanent construction organizations, who manage company finances, central functions, assets, strategies, and so on, are considerably more likely to adopt modern IT tools than more temporary project organizations that conduct planning and execute infrastructure construction projects. This section therefore discusses how the methods proposed in this thesis could be used by permanent construction organizations at a more strategic level.

The Eco-Hauling and PSED methods presented in Papers IV and V do not necessarily have to model only the equipment and equipment configurations that a contractor currently owns or can access; it would be possible to include other equipment types to investigate potential future equipment acquisitions or develop equipment acquisition strategies. Moreover, possible alternative equipment configurations could be investigated in more detail to identify configurations with superior performance in terms of carbon emissions, costs, and duration. These methods could thus be used by contractors to identify optimal equipment configurations within a project, and to determine how equipment configurations could be assigned to different projects to optimize utility rates at a strategic level. The operational guidelines based on hauling distance tipping points discussed in Paper V and in chapter 6.2, could also be used at a strategic level. The allocation of equipment configurations to different projects could include specific hauling distance guidelines relevant to the chosen equipment configurations to assist members of the project organizations responsible for executing the construction processes.

Such strategic uses of the proposed methods could provide new opportunities to identify carbon mitigation hotspots that operate at an inter-project level. For instance, optimization of equipment configurations using the PSED method may not reveal hotspots within individual projects, but could hypothetically be a major hotspot at the inter-project level if it delivered consistent carbon reductions across multiple projects over a longer time period. Likewise, the use of HVO instead of diesel is clearly a carbon mitigation hotspot that operates at both the project level and the strategic level, which spans multiple projects. This inter-project view of carbon mitigation hotspots has not been addressed in previous studies (Miliutenko, 2016), but could reveal additional ways of mitigating carbon emissions related to transport infrastructure construction.

The refinement of assessment methods could also be seen as a strategic task to be conducted continuously. For instance, data gathered during completed projects could be used to fine-tune and expand the scope of assessment methods. Methods such as Eco-Hauling and PSED could benefit from the use of digital production control methods that can track resources and construction processes in real time. This would make it possible to investigate the tradeoff between carbon emissions, duration, and costs over time in more detail. Paper III also showed that the benefits of the assessment methods could be enhanced by storing collected data in a database so that it could be automatically made available to the DES and BIM engines. The discussion of the implementation of the EEE method in Paper III notes that carbon assessment could be simplified by implementing more standardized products and processes. This would simplify data gathering and ensure that much data could be reused across projects, facilitating the use of assessment methods and supporting their gradual improvement. Standardization of products in particular may warrant the declaration of EPDs for those products, which could make them more useful in the STA’s emission reduction schemes.

6.4 Research questions and fulfillment of aim

The following section outlines the answers to the research questions based on the results obtained and discusses the extent to which the work presented here achieved its aims.

RQ 1: How can the circumstances of specific projects be taken into account when assessing carbon emissions during transport infrastructure construction?

The proposed methods for assessing carbon emissions during transport infrastructure construction differ in scope, level of detail, and applicability to specific phases of the project life cycle. The findings are drawn from the development of the methods, the tools and information used in the assessments, and experience from the case studies:

- The MFE method for assessing carbon emissions is based on the mass flows in a project. These flows provide a comprehensive picture of onsite activities including excavation and crushing of materials as well as hauling distances from material sources to intermediate locations and final destinations. Unlike methods based on average industry values, the MFE method uses BOQ and other project planning data to model mass flows, producing highly enriched datasets for assessing carbon emissions. Project planning tools such as DynaRoad can be used to enrich the BOQ with mass-optimized planning data.

- The EEE method can be used to assess carbon emissions based on detailed information from construction plans and equipment specification sheets. The EEE method uses BIM and DES, which facilitate the generation of project-specific data for embodied carbon emissions assessments. DES is used to specifically address dynamic processes onsite, while BIM provides access to quantity information relevant to the whole upstream phase.
- The Eco-Hauling method can be used to assess the carbon emissions of earthmoving processes based on different operational parameters such as base speeds, speed adaptions due to obstacles, fuel types, earthmoving plans, and numbers of haulers. The method uses DES to simulate these processes, making it possible to capture subtle differences between different parameter combinations.
- The carbon emissions of selected earthmoving equipment configurations can be assessed using the PSED method. The DES component of this method is used to model the impacts of hauling distances, material densities, and the hauling surface grade on a full project scale. Carbon emissions are predicted for specific earthmoving stations, which represent a single cut together with its planned fill area(s).
- DES can support the generation of more project-specific assessments of onsite processes. DES could therefore be an important component of LCA-based carbon assessment methods with a larger scope.
- BIM enables automated quantity take-offs for an infrastructure design, which plays an important role in enabling project-specific carbon emission assessments. The BOQ is important for quantifying a project’s overall material production needs, transportation to the construction site, and on-site work. BIM tools such as Quantm can be used to quickly generate many alignments that can then be assessed using the MFE method.

RQ 2: How can the assessed carbon emissions be mitigated during the planning and execution stages of transport infrastructure projects?

Several ways to facilitate the mitigation of carbon emissions during the planning and execution stages of transport infrastructure projects were discovered. Specifically:

- The MFE method can facilitate assessment of alternatives when limited and preliminary data are available, e.g. during the early stages of the planning process. MFE provides project-specific assessments of onsite construction processes because it is based on mass flows, which can be modeled using project planning software such as DynaRoad. This method can be used to assess alternative locations for the planned infrastructure during the corridor selection stage. Early design software such as Quantm can also be integrated to facilitate the generation of alternative alignments. In addition, MFE can be used during preliminary design to assess other large-scale alternatives, such as supply chains or designs.
- Later in the planning process, in particular when contractors have been selected and there is knowledge of available equipment, more detailed assessment methods such as the EEE method can be used. Simulations may also be used to identify favorable combinations of process parameters that could reduce carbon emissions.
- Cost and duration indicators, as provided by the Eco-Hauling and PSED methods, can be used to determine the feasibility of carbon reduction measures or strategies. These indicators sometimes exhibit complex interdependencies, necessitating tradeoffs. Tradeoff assessments using these methods could be particularly useful for contractors who might not have incentives to reduce their carbon emissions in the absence of cost savings.

With respect to the fulfilment of the aims of the thesis, the work presented herein suggests that the key to facilitating the mitigation of carbon emissions in transport infrastructure projects is to bridge the gap between what is known in a project and the ability to influence project parameters by extending and enriching the information available in different stages of the project. Project stakeholders would then have a basis for making more informed decisions relating to the implementation of carbon reduction measures. This will require the identification and systematic assessment of realistic project alternatives throughout the project, and the implementation and enactment of the best alternatives before the windows of opportunity close as the project progresses. Importantly, the case studies showed that the methods used in this work can be used in conjunction with established tools that are widely used in the industry to plan and execute transport infrastructure construction. Finally, it should be noted that mitigation of carbon emissions depends on implementing favorable alternatives in a project, and these alternatives may differ markedly between projects because each project has its own unique characteristics. Despite this, a number of carbon emission hotspots were identified in the thesis, illustrating aspects that may warrant further assessment:

- In Paper I, the use of diesel-powered electric generators to power aggregate crushing machines was identified as a major contributor to carbon emissions. Running crushing plants on grid electricity could thus reduce overall carbon emissions even if it requires longer hauling distances.
- Offsite production of components and materials for a prefabricated bridge was identified as another potential hotspot, at least in comparison to the other upstream activities (i.e., transportation to the site and onsite work activities), as demonstrated in Paper III.
- Paper IV showed that fuel use strongly affects carbon emissions, and that replacing diesel with HVO can substantially reduce emissions from construction equipment.

7 CONCLUSION

This concluding chapter presents the main contributions and practical implications that can be drawn from the research underpinning this thesis. Lastly, some limitations of this work are discussed as topics for further study.

7.1 Contributions

The most important outcome of the research presented in this thesis is the integration of the developed carbon assessment methods into the different planning and execution stages of transport infrastructure projects. This gives the construction management field, which primarily addresses project performance from the standpoint of costs, duration, and quality (Chan and Chan, 2004), a comprehensive way to assess carbon emissions performance during the different stages of transport infrastructure projects. Additionally, the methods proposed for the execution stage integrate carbon assessments with assessments of costs and duration, creating opportunities for tradeoff analysis between carbon, cost, and duration.

The previously recognized gap between the ability to influence and the ability to assess (Austern et al., 2018; Bogenstätter, 2000; Lu et al., 2014; Paulson, 1976) has partially been closed by the development of the carbon emissions assessment methods presented in this thesis (see Figure 14), which enable project-specific assessments of carbon emissions to support stakeholders' decision-making as a project progresses. The connections between carbon assessment methods and the different project stages were largely ignored in previous studies, as noted by Dongier and Lovei (2006) and Kenley and Harfield (2011). Furthermore, many LCA methods depend on industry average values, which are unsuitable for providing decision support to project managers who must choose between project alternatives (Lasvaux et al., 2015; Reap et al., 2008; Thiede et al., 2013).

The results presented in this thesis also have some implications for the STA's goal of reducing carbon emissions during the construction of transport infrastructure projects. Klimatkalkyl, the assessment method prescribed by the STA, was unable to differentiate between certain project alternatives considered in section 5 because of its dependence on industry average emission factors, particularly in relation to material quantities. Therefore, while the STA's carbon reduction scheme is a welcome initiative, it could be taken further by incorporating the methods for assessing and mitigating project-related carbon emissions presented in this thesis.

This thesis has a number of practical implications that could help practitioners and stakeholders in their efforts to reduce carbon emissions during transport infrastructure projects:

- Practitioners should conduct systematic analyses of project alternatives in all stages of the planning and execution of transport infrastructure projects. Decisions stemming from such analyses could give rise to considerable reductions in carbon emissions, costs and project duration.
- Measures intended to reduce carbon emissions reductions can have substantial unforeseen positive or negative effects on other parts of the construction system. Practitioners should therefore adopt a wide scope in their analyses. Additionally, the complexity of infrastructure construction systems necessitates detailed analyses instead of intuitions or rules of thumb. The proposed methods can support such analyses.
- Earthmoving plans based on BOQs can be used to support decision-making regarding carbon emissions. Such plans enable assessment of construction processes in the early planning stages of projects.
- Methods based on DES can support the development of operational rules and guidelines based on the tradeoff between carbon emissions, costs, and duration. Hauling distance is an important variable to consider when selecting equipment configurations. Other important parameters are fuel types, base speeds, and earthmoving plans.
- Contractors seeking to reduce the carbon emissions, costs, and durations of their projects are advised to identify equipment configurations with high utilization rates. These configurations can later be reused in other projects with similar conditions.

7.2 Limitations and further research

The exploratory research presented in this thesis have some limitations and will require further development to be used effectively in the construction industry to meet carbon reduction targets. These limitations, which reveal opportunities for future work, include:

- The STA's carbon reduction scheme and Klimatkalkyl are pioneering practical efforts to reach net zero carbon emissions in infrastructure construction. However, comparisons between the methods developed in this thesis and Klimatkalkyl show that the latter cannot capture all viable ways of reducing carbon emissions, especially those relating to process dynamics and variability. An important aspect of the STA's scheme is that carbon reduction measures must be adequately verified, e.g. with EPDs. However, process-based aspects of projects are harder to verify. Therefore, an important objective for future research will be to find ways of incorporating process aspects into national carbon reduction schemes such as that developed by the STA. It may be that the verification mechanisms used for DES models could serve a similar verification function as EPDs.
- The use and selection of planning tools may influence the assessment of carbon emissions in transport infrastructure construction. More research is needed to determine how assessed carbon emissions differ when different planning tools are used.
- Although the result in this thesis have provided insights into ways of making carbon assessments more project-specific, several LCA aspects and impact categories were disregarded. The scope of the methods developed here must therefore be extended to encompass all LCA impact categories. The resulting comprehensive method may be more useful to relevant stakeholders than methods with a limited scope.
- The methods proposed in this thesis have been implemented in case studies. However, to meet the needs of practitioners, these methods will require refinement to increase their ease of use. It would thus be desirable to explore ways of further developing the assessment methods for industrial use. This will require more research, development and testing in industry cases.
- The methods proposed in this thesis have been applied to road and bridge construction projects. However, in neither case was the entire transport

infrastructure project studied. More case studies examining infrastructural elements holistically are needed to find ways of further developing the proposed methods. Case studies on other kinds of transport infrastructure projects such as railroads, seaports, and waterways should also be conducted.

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Paper I

Analysis of alternative road construction staging approaches to reduce carbon dioxide emissions

Krantz, J. Lu, W. Johansson, T. Olofsson, T.

Published in Journal of Cleaner Production, 143, 980-988.

https://doi.org/10.1016/j.jclepro.2016.12.023

February 2017

Journal of Cleaner Production 143 (2017) 980–988

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Analysis of alternative road construction staging approaches to reduce carbon dioxide emissions

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ARTICLE INFO

Article history:
Received 19 November 2015
Received in revised form
2 December 2016
Accepted 6 December 2016
Available online 10 December 2016

Keywords:
Earthworks
Energy estimation
Project alternatives evaluation
Mass-haul
Construction equipment

ABSTRACT

Despite many studies focusing on assessing energy use and carbon dioxide emissions in road projects, limited attention has been given to practical methods for mitigating environmental impacts at the project planning stage. Our study addresses this issue by proposing a model incorporating a step-by-step guide for calculating carbon dioxide emissions in the project. This model is practically applied to a road construction project where two major supply chain alternatives are evaluated and compared. The findings suggest that major reductions of carbon dioxide emissions can be achieved by (1) identifying and comparing a set of realistic project alternatives, and (2) conducting this at an early stage of the project planning process so that favorable alternatives can be implemented during construction.

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1. Introduction

Road construction projects generate considerable amounts of greenhouse gas (GHG) emissions such as carbon dioxide (CO_2) due to the large-scale use of heavy duty diesel (HDD) construction equipment (Hajji and Lewis, 2013), as well as extensive earthworks and earthmoving operations (Kenley and Harfield, 2011). The Swedish Transport Administration (STA) has declared that a reduction of energy use and associated CO_2 emissions in road construction should be a priority (Trafikverket, 2012). Despite this, previous studies have largely disregarded emissions of CO_2 occurring at construction sites according to Davies et al. (2013), Kenley and Harfield (2011), Kim et al. (2011). Instead, the primary indicators of construction performance are construction time, costs and quality (Chan and Chan, 2004).

Some concepts of “efficiency” motivated the early approaches or rules of thumb used in road construction, such as *cut to fill*, used to keep earthworks processes within the construction site (Mawdesley et al., 2002) and *short haul first*, used to minimize mass hauls (Askew et al., 2002). Modern-day project managers use more systematized approaches in road construction, such as mass haul diagrams for visual aid (Jayawardane and Harris, 1990) and linear programming-based mass haul optimization methods (Easa, 1988). Mass haul diagrams and linear programming-based optimization have been adopted in some commercial planning software, such as TILOS and DynaRoad (Shah and Dawood, 2011). Linear programming-based mass haul optimization has been combined with geographic information systems (GIS) (Moselhi and Alshibani, 2009) and productivity simulation (Ji et al., 2011) in recent research. Although approaches like mass haul optimization offer potential to significantly reduce CO_2 emissions, research on the topic has so far been limited (Kenley and Harfield, 2011).

Research has also been conducted on single construction equipment, much of it focusing on measuring emissions or energy use with portable emissions measurement systems (PEMS) (Abolhasani et al., 2008; Frey et al., 2010), engine dynamometers (Babbitt and Moskwa, 1999) or chassis dynamometers (Yanowitz et al., 2000). Models such as MOVES (EPA, 2015) and California Air Resources Board's (2011) OFFROAD (now being replaced by equipment specific models) have been used for developing emission inventories and assessing energy use on national, state and local levels. The emission factors in these models are based on lab testing using engine dynamometers (Rasdorf et al., 2010). Emission inventory data have been used to assess emissions or energy use on a project level (Rasdorf et al., 2012). In fact, MOVES also allows estimation of project emissions based on equipment data selected from its equipment inventory database and user specified duration

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http://dx.doi.org/10.1016/j.jclepro.2016.12.023
0959-6526/© 2016 Published by Elsevier Ltd.

data (EPA, 2015).

Life-cycle assessment (LCA) approaches have been applied to road projects but have rarely included all life-cycle stages. For instance, Stripple (2001) did not include end of life treatment, Huang et al. (2009) left out end of life and earthworks and Melanta et al. (2013) included earthworks but left out maintenance and end of life. The differences in methodologies and scope provide no clear view about the relative importance of different life cycle phases to project CO_2 emissions. For example, Barandica et al. (2013) concluded that earthworks on the construction site were a primary cause of CO_2 emissions in road projects, whereas Stripple (2001) found it to have a relatively low importance. Beside methodology and scope, project and location specific aspects are probably responsible for the varying results, but further research is needed.

Whereas most studies in the field have recognized a reduction of CO_2 emissions in road projects as vital, few have demonstrated practical approaches for actually achieving this. Instead many studies have focused on merely calculating, assessing and evaluating CO_2 emissions. However, some research has provided valuable insights into how a reduction of CO_2 emissions in road construction projects could be achieved. Mass haul optimization, whose use is mainly motivated on financial grounds, can potentially provide significant reductions of CO_2 emissions associated with earthworks activities (Kenley et al., 2011). Implemented measures need to be compared or contrasted to a “base scenario” or common practice, i.e., alternatives need to be compared and favorable alternatives from a sustainability perspective need to be selected (Fernández-Sánchez et al., 2015). If this process is carried out during the project planning stage (Trani et al., 2015), investments, commitments and decisions may have orders of magnitude greater impact on project costs, according to Paulson (1976). This concept also holds for environmental pollution (Bogenstätter, 2000).

The aim of this study was to explore how CO_2 emitted by construction equipment can be reduced by evaluating and comparing a set of alternatives at early stages of a road project, i.e., the engineering/design stage, often prior to selecting contractors. The proposed approach, called the mass flow emissions (MFE) model, provides generic implementation steps for assessing the energy use and associated CO_2 emissions of several project alternatives despite only access to crude project data. Use of the MFE model is demonstrated for a case study where two large-scale supply chain alternatives are assessed and compared. Work related to constructing the subgrade, base course and subbase layers were considered in the assessment. The results indicate that considerable reductions of CO_2 emissions can be achieved. Further, early implementation of the model allows plenty of time to practically implement the most favorable alternative.

The remainder of the study is structured as follows. On the basis of knowledge gaps discovered from our literature review, a model for evaluating CO_2 emissions in road projects is proposed. The MFE model is then demonstrated practically in two interrelated road construction projects. Finally, the contributions and limitations of the study are discussed and conclusions presented.

2. The mass flow emissions (MFE) model

In this section, the MFE model for road construction is presented. MFE is a conceptual model intended to support the assessment of CO_2 emissions from construction equipment based on mass flows in a road project. With the stated aim in mind, initial conceptualization of the model was performed based on a general understanding of on-site processes and mass movements in road projects. Much of the details were then worked out through exploration of mass haul optimization methods, studies of relevant literature and experiences from our studied case. The work flow of the model is shown in Fig. 1. The model utilizes mass flow data, e.g., distances, quantities and mass types, and equipment data to estimate CO_2 emissions associated with the on-site construction. The model uses rough planning data available at early stages of road construction projects. Four steps for executing the CO_2 emissions calculations are included in the model.

The first step is to gather project specific data to aid the identification of project alternatives. Project alternatives can, for instance, include alternative equipment, materials, supply chains or designs. Relevant data include the project quantities added to or removed from the road line; all added materials are defined as fills, whereas the removed materials are defined as cuts. Equipment data contain information on productivity and energy use of the equipment used in the construction project. Project managers can support the process of identifying project alternatives, as well as gathering the necessary data.

In step two, based on the project quantities, a mass haul plan is established using an optimization method to minimize hauling distances. The mass haul plan includes detailed information about material types, quantities and the distances they need to be hauled in the project. Furthermore, the locations of possible production plants (crushing, concreting and asphalt) as well as material stockpiles, such as borrow pits[1] and disposal areas, are specified.

In the next step, energy calculation models need to be selected and energy use calculated based on data from the previous steps. Energy using activities are categorized as *work activities*, *aggregate production* and *mass hauling* as they vary in terms of how their energy use is calculated. *Work activities* include cutting, filling, loading, compacting, etc. *Aggregate production* is the large scale production of construction aggregate, for instance through crushing. *Mass hauling* is the activity of moving masses using specific hauling vehicles, such as articulated haulers and trucks with trailers.

In the final step, CO_2 emissions are calculated based on the energy use. The energy use is often expressed in terms of electricity or fuel, e.g., diesel, use. Emissions resulting from electricity use depend upon how the electricity is produced and are based on the energy mix of the region where the road project is located. Fuel combustion, on the other hand, has direct emissions dependent on the fuel type used. The calculated CO_2 emissions of each alternative can aid project managers in making decisions.

3. Case study

To examine the applicability, possible potentials and complications of the MFE model, a case study was undertaken. Moreover, this helped to acquire additional knowledge about these types of CO_2 estimations in general. Case studies are particularly useful in exploratory and preliminary studies, where practical insights might be hard to gain through other methods (Rowley, 2002). Two interrelated road projects were studied - relocation of roads E10 and 870 in Kiruna Municipality in the north of Sweden. These roads had to be relocated owing to subsidence caused by the local mining industry. The MFE model was implemented during the design stage when the road corridor for both roads was selected and the road alignments were determined in detail. Preliminary road alignments with a bill of quantities (BOQ)[2] and a map were used as major modifications were considered unlikely. In this case study,

[1] An area outside of the planned road alignment where material is excavated to be used in the project.

[2] A detailed record of the types and quantities of material that need to be added and removed per specified distance (chainage) interval in a road project.

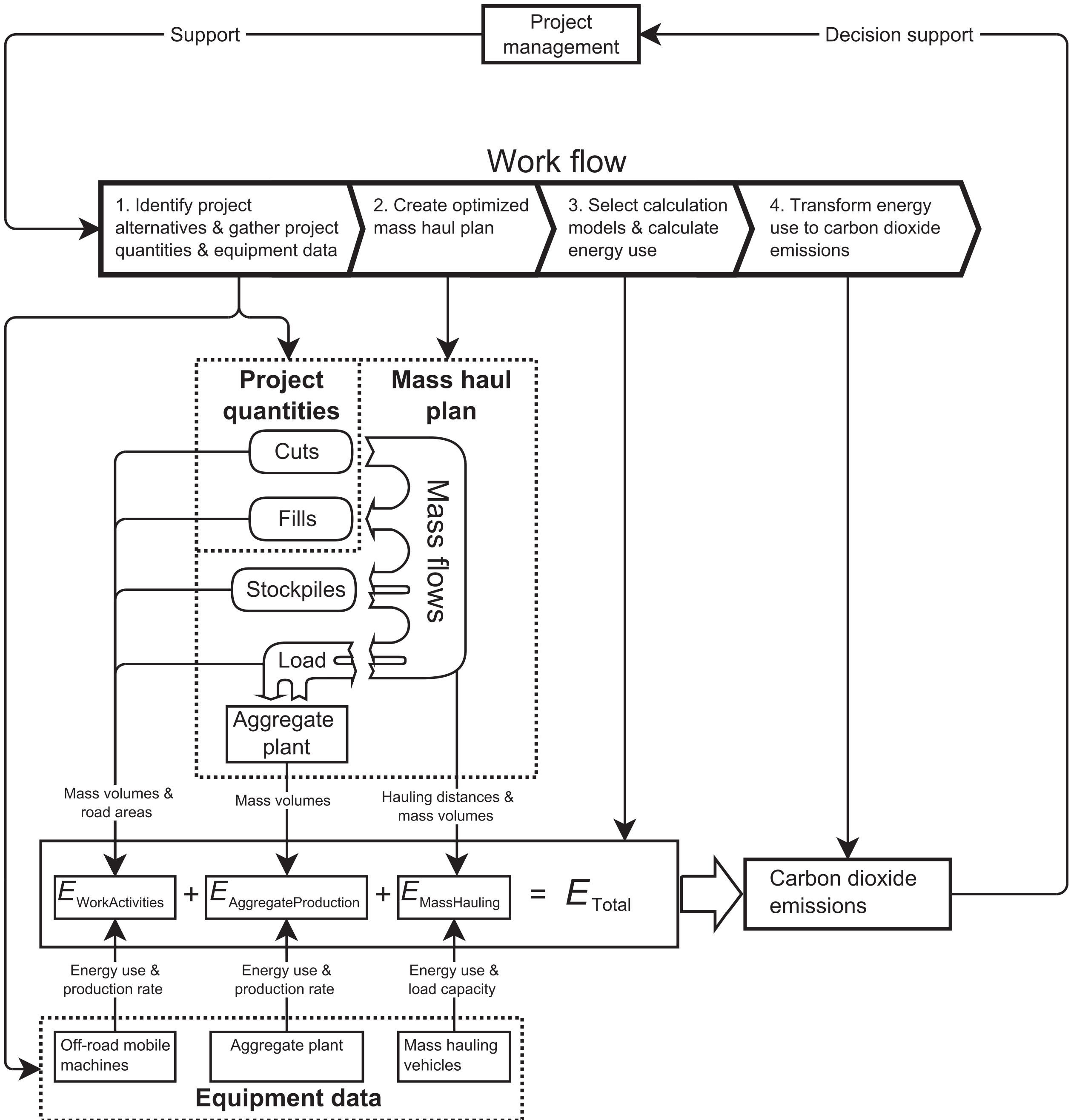

Fig. 1. The mass flow emissions (MFE) model.

construction of the subgrade, sub base and base course layers were considered. This included mass hauls, crushing of aggregates and acquisition and disposal of material off-site. Top soil removal, surface layers and other bound layers were not included in the evaluation; thus, asphalt or concrete production is not considered. Furthermore, whereas excavation of surplus earth cut was included in the study, hauling and end usage of this surplus earth were not accounted for. The case study was organized according to the steps in the MFE model, where each step has its own section followed by a results and analysis section.

3.1. Project alternatives, quantities and equipment data

The client of both projects were the STA. In conjunction with their project managers, two initial supply chain alternatives were identified. In alternative 1, some of the crushed aggregates used for the E10 road project were produced locally near the road line using a mobile crushing plant. The project managers deemed it unfeasible and unrealistic to use electricity from the grid to power the mobile crushing plant, proposing instead to power it with a diesel driven electric generator. However, in alternative 2, all the necessary crushed aggregates were produced by the mining company Luossavaara-Kiirunavaara Aktiebolag (LKAB) in the municipality using electricity from the grid. There were ample supplies of loosened rock from previous mining activities at each plant location to meet the needs for the production of aggregates in both road projects. Fig. 2 shows the location of the crushing plants and hauling routes of crushed aggregates for each alternative.

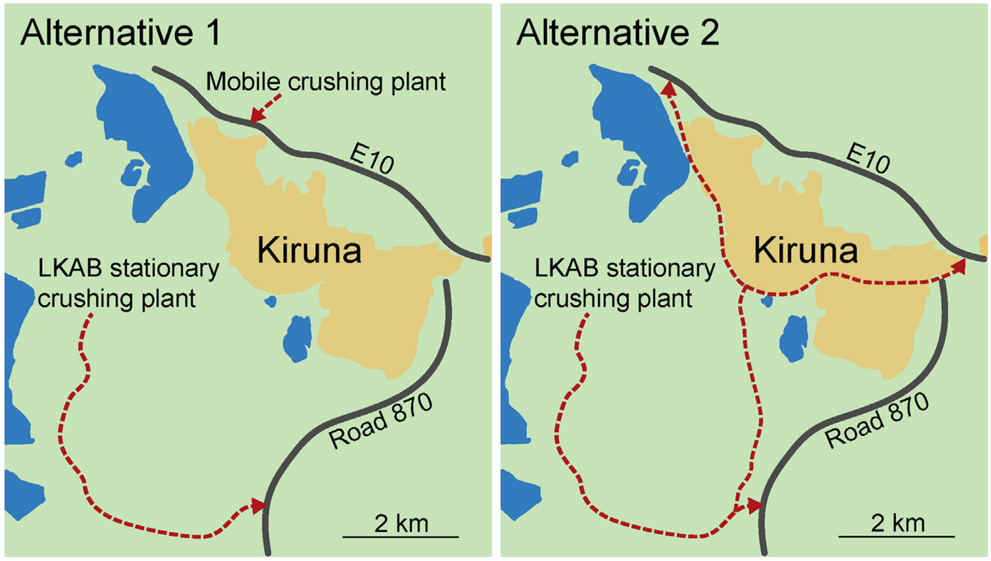

Fig. 2. Alternatives 1 and 2 with their crushing plant locations and hauling routes (marked in red) for crushed aggregates. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

It was predicted by the project managers that production of crushed aggregates near the road line, as in alternative 1, would require shorter hauls, and therefore lower energy use and CO_2 emissions, than if LKAB provided the material, which is common practice in Kiruna. Preliminary BOQs in Excel format for the roads E10 and 870 were provided by the project managers. These detailed the distribution of material quantities needed to be added or removed at 20 m station (chainage) intervals along each road.

Table 1 presents how swelling and shrinking of the different materials are accounted for by using bank cubic meters (BCM) and compacted cubic meters (CCM) as mass states. BCM quantifies the material in its natural state prior to cutting, whereas CCM refers to the material in its compacted state after filling. The mass (tonnes) is used as the common denominator when transforming rock to subbase or base course materials through crushing. It is also used for calculating material hauling quantities since the average load capacities of the vehicles are expressed in mass units.

The material quantities in the case study are summarized in Table 2. Each material is connected to a work activity using different off-road mobile equipment. The aggregate production considered in this study, the crushing of rock to produce subbase and base course, requires work activities using off-road mobile equipment to feed the crushing plant. Beside work activities and aggregate production, materials in the project need to be hauled from cuts and crushing plants to fills. Details of the equipment used for off-road mobile equipment, crushing plants and hauling vehicles are presented in section 3.3.

3.2. Mass haul plan

DynaRoad software was used to develop a mass haul plan for the two alternatives. This allowed optimization of the haulage of construction materials to the project site and estimation of the energy use of the vehicles from the output data. The road lines were "drawn" over the map and imported quantities from the BOQs were distributed along the road lines. Next, the selected areas for the crushing plants and disposals were placed on the map and connected to the road lines with access roads. Materials, their relations and swelling and shrinking correction factors were specified in the software. To optimize mass hauls, road lines and access roads were interpreted as paths, whereas cut and fill quantities are interpreted as weighted nodes forming a shortest path problem (Son et al., 2005). In its simplest form, this can be expressed as a linear program (LP), where objective function (1) is minimized and (2), (3) and (4) are its constraints:

$$\min \sum_{jk} Q_{jk} D_{jk} \quad (1)$$

$$\sum_{j} Q_j = \sum_{j} B_j \quad (2)$$

$$\sum_{k} Q_k = \sum_{k} B_k \quad (3)$$

$$Q_{ij} \geq 0 \quad (4)$$

where Q_{jk} = mass quantity hauled from cut j to fill k (decision variable); D_{jk} = haul distance from cut j to fill k; Q_j = mass quantity hauled from cut j; B_j = mass quantity in cut j (according to BOQ); Q_k = mass quantity hauled to fill k; B_k = mass quantity deficit in fill k (according to BOQ). Additional constraints may be required if the project contains, e.g., crushing plants, disposal areas and multiple material types. Project constraints, such as hauling constraints and material suitability, are specified in to enable DynaRoad to solve the LP using its solution algorithm based on Dijkstra's algorithm.

The mass haul plan provides the quantities and types of materials, their sources and final locations, as well as the hauling distance between the two. The level of detail of the mass haul plan can

Table 1
Shrinkage and swelling factors of the material types.

Material	BCM	CCM	Tonnes
Rock	1	1.45	2.7
Earth	1	1	2
Subbase	–	1	2.15
Base course	–	1	2.25

Table 2
Summary of material quantities in each road project.

Road project	Earth cut (BCM)	Earth fill (CCM)	Rock cut (BCM)	Rock fill (CCM)	Subbase (CCM)	Base course (CCM)
E10	478072	160538	54000	2621	284423	17086
Road 870	99939	92951	0	0	196803	12140
Total	**578011**	**253489**	**54000**	**2621**	**481226**	**29226**

range from individual cuts and fills to summaries of material types or road lines depending on the type of reports generated by DynaRoad. In the case study, the level of detail of the mass haul plan corresponded to the selected hauling equipment and energy calculation models used for hauling. The type of hauling vehicle used for each haul in the mass haul plan is presented in Table 3.

3.3. Energy calculation

Four energy calculation models were selected for this case study: material hauling with trucks and trailers used a distance-based calculation model and articulated haulers used a time-based calculation model. *Aggregate production,* i.e., crushing of aggregates, was described by an equation that depended on the energy use per crushed tonne, whereas *work activities* with off-road mobile machines were described by a formula based on the rated power, average load factor, brake-specific fuel consumption and activity of the machine.

3.4. Hauling with trucks and trailers

Trucks and trailers require fairly good road conditions and are only used for hauling base course materials from the LKAB to the final locations in the road line. Their estimated fuel use was calculated from Eq. (5) and depended on the transport distances, load capacities of the trucks, total masses to be hauled and the average fuel use per km of the truck. The factor 2 in the equation was based on the assumption that trucks had to drive double the haul distance as a round trip from the cut to the fill.

$$F_{\mathrm{truck}} = \sum_i (L_t/L_c \cdot 2 \cdot T_d \cdot F_c)_i \tag{5}$$

where F_{truck} = fuel use of trucks; L_t = masses to haul; L_c = load capacity of vehicle; T_d = haul distance; F_c = fuel consumption of vehicle; i = all truck configurations in the project. Furthermore, a correction factor of 1.44 was used to account for extra fuel use of trucks running on dirt roads (Abelson, 1973). About 25% of the hauling route for base course from LKAB's crushing plant in alternative 1 consists of dirt road. Hence, a correction factor of 1.11 was used. Hauls of the subbase and base course to road E10 and base course to road 870 from LKAB's crushing plant in alternative 2 were subjected to the correction factors respectively 1.07, 1.07, 1.11, respectively. The truck type was assumed to be a 3-axle truck with 4-axle trailer with average load of 40 tonnes when loaded. The average diesel consumption was taken as 0.48 kg/km assuming that the truck was fully loaded one way and empty on the return trip. The truck and average fuel consumption data were obtained from the Swedish construction firm BDX (personal communication, October 4, 2012).

3.5. Hauling using articulated haulers

Articulated haulers can be used for worse road conditions than possible with trucks with trailers. The fuel use of articulated haulers was calculated by Eq. (6). This equation is based on hauling time, which is dependent on the hauling distances, as also the case in Eq. (5).

$$F_{\mathrm{hauler}} = \sum_i (L_t/L_c \cdot C_t \cdot F_c)_i \tag{6}$$

where F_{hauler} = fuel use of articulated haulers; L_t = masses to haul; L_c = load capacity of vehicle; C_t = cycle time; F_c = fuel consumption of vehicle; i = all articulated hauler configurations in the project. The method is explained in the Caterpillar Performance Handbook (Caterpillar Inc, 2012). Although a Volvo A40 was assumed as the type of articulated hauler used, to calculate the cycle times and fuel use, a Caterpillar 740 Tier 3 was assumed as equivalent. 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. Other assumptions for

Table 3
The mass haul plans for each alternative including the selected hauling vehicle used for each haul.

Source	Destination	Quantity (tonnes)	Distance (m)	Hauling vehicle
Alternative 1				
Earth cut	Earth fill	506 978	937	Articulated hauler
Rock cut	Rock fill	7 077	2 758	Articulated hauler
Rock cut	Mobile crushing plant	138 723	306	Articulated hauler
Mobile crushing plant	Subbase (E10)	611 508	2 448	Articulated hauler
Mobile crushing plant	Base course (E10)	38 443	2 335	Articulated hauler
LKAB crushing plant	Subbase (Road 870)	423 127	9 539	Articulated hauler
LKAB crushing plant	Base course (Road 870)	27 315	9 581	Truck and trailer
Total		**1 753 171**	**3 663**	
Alternative 2				
Earth cut	Earth fill	506 978	937	Articulated hauler
Rock cut	Rock fill	7 077	2 758	Articulated hauler
Rock cut	Disposal area	1 38 723	1 758	Articulated hauler
LKAB crushing plant	Subbase (E10)	6 11 508	16 120	Truck and trailer
LKAB crushing plant	Base course (E10)	38 443	16 163	Truck and trailer
LKAB crushing plant	Subbase (Road 870)	4 23 127	9 539	Articulated hauler
LKAB crushing plant	Base course (Road 870)	27 315	9 581	Truck and trailer
Total		**1 753 171**	**8 850**	

the articulated hauler were the diesel use (20 l/h or 16.64 kg/h where 1 l equals 0.832 kg) and the average load when loaded (36 tonnes).

3.6. Aggregate production with crushing plants

Aggregate production considered in this study comprised production of the base course and sub base aggregates through crushing. Eq. (7) shows the basic relationship assumed for the energy needed for crushing.

$$E_{\text{crushing}} = \sum_i (E_c \cdot M_t)_i \tag{7}$$

where E_{crushing} = electricity use of crushing; E_c = energy use per crushed tonne; M_t = total amount of materials to be crushed; i = all crushing plant configurations in the project. The crushing plant was assumed to be a Sandvik HJ3800 crusher with an estimated electricity consumption of 5.54 kWh/tonne of produced end material. This electricity consumption allowed for the fact that different fractions need to be crushed several times. The electricity sources of the crushing plants in alternative 1 were the electric grid and a diesel driven electric generator, whereas alternative 2 only used electricity from the grid since all crushing was done by LKAB. Electricity from the grid was assumed to have characteristics in line with the Swedish average. Therefore, CO_2 emissions associated with the consumption of electricity were also calculated from the Swedish average and equaled 0.02 kg CO_2/kWh (Svensk Energi, 2014). The diesel driven electric generator was assumed to have an efficiency of 38% in its generation of electricity and the energy content of 1 kg of diesel is 11.78 kWh. Therefore, CO_2 emissions from crushing plants driven by diesel driven electric generators were therefore assumed to stem entirely from diesel combustion.

3.7. Work activities with off-road mobile machines

To calculate the fuel use of the off-road mobile machines, Eq. (8) was used:

$$E_{\text{offroad}} = \sum_i \left(A \cdot P \cdot L_f \cdot B_e\right)_i \tag{8}$$

where E_{offroad} = fuel use of off-road equipment, A = activity of the machine; P = rated power; L_f = average load factor; B_e = brake-specific fuel consumption; i = all off-road mobile equipment configurations in the project. The rated power of the machine (P) can be easily calculated once the machine is selected. The value L_f for excavator activities was based on research by Persson and Kindblom (1999), whereas the remaining load factors were obtained from the EPA (2010). The B_e values were based on work by Lindgren (2007) and were a function of the rated power. The activity (A) was a function of the amount of material handled per hour for a specific task conducted with a specific piece of equipment operating under specific conditions, such as bucket size and material type. This was gathered from diagrams and tables found in the handbook *Kapacitetsdata* (Vägverket, 1991). Table 4 presents a list of possible mass quantity based activities; note that the brake-specific fuel consumption (B_e) is 0.254 kg/kWh for all the machines.

Besides being a function of the materials worked, activities may also depend on the surface area worked, which is predominantly the case when compacting or leveling. The surface-based activities and their corresponding machines are presented in Table 5. The total road length in the project was 16960 m and it was estimated that a road roller would need 18 trips or 9 round trips on the roads to compact each layer. The motor grader was estimated to need 9 trips in total or 4.5 round trips to level the base course. Both the number of round trips and speeds of the road roller and motor graders were estimated together with the project managers.

3.8. Carbon dioxide emissions

Energy use may cause CO_2 emissions depending on the type of energy used. In this case study, the energy types were fuel (diesel) and electricity. To account for CO_2 emissions caused by electricity consumption, average Swedish emissions were assumed, i.e., 0.02 kg CO_2/kWh (Svensk Energi, 2014). Diesel combustion was assumed to cause emissions of 3.22 kg CO_2 per kg diesel combusted.

4. Results and analysis

The results are shown in Fig. 3. Alternative 1 generated 5000 tonnes of CO_2 emissions, which was almost 2000 tonnes more than alternative 2. The CO_2 emissions from alternative 2 were about 37% lower than alternative 1. The main reason for this difference is the extensive CO_2 emissions caused by aggregate production, i.e., the crushing of rock in alternative 1. Alternative 1 had considerably lower hauling distances and diesel use associated with hauling compared to alternative 2. However, aggregate production by crushing required over 800 tonnes of diesel in alternative 1 owing to the need for a diesel driven electric generator. In contrast, all the crushing in alternative 2 was performed with electricity. Therefore, the electricity use for alternative 2 was considerably higher than for alternative 1. The work activities and energy use were the same in both examples because the road design and underlying work activities were the same. In summary, alternative 2 appeared to be a better option than alternative 1 in terms of CO_2 emissions as a result of its considerably lower total use of diesel: Alternative 1 used over 1500 tonnes of diesel, over 500 tonnes more than alternative 2.

The project managers adhered to the results of the case study by deciding not to establish a mobile crushing plant next to the E10, in accordance with alternative 2.

5. Discussion

This study has shown that the intuitions of project managers may be wrong, which strongly suggests that more analytical methods are vital for reducing CO_2 emissions in road projects. By systematically evaluating and comparing specific project alternatives during early planning stages, we demonstrated that the projects could considerably reduce their CO_2 emissions and save about 500 tonnes of diesel, which in Sweden costs about € 750 000. Our findings substantiate previous research by Trani et al. (2015), who argued for comparisons of design alternatives, as well as in the related LCA-field by Fernández-Sánchez et al. (2015), who illustrated that evaluating and comparing scenarios (alternatives) can be a useful strategy to reduce CO_2 emissions. Although our study only examined two supply chain alternatives, these were complex, large-scale and differed considerably in terms of both their energy use and CO_2 emissions. These alternatives were also identified and compared during the design stage, allowing enough time to plan and practically implement the best alternative. This observation resembles Paulson's (1976) *level of influence* concept and its environmental equivalent by Bogenstätter (2000), who both explained the high degree of influence that decisions and commitments in early project stages have on later costs and environmental impacts. Sizeable alternatives ought to be identified and compared early on in a project as they require considerable time and planning to implement because of their complexity, but they can potentially allow significant reductions of CO_2 emissions, as shown in our case

Table 4
Description of mass-based activities, corresponding machines, productivities and quantities worked.

Activity	Machine	L_f	P (kW)	Productivity (Unit/h)	Quantity (Unit)	Unit	Material
Loosening earth cuts and loading to hauling vehicle	Excavator 45 tons	0.40	250	175	578011	BCM	Earth
Receiving loosened earth and spreading to fill	Bulldozer CAT D7	0.58	175	150	253489	CCM	Earth
Loosening rock cut	Drill Rig Sandvik DX780	0.43	151	100	54000	BCM	Rock
Loading loosened rock to hauling vehicle	Excavator 45 tons	0.40	250	130	54000	BCM	Rock
Receiving loosened rock and spreading it at a rock fill	Bulldozer CAT D7	0.58	175	150	2621	BCM	Rock
Loading rock to crushing plant	Excavator 45 tons	0.40	250	100	407553	BCM	Rock
Loading subbase to hauling vehicle	Loader CAT 980	0.48	260	175	481226	CCM	Subbase
Loading base course to hauling vehicle	Loader CAT 980	0.48	260	175	29226	CCM	Base course
Receiving subbase and spreading it	Bulldozer CAT D7	0.58	175	150	481226	CCM	Subbase

Table 5
Description of 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

study. However, the case study contained unique conditions because of the project's location in a mining community. Consequently, other projects might not achieve similar results.

While not necessarily being a completely linear process in reality, the proposed MFE model provides guidance on the steps required to make the assessments. Furthermore, it categorizes the energy using activities and visualizes the interrelationships between the data gathered, generated or processed and the calculations. A core component of the model is mass haul optimization, in which the site layout can be modeled, optimal mass hauls and detailed hauling distances can be obtained, much of the work is automated and the project can be visualized, helping to identify the best project alternatives.

Some limitations and challenges were encountered in this study, all of which are appropriate topics to address in future research. Firstly, as Mawdesley et al. (2002) also observed, the project planning relied on the experience of the planners and project managers and their knowledge of the location and specific conditions associated with the road project. When identifying project alternatives with these types of experience-based approaches, there is a risk that promising alternatives are not identified or that

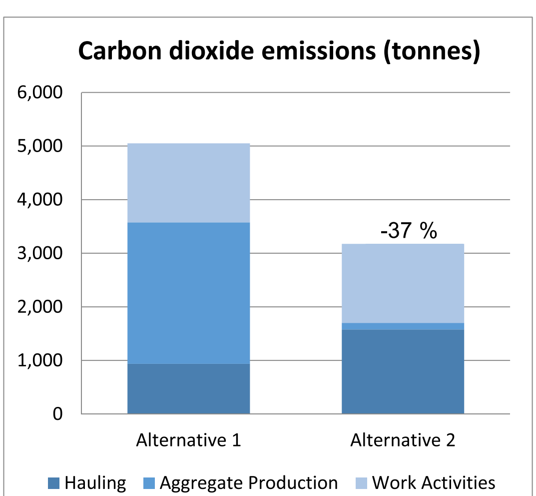

Fig. 3. Results of the two alternatives in terms of carbon dioxide emissions.

some are discarded without having evaluated sufficient information. A faster and more automated process could make it feasible to evaluate and compare a larger number of alternatives with respect to the road alignment, design, supply chains material sources, transportation and equipment. This would not only require development of appropriate software but also a general systematization and categorization of project alternatives that could serve as guidance in new projects. More systematic use of existing equipment data and databases, such as the MOVES model, should also be studied in further detail.

Secondly, because calculation models partly rely on simplifications, their accuracy may limit comparison between project alternatives. Although equipment energy use depends on, for instance, material properties, weather conditions and dynamic site factors, these were not considered in our study. Although our proposed MFE model does not contain specified calculation models per se, they have to be selected whenever the model is used. Consequently, if the model is applied to a project during its early stages, available data might be preliminary, incomplete or coarse, almost inevitably resulting in a high degree of uncertainty. However, when comparing project alternatives, there is a possibility that inaccuracies in each alternative cancel out as a result of the same calculation models and similar data used. Thus, the certainty in the relative difference between alternatives is likely to be higher than the certainty about the real emissions in each alternative. However, our study did not quantify the magnitude of any inaccuracies or uncertainties. Further research on this topic should consider the development of appropriate calculation models, data and correction factors, as well as other pathways, to ensure that sufficient accuracy is reached. Consideration to location, project-specific and other special conditions is important in these types of analyses. For instance, electricity supply and demand might vary during the year and time of the day, which could have considerable effect on the emissions from electricity generation. Although this is not a major issue in Sweden because its hydropower system is capable of handling variations, it may be a concern in other countries.

Thirdly, the scope of this study was limited by the fact that CO_2 was the only GHG examined and only work related to the earth and unbound aggregate layers of the road were considered. Furthermore, only direct equipment emissions occurring at/between the construction site and material source locations were addressed. Thus, the potential of the study for reducing emissions in road projects could be increased by expanding the scope to include life-cycle perspectives, such as material embodied emissions and other upstream emissions, maintenance or end-of-life treatment, as well as evaluating all GHGs. Other potentially significant topics for further studies are asphalt and concrete works, as well as carbon sequestration capacity lost or gained through, e.g., deforestation, reforestation or concrete carbonation.

Lastly, there is an inherent dilemma with evaluation and comparisons of alternatives regardless of whether they are conducted early or late in the project: Whereas the potential for reducing CO_2 emissions diminishes as the project progresses, the quality and certainty of relevant project data and knowledge generated increases. Simply put, early evaluation and comparison will generally suffer from a higher degree of uncertainty, whereas later evaluation will generally suffer from a lower potential for significant reductions of CO_2 emissions. Initial evaluations and comparisons should be followed up as the project progresses to ascertain the quality of the initial assessments. Once contractors have been selected and the equipment fleet set, more detailed calculations can be made and interactions between equipment can be modeled. A possible strategy could be to evaluate alternatives throughout the entire project, beginning with broad, macroscopic assessments and progressively evaluating smaller alternatives as the project advances until the construction is completed.

6. Conclusion

Our study investigated how CO_2 emissions occurring in road construction can be reduced. The findings demonstrated that considerable reductions of CO_2 emissions can be achieved by identifying and systematically evaluating and comparing different project alternatives. We proposed a model, called the MFE model, which provides a step-by-step guide for necessary data gathering, processing and evaluation of alternatives. The model makes use of mass haul optimization software to optimize and minimize the mass hauls. Presented in the model is also a categorization of the energy using activities according to the type of input data required to perform the calculations. In summary, this study furthers the development of practical approaches and knowledge for mitigating CO_2 emissions in road construction projects.

Acknowledgements

This work was funded by the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning and supported by the Swedish Transport Administration.

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Paper II

Evaluating Construction-based Greenhouse Gas Emissions of Alternative Road Alignments

Krantz, J. Johansson, T.

Proceedings of the 2016 International Conference on Construction and Real Estate Management, Edmonton, Canada.

https://doi.org/10.1061/9780784480274.063

September 2016

Evaluating Construction-based Greenhouse Gas Emissions of Alternative Road Alignments

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ABSTRACT

Road projects generally begin with broad investigations and progressively advance towards more detailed and immediate issues. Road corridors, which represent rough locations of alternative road alignments, are usually identified, evaluated and compared in early planning stages. Commonly at this stage, costs estimates of the identified road alignment are made whereas their environmental impacts, such as greenhouse gas (GHG) emissions, often are insufficiently accounted for. GHG emissions caused by the construction process are frequently ignored altogether. Despite indications that benefits of decisions and measures can be considerably higher if implemented in early planning stages, much emphasis is put on later stages. Our study presents an approach for estimating project-based GHG emissions of alternative alignments in early planning stages. The findings indicate that if adopted in the planning process, the approach can support projects in reducing their GHG emissions.

INTRODUCTION

Road construction emits large amounts of greenhouse gases (GHG) both from material production processes (Cass and Mukherjee 2011) and on-site construction activities (Hajji and Lewis 2013). Recent reports estimate that Swedish road and railway construction, including related material production and supply, emit between 1.6 - 3 million (Boverket 2014; IVA 2014) of Sweden's total of 54.4 million tonnes of CO_2 equivalent emissions in 2014 (Swedish Environmental Protection Agency 2015). Consequently, the Swedish Transport Administration (STA) is increasingly prioritizing measures for reducing GHG emissions in road construction processes (Trafikverket 2012a). Researchers have also taken interest in the matter by suggesting approaches ranging from LCA-based tools (Barandica et al. 2013; Melanta et al. 2013) to evaluating individual construction equipment (Abolhasani et al. 2008; Rasdorf et al. 2010). A more recent study suggests comparing scenarios, such as alternative equipment or materials, to find favorable alternatives

(Fernández-Sánchez et al. 2015). By evaluating alternatives early in the project, the potential impact is high, but as the project progresses, the impact of remaining decisions to be made, decreases (Paulson 1976). To achieve significant reductions of GHG emissions, it's therefore necessary to evaluate large-scale alternatives early in the project. Prior to considering equipment or materials, the approximate location of the road is determined from a set of alternative corridors (Jha 2003). This often is a complex and time consuming process as several factors, such as overall mass balances, costs and project duration, are considered (Kim et al. 2014). Previous studies have modeled emissions (Mishra et al. 2014) and fuel use (Kang et al. 2013) of vehicle traffic on alternative road alignments, but evaluation of GHG emissions caused by construction of alternative road alignments or corridors is largely an unexplored topic.

Therefore, our study proposes a model for assessing GHG emissions caused by the construction phase of alternative road alignments. The model is designed for assessing construction-based GHG emissions of project alternatives. The project alternatives in this case are road alignments specified using Quantm (Trimble 2012), a software specifically adapted for creating and generating low-cost road alignments. The method is demonstrated in a small case study of three alternative road alignments for the new E10 near the city of Kiruna in Sweden. The findings indicate show that the proposed model can be used to predict construction-based GHG emissions of different road alignments providing a practical approach for projects in reducing their emissions.

PROPOSED MODEL

To assess GHG emissions of alternative road alignments we propose a model to guide the process. This model, presented in Table 1, uses mass flow data such as distances hauled, mass quantities and types as well as equipment data in order to conduct the GHG estimations. Although four steps are included in the model to conduct the evaluation, this is not a strictly linear process. In the first step alternative alignments are specified and their quantities are collected. Furthermore, data of the required equipment to execute each project is collected. In the next step a mass haul plan for each alignment is created. The mass haul plan details the quantity of different materials and from where to where they are hauled yelding a set of hauling distances and associated quantities. Prior to calculating GHG emissions the energy calculation models need to be selected and used to calculate the total energy use of different energy carriers and sources. As a last step of implementing the model the energy use is transformed into GHG emissions. For electricity the emissions are caused during generation whereas for fuels the actual combustion causes the emissions.

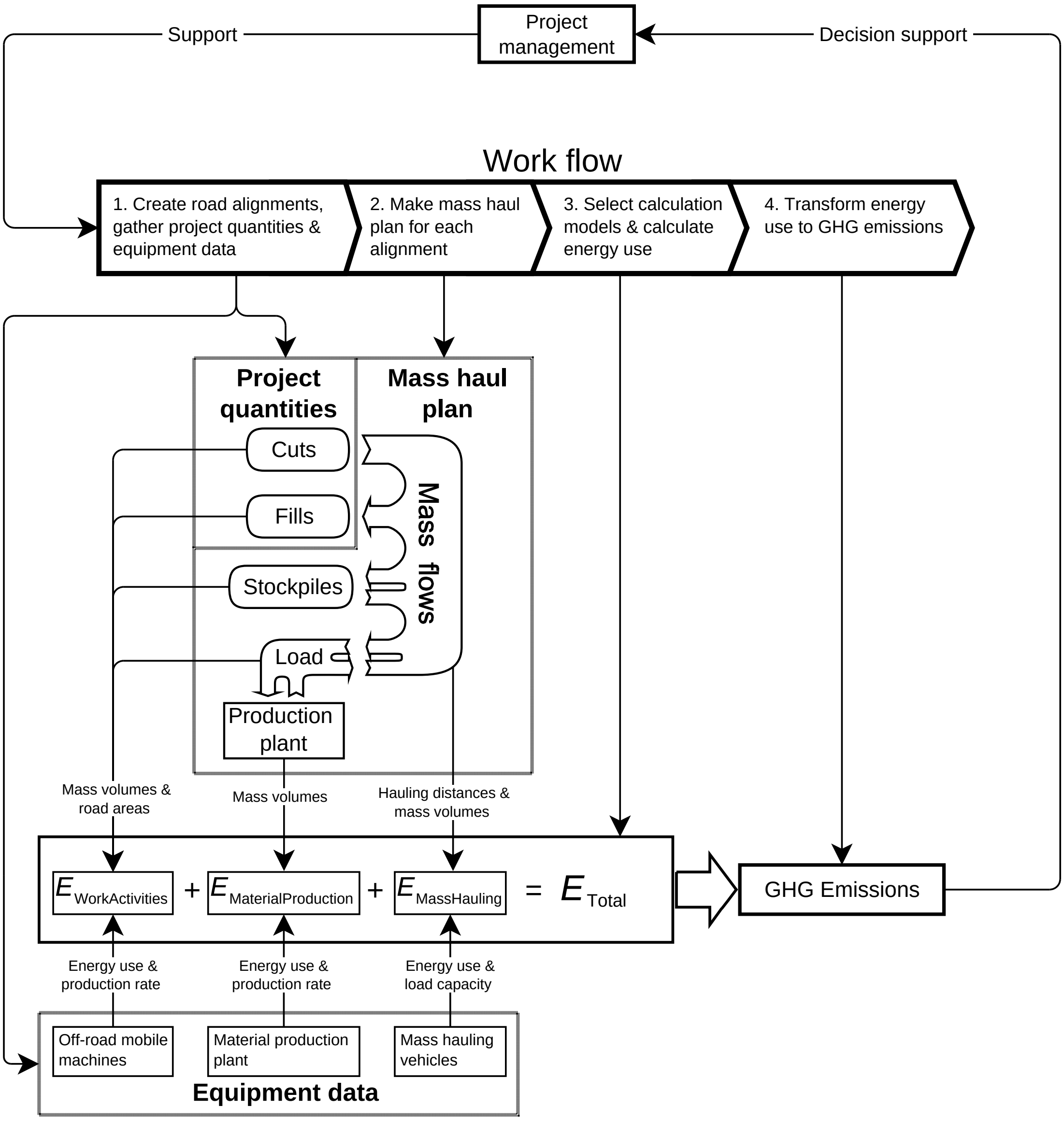

Figure 1. The proposed model containing its four implementation steps.

DEMONSTRATION

Our proposed model is demonstrated in a small case study consisting of a relocation of the E10 near the city of Kiruna in the north of Sweden. This demonstration is not entirely presented in the same chronology as the model suggests, but the work process largely follows it. The new alignment of this road is already determined, however, in our demonstration the start and finish points of this alignment are used for evaluating alternative alignments each representing a specific road corridor. Quantm software is used to create three alternative alignments that can be seen in Figure 2. Before the alignments can be created in Quantm a digital terrain model (DTM), costs and geometric parameters have to be prepared to create more realistic conditions. Area costs are manually specified on the DTM in Quantm.

Passage through skiing areas is assumed an additional cost of 100 SEK/m^2 whereas passage through golf courses adds 500 SEK/m^2. The geometric properties are standard requirements dictated by the STA for roads with an annual average daily traffic (AADT) of at least 4000 vehicles and a speed of 80 km/h (Trafikverket 2012b). Cost parameters are gathered from Olsson (2013).

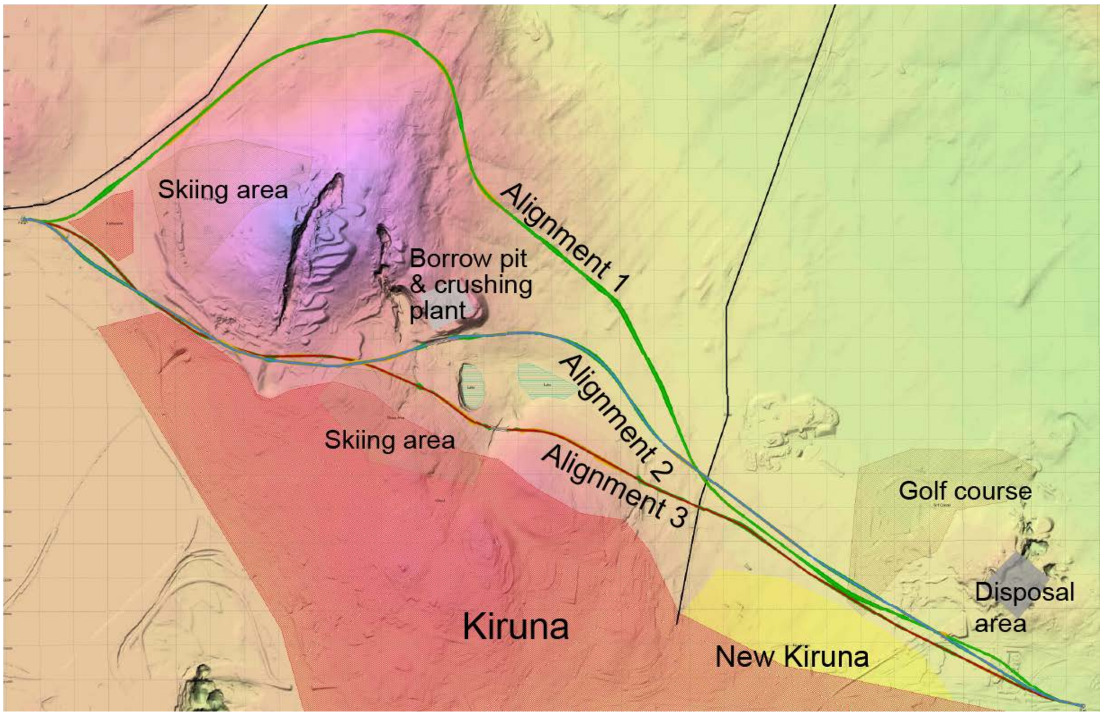

Figure 2. The demonstrated case encompassing alignments and area features.

Maximum bank height and cutting depth is set at 8 meters, meaning that Quantm will automatically create alternative structures such as retaining walls, bridges or tunnels at locations where the alignment is more than 8 meters above or below ground surface. This has generated a bridge both for alignment 2 and 3 whereas alignment 1 has no bridges. Quantm automatically calculates the total costs and provides further data of the alignments which can be seen in Table 1.

Table 1. Alignment data extracted from Quantm.

Alignment	Cost (MSEK)	Length (m)	Mass balance (m^3)	Bridge (m)
Alignment 1	227	8442	- 38 458	0
Alignment 2	259	7204	18 878	137
Alignment 3	243	6953	24 550	98

The cut, fill, pavement and bridge wall quantities of each alignment are gathered to model the construction phase. The quantities are divided into section (chainage) intervals of 20 meters for each alignment. DynaRoad software (DynaRoad 2015) is used in this model to generate optimized mass haul plans and to model the construction of each alignment and thereby project-specific output data regarding e.g., hauling distances and mass usage can be generated. The DTM from Quantm is exported to DynaRoad in pdf as a background map. This allows for straightforward modeling of road alignments, borrow pits, disposal areas, crushing plants and access roads between different locations at the construction site. One possible borrow pit, containing large quantities of loose broken rock and can be equipped with a crushing plant, is located near the skiing areas. A possible disposal area with high capacity is located near the golf course. The borrow pit and disposal area need to be connected with access roads along existing dirt roads to each alignment. 0.5 compacted cubic meters (CCM) of subbase and 0.5 CCM of landfill are assumed to be required per meter of access road to stabilize the ground for mass hauling. Broken rock is used both for creating crushed aggregates and as fill material for alignments with a mass deficit. Alignments with a mass surplus dump their excess material at the disposal area. Swelling and shrinking is accounted for with correction factors depending on the states of the materials. A bank cubic meter (BCM) of soil weighs 2 tonnes and maintains its bank volume when compacted in a landfill. A BCM of rock weighs 2.7 tonnes and swells to 1.45 in its compacted state as landfill material. Rock that is crushed weighs 2.25 tonnes per CCM. After the alignments, borrow pits, disposal areas, crushing plants and access roads are modeled, the mass hauls are calculated providing the minimum hauling distances to fulfill each alternative project.

The construction-based energy use consists of material hauling, crushing, and off-road mobile machines. All material hauling is assumed to require an articulated hauler of the model Caterpillar 740. The calculation model used for material hauling is shown in Eq. (1) and is explained in Caterpillar Performance Handbook (Caterpillar Inc. 2012). Its assumed average speed during operation is 24 km/h whereas it's loading and dumping time combined is 3 minutes. Furthermore, the load capacity of the articulated hauler is 36 tonnes and its average fuel use during operation is 17 kg/h. The rock crushing is accounted for with Eq. (2). The crushing plant was assumed to consist of Sandvik crushers and its estimate electricity consumption is 5.54 kWh/t of base course or subbase. The electricity is generated through a diesel driven electric generator with an efficiency of 38%. The energy use of the off-road mobile machines is calculated with Eq. (3). This category includes activities such as excavating, spreading, leveling and compacting materials as well as loading material to crushers and articulated haulers.

$$E_{\mathrm{hauler}} = \sum_i (L_{\mathrm{t}} / L_{\mathrm{c}} \cdot C_{\mathrm{t}} \cdot F_{\mathrm{c}})_i \tag{1}$$

$$E_{\mathrm{crushing}} = \sum_i (E_{\mathrm{c}} \cdot M_{\mathrm{t}})_i \tag{2}$$

$$E_{\mathrm{offroad}} = \sum_i (A \cdot P \cdot L_{\mathrm{f}} \cdot B_{\mathrm{e}})_i \tag{3}$$

Where E = energy use; L_{t} = mass quantity; L_{c} = load capacity of hauler; C_{t} = cycle time; F_{c} = fuel consumption of vehicle; E_{c} = energy use per crushed tonne; M_{t} = total amount of materials to be crushed; A = activity of machine in hours; P = rated power;

L_f = average load factor; B_e = brake-specific fuel consumption; i = all configurations in the project. L_f and B_e are tabular values attained from EPA (2010), Persson and Kindblom (1999), and Lindgren (2007). The work activities and off-road mobile equipment used in the work activities are presented in Table 2.

Table 2. Work activities with their corresponding machines and capacities

Activity	Machine	$L_f \cdot B_e$	P (kW)	Productivity (BCM/h)
Excavate cut and load onto hauler	Excavator	0.102	250	175
Load loose rock to hauler	Excavator	0.102	250	130
Load loose rock to crushing plant	Loader	0.122	260	250
Load crushed aggregates to hauler	Loader	0.122	260	250
Receive and spread fill material	Bulldozer	0.147	175	150
				Speed (m/h)
Compact base course (18 trips)	Roller	0.153	110	500
Level base course (9 trips)	Grader	0.150	159	5000

In the next step the energy use is calculated and the results are transformed to GHG emissions. This transformation is dependent on the types of energy use and their GHG impact consumed or generated. Although electricity was used for crushing of aggregates, the electricity was generated by a diesel driven electric generator, hence that is what is considered in this study. For Diesel the emissions are assumed to be 3.22 kg CO_2 per kg of diesel combusted. The resulting GHG emissions in form of CO_2 for material hauling, crushing and work activities for each alternative are presented in Figure 3. The total CO_2 emissions of alignments 1 through 3 were 1701 tonnes, 1325 tonnes and 1316 respectively. The considerably higher emissions of alignment 1 compared to the other alignments is largely due to it being over 1 km longer than the other alignments. It also required longer access roads due to its distance from the borrow pit and crushing plant location. Alignment 3, which is the shortest alignment by about 250 meters, emits more than Alignment 2 both from hauling and work activities. The main reason for this is longer access roads, hauling distances and higher volumes of cut and fill. GHG emissions from bridge construction are not considered in this study.

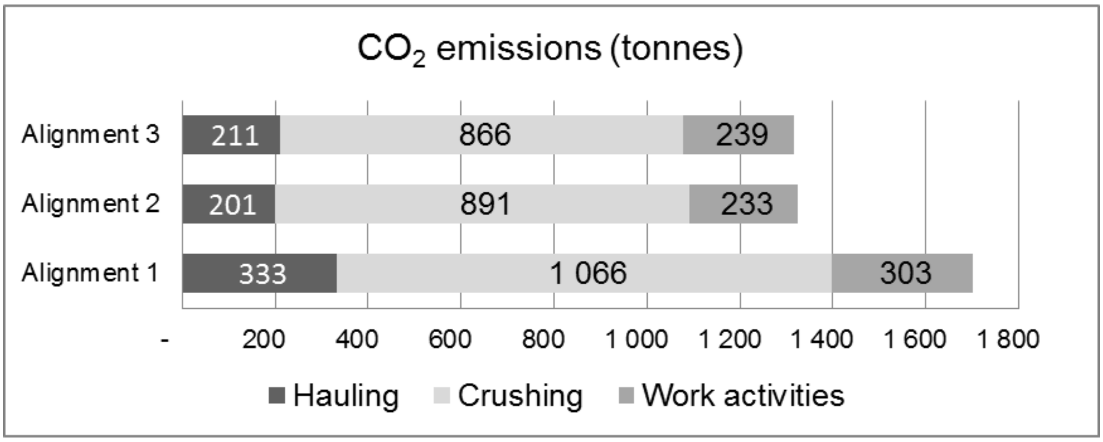

Figure 3. Case study results with CO_2 emissions of each alignment.

CONCLUSION

This exploratory study demonstrated a novel model designed for aiding the assessment of GHG emissions from the construction phase of three different road alignments. If adopted in the planning process this model may support projects in reducing their emissions besides offering additional decision support. The use of Quantm and DynaRoad software facilitated the implementation of the model as they enabled for straightforward generation/creation of alignments and modeling of the construction phase, providing the necessary data to conduct the assessments.

Several limitations exist in this study, all of which pose good topics for more detailed studies. Firstly, while being straightforward to conduct, the demonstration did not consider GHG emissions associated with construction of the bridges. The scale of the bridges required for alignments 2 and 3 would most certainly generate considerable GHG emissions. Methods for assessing bridges, tunnels and other special features in a similar fashion as the rest of the road at early project stages would improve the realism of the assessments. Secondly, this study did not consider the sequence or timing of the construction work. Complex projects may contain constraints that result in longer mass hauls, duration and more complicated work processes, thus often increasing the GHG emissions. By identifying constraints and scheduling the work with approaches such as time-location based scheduling, the progress can be modeled providing more realistic data for assessing the GHG emissions. Lastly, the scope of our study contains several limitations. The study only considered the construction phase whereas other phases of a project life cycle were disregarded. Only CO_2 was considered leaving other GHG unaccounted for. Furthermore, the demonstration was small scale, disregarding several cost areas, features and connection points. As a result, far-reaching conclusions cannot be drawn from this study.

Overall, this study has demonstrated that construction-based GHG emissions can be assessed as early in a project as when road alignments are compared. This offers the possibility to reduce the environmental impact of the road projects which is becoming an increasingly important challenge.

ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support of the Swedish Research Council for Environment, Agricultural Sciences, and Spatial Planning (FORMAS), and Sweden's innovation agency, VINNOVA.

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Paper III

Assessing Embodied Energy and Greenhouse Gas Emissions in Infrastructure Projects

Krantz, J. Larsson, J. Lu, W. Olofsson, T.

Published in Buildings, 5(4), 1156-1170.

https://doi.org/10.3390/buildings5041156

October 2015

Buildings **2015**, *5*, 1156-1170; doi:10.3390/buildings5041156

OPEN ACCESS

buildings

ISSN 2075-5309

www.mdpi.com/journal/buildings/

Article

Assessing Embodied Energy and Greenhouse Gas Emissions in Infrastructure Projects

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Academic Editor: Tanyel Bulbul

Received: 5 August 2015 / Accepted: 13 October 2015 / Published: 16 October 2015

Abstract: Greenhouse gas (GHG) emissions from construction processes are a serious concern globally. Of the several approaches taken to assess emissions, Life Cycle Assessment (LCA) based methods do not just take into account the construction phase, but consider all phases of the life cycle of the construction. However, many current LCA approaches make general assumptions regarding location and effects, which do not do justice to the inherent dynamics of normal construction projects. This study presents a model to assess the embodied energy and associated GHG emissions, which is specifically adapted to address the dynamics of infrastructure construction projects. The use of the model is demonstrated on the superstructure of a prefabricated bridge. The findings indicate that Building Information Models/Modeling (BIM) and Discrete Event Simulation (DES) can be used to efficiently generate project-specific data, which is needed for estimating the embodied energy and associated GHG emissions in construction settings. This study has implications for the advancement of LCA-based methods (as well as project management) as a way of assessing embodied energy and associated GHG emissions related to construction.

Keywords: building information model/modeling (BIM); discrete event simulation (DES); life cycle assessment (LCA); construction energy

1. Introduction

Construction-related energy use and associated emissions of greenhouse gases (GHG) is a major concern globally [1]. Environmental measures are therefore becoming an increasingly important collective indicator for evaluating the performance of construction projects [2]. To reduce GHG emissions in construction processes, there is a need to compare alternatives in the planning stage in order to identify and implement the most favorable one [3,4].

Of the current environmental measures, many focus only on individual phases of the life cycle [5], although several of the life cycle phases of a construction project have substantial energy use and GHG emissions. In buildings, for instance, the embodied energy—meaning the energy used for the necessary activities prior to the operational phase [6]—ranges from a few percent up to about half of the total life cycle energy use, whereas the operational energy use accounts for most of what remains [7]. The embodied energy in infrastructure such as roads is even higher, and constitutes almost all of the total life cycle energy for roads that lack lighting and traffic signals [8].

There are, however, approaches that take life cycle perspectives into consideration, e.g., the Life Cycle Assessment (LCA) [9], Life Cycle Energy Assessment (LCEA) [10] and the Environmental Product Declaration (EPD) [11]. Most Conventional LCA approaches are static, and disregard the dynamic evolution of construction projects [12], resulting in location-independent evaluation and erroneous assumptions of homogenous effects [13].

To adapt the assessments to specific construction settings, Building Information Modeling (BIM) can offer a source for generating rich data such as project-specific material quantities [14]. Discrete Event Simulation (DES) allows for the modeling of uncertainties, for instance in terms of probability distributions and dynamic relations between resources and processes that are inherent to construction projects and can thereby incorporate variation into the schedules generated [15].

This study presents a model that incorporates project-specific data into the assessment of embodied energy use and associated GHG emissions of construction projects. Whereas previous research has used the connection between BIM and DES to assess construction performance in terms of time [16], this study uses BIM and DES to assess energy use and GHG emissions. The proposed model is demonstrated and tested in the construction of a bridge superstructure. The model only evaluates the energy used during the upstream flow of the project, *i.e.*, the embodied energy, and associated GHG emissions as this phase constitutes most of the life cycle energy use in infrastructure projects of this kind.

This study is organized as follows. First, a literature review is presented that highlights the weakness of generality related to conventional LCA-based approaches in construction and suggests the use of BIM and DES to create project-specific data. A model is then proposed that shows how BIM and DES can aid the estimation of embodied energy and associated GHG emissions. This model is then demonstrated on a bridge superstructure to explore its practical usefulness. Next, the discussion section highlights limitations and suggestions for future research. Finally, conclusions are presented and the contribution of the study is summarized.

2. Previous Research

2.1. Life Cycle Assessments on Construction

The energy used in construction and its related processes originates from fossil fuels, renewables, and other sources. Whereas all energy systems cause GHG emissions during their life cycle [17], fossil fuel based systems cause GHG emissions per unit of produced energy in considerably higher quantities than other sources [18]. To meet the threats to the environment from global warming due to GHG emissions, several environmental impact assessment tools have been developed [19]. LCA-based tools are used to quantify the environmental burdens of products or processes from cradle to grave. An LCA is carried out according to a framework defined in the ISO 14040 series [20]. Four primary steps are included in an LCA, namely goal and scope definition, inventory analysis, impact assessment, and interpretation [21]. LCA-based tools such as LCEAs [10] and EPDs [11] are used to assess and communicate environmental impacts. In the construction industry, LCAs and EPDs are commonly divided into specific life cycle phases or stages. However, current research provides not one single definition, but rather a multitude of definitions and labels of these life cycle stages and phases [22]. For instance, in some studies the embodied energy includes not only the energy used until the project completion but also what is called recurrent embodied energy, which occurs during renovation and refurbishment, and demolition energy, which is used for deconstruction and final disposal [23,24].

While creating LCAs has become more elementary with the help of specific software and databases [25], there still remain uncertainties regarding the issue of their overall accuracy [14,26]. Whereas construction projects are undertaken in uncertain environments where resources and activities interact in a complex manner [16]; conventional LCA approaches are static and do not take into consideration these dynamic interactions and uncertainties at the construction site [12]. Instead, many current LCA approaches make general assumptions regarding locations and effects [13].

2.2. Discrete Event Simulation and Building Information Modeling

DES, which was first applied to construction with the introduction of the CYCLic Operations NEtwork (CYCLONE) [27] can specifically take into account the inherent uncertainties and dynamic interactions related to construction, and evaluate the performance of the project from several perspectives [28]. Recent development in the field has expanded DES towards evaluating environmental performance in construction projects. For instance, by optimizing the allocation of resources with DES, the fugitive and exhaust emissions of construction processes can be minimized [29]. Data from static models such as the NONROAD emissions inventory model [30] can be combined with DES to estimate emissions from construction equipment to reflect uncertainty, randomness, and the dynamics of construction [31]. Compared with other existing approaches, DES-based estimating enables the estimation of emissions at a microscopic level using project-specific data [32].

The large amount of data required to build and maintain a simulation model has been identified as a challenge for the utilization of DES to quantify the environmental impacts related to construction [33]. However, by linking databases containing necessary input data to DES, the simulation process can be facilitated. Consequently, BIM—which serves as a repository of life cycle information of buildings—provides a possible data source to parameterize the DES model. Building information models are data-rich parametric digital representations of facilities, from which relevant data, such as material quantities, can be extracted to perform environmental assessments [34]. BIM has successfully been integrated and used by other analytical tools—for instance BIM-assisted material quantification and cost estimates—that have achieved better performance over traditional methods [35]. An extension of BIM has been to enable the generation of construction tasks and activity duration by connecting BIM to a database containing productivity rates [36]. BIM has also been used for thermal simulation and analysis, which has allowed for exploration of the thermal performance in different phases of the life cycle of the building [37]. Operational energy simulation software has successfully been combined with BIM to semi-automate Building Energy Performance (BEP) simulation, which results in faster implementation compared with traditional methods of processing the same data [38]. Lu and Olofsson [16], developed a BIM–DES framework in which BIM provides the product and process information to DES, facilitating the building of the DES model. The DES model evaluates the construction performance in terms of time and provides valuable feedback to the BIM process for decision support.

This study aims to mitigate weaknesses identified with current LCA approaches by incorporating project-specific data, generated by BIM and DES, into a proposed model. Based on previous research [16], this study intends to quantify environmental performance with project-dependent specific evaluation using the proposed model. The system boundary of the evaluation is the embodied energy and associated GHG of construction projects, meaning off-site material production, transportation, and on-site construction.

3. Proposed Model

To facilitate the estimation of embodied energy and GHG emissions in infrastructure construction, a model is proposed which can be seen in Figure 1.

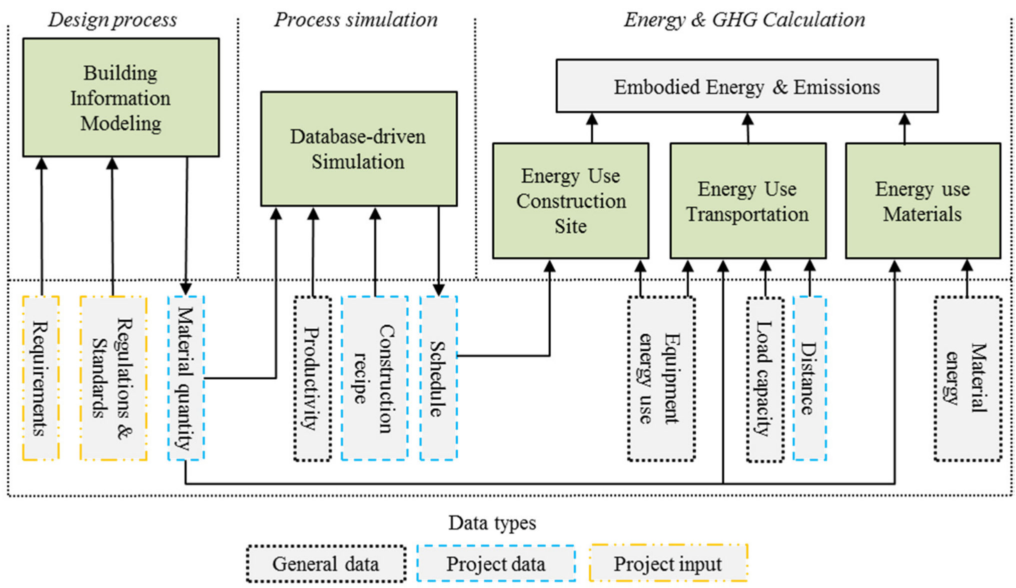

Figure 1. The model for assessing embodied energy associated emissions.

The purpose of the model is to allow for project-specific estimation of embodied energy and GHG emissions using BIM and DES. The top portion of the model details the activities needed to calculate the embodied energy and GHG emissions. The lower part shows the data types that are needed as well as created during the process. General data is information of a general nature that is stored long term in a relational database and can be used in multiple projects. Project data, on the other hand, comes from the specific project or construction, and so changes for each project and is therefore unnecessary to store (long term) in a database. Project inputs are the specific customer requirements, regulations and standards that dictate the course of the construction project.

3.1. Design Process

In the design process, which is the first step in constructing the model, the requirements of the customer, as well as existing regulations and standards dictating the product model, which is represented as a specific BIM. BIM generates the material types and quantities of the product, which are extracted and stored in a relational database for further use. The data is used both in the process simulation and during calculations of energy use and GHG emissions.

3.2. Process Simulation

A database-driven simulation approach similar to that proposed by Lu and Olofsson [16] is used to build the process simulation. A DES model in a database-driven simulation is parameterized by data provided through a set of sources such as data forms, tables, spreadsheets, and relational databases [39]. This type of simulation is particularly suitable for construction projects where knowledge is stored and maintained in a database. The simulation engine is used for the on-site construction processes and can model uncertainties, for instance by including probability distributions to allow for more realistic construction settings.

The previously generated material quantity data, as well as productivity data and construction recipes are used as input data for the process simulation and are stored in a database. The internal process of the simulation starts with each activity requesting the database for the status of preceding activities and the necessary resources (machines, workers, materials) for the activity. Each activity "competes" with other activities in the schedule for available resources in this process. If the requested resource is available it sends a confirmation to the activity. If not, it tells the activity to hold and monitor the system for the status to change.

If all the required resources are available, and if preceding activities are finished, the activity can start. When an activity is completed it is marked as finished together with a time stamp. The system status is changed and all remaining activities are checked to determine whether their prerequisites for starting are fulfilled. This process is repeated until all activities in the schedule are completed and the time data from the simulation is reported.

3.3. Energy and GHG Calculation

In the next step, the energy use and GHG emissions for the materials, transportation, and construction are calculated. Energy and fuel data from each piece of construction equipment and the scheduling data are used for the calculation of construction site energy use. The energy use of transportation is calculated based on vehicle fuel data, load capacity of the vehicle, material quantity, and transportation distance. Finally, the energy use connected to the off-site material manufacturing and extraction is calculated based on the material quantity and the embodied energy of each material type. The energy use of materials may be acquired from the manufacturer of the material or by consulting published EPDs, and includes the energy used from cradle to factory gate, *i.e.*, modules A1 to A3 [40,41].

4. Demonstration

The superstructure of a semi-prefabricated beam bridge was selected to assess the usefulness of the proposed model. To gain greater knowledge and understanding of the product and its corresponding production processes, a construction project was observed in order to gather data. This approach was selected since it is appropriate for obtaining a rich contextual understanding of a system such as a construction site [42]. In the demonstrated scenario, the locations of the suppliers and the construction site are not specified and transportation distances are therefore hypothetical (see Table 1). The bridge has a length of 18 meters and the width is eight meters. The superstructure of the bridge is constructed by both traditional on-site construction methods and the use of prefabricated parts manufactured at a factory. Being a standardized product, the bridge enables an assessment to be made of the effects of scalability of the product and process performance.

Table 1. Project-specific data of distances, material quantities and workers.

Parameters	**Quantity**	**Unit**	
Distance			
Precast supplier	100	km	
Concrete pump	50	km	
Reinforcement	50	km	
Construction site cabin	50	km	
Construction Material			
Beam	7	Qty [a]	
Edge beam	2	Qty [b]	
Plate	48	Qty [c]	
Concrete	35.1	m^3	
Reinforcement	5.4	tonne	
Tasks	**Workers**	**Crane**	**Concrete Pump**
Establish crane	1	–	–
Mount precast components	3	1	–
Fill joints	2	–	–
Reinforcement work	2	1	–
Pump concrete	1	–	1
Concreting	4	–	–
Coverage and water treatment	2	1	–
After treatment	3	–	–

Note: [a] 1 Qty = 5.8 m^3 of concrete and 1.1 tonnes of reinforcement; [b] 1 Qty = 7.0 m^3 of concrete and 1.3 tonnes of reinforcement; [c] 1 Qty = 0.17 m^3 of concrete and 25 kg of reinforcement.

Before the implementation of the proposed model could take place, it was necessary to hold discussions with the product manager (Contractor 1) and inspect support documents, e.g., drawings and schedules, of the bridge. Data of the product and production process were then collected by two weeks of observations of the work conducted at the construction site.

After observing the construction at site, the construction process was mapped. The construction process starts with the mounting of the prefabricated beams—firstly the edge beams and after the internal beams—on top of the on-site constructed substructure (Figure 2). Prefabricated plates are mounted between the beams, and joints are filled to create a left formwork enabling construction of the cover. Finally, the cover is constructed, which consists of reinforcement that is assembled into the formwork and concrete is poured into the formwork to create a continuous superstructure.

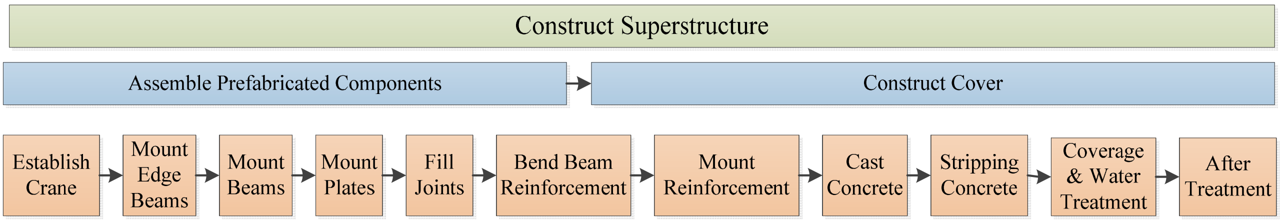

Figure 2. Construction process of the bridge superstructure.

4.1. Model Implementation

The design process is the initial step in implementing the model. A BIM of the bridge is made in Revit [43] that enables the quantity take offs to quantify the materials used in the bridge superstructure. Figure 3 illustrates the BIM model of the bridge, including components in the studied superstructure. The material quantities that are generated from the BIM and used during the demonstration can be seen in Table 1.

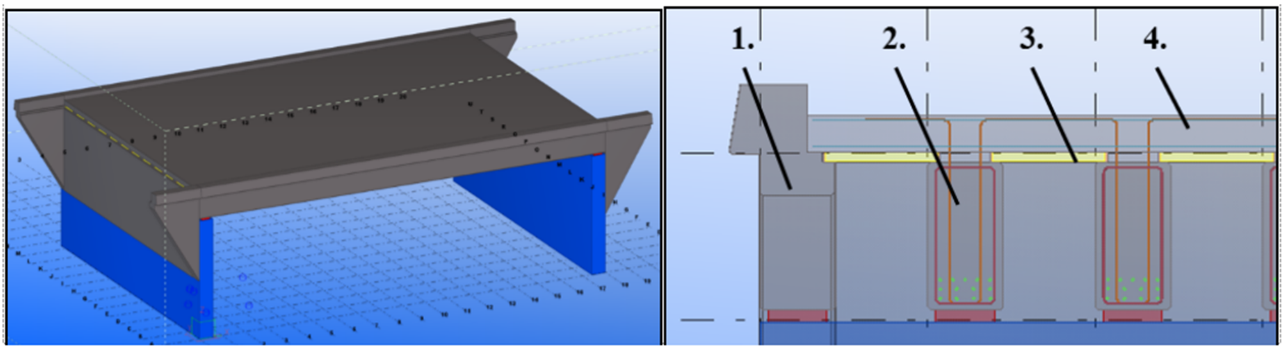

Figure 3. (**Left**) BIM of the bridge; (**Right**) superstructure components 1 = Edge beam, 2 = Beam, 3 = Plate, 4 = Cover.

The next step in implementing the model is the process simulation where a Simio DES engine [44] was used. In order to simulate the construction processes shown in Figure 2, the previously acquired material quantities, productivity data, and detailed construction recipes are needed. The productivity values for each task seen in Table 2 are collected and stored in a relational database that the simulation engine reads. To include uncertainty aspects in the simulation, the productivity values are expressed in terms of triangular probability distributions. While Figure 2 shows the sequence of each task in the construction of the bridge superstructure, some non-sequential dependencies also exist. Stripping concrete is e.g., performed parallel with casting concrete but with a delayed start of 0.5 h, and after treatment cannot start before the concrete has hardened for at least four days. This information was specified in the simulation engine.

Table 2. General data added to the database.

Category Material	Energy Use MJ/FU	GWP CO_2 Equivalent/FU	Functional Unit (FU)	Source
Concrete	1495	188	m^3	[45]
Reinforcement	11 556	785	tonne	[46]
Edge beam	64 473	2599	qty	Supplier 1
Beam	53 781	2168	qty	Supplier 1
Plate	1518	61	qty	Supplier 1
Transportation	**Diesel Use**	**Capacity**		**Source**
Concrete	0.45 L/km	7 m^3		Contractor 2
Reinforcement	0.45 L/km	10 tonnes		Contractor 2
Edge beam	0.52 L/km	1 Qty		Contractor 2
Beam	0.52 L/km	2 Qty		Contractor 2
Plate	0.45 L/km	48 Qty		Contractor 2
Construction site cabin	0.45 L/km	1 Qty		Contractor 2
Construction	**Energy Use**	**Energy Carrier**		**Source**
Mobile crane	26.8 L/h	diesel		[47]
Concrete pump	29.2 L/h	diesel		[48]
Construction site cabin	50.4 MJ/day	electricity		[49]
Task		**Scheduled Mean Productivity**		**Source**
Establishment of crane		2 h/Qty		Contractor 1
Mount edge beam		0.5 h/Qty		Contractor 1
Mount beam		0.36 h/Qty		Contractor 1
Mount plate		0.11 h/Qty		Contractor 1
Fill joint		0.05 h/m		Contractor 1
Bend beam reinforcement		0.4 h/m		Contractor 1
Mount reinforcement		20 h/tonne		Contractor 1
Pour concrete		0.5 h/m^3		Contractor 1
Pump concrete		0.05 h/m^3		Contractor 1
Stripping of concrete		0.1 h/m^2		Contractor 1
Coverage and water treatment		0.8 h/m^2		Contractor 1
After treatment		0.1 h/m^2		Contractor 1

The number of workers and construction equipment in every task, as well as materials used during the construction process, are also specified in the simulation engine. These values are presented in Table 1.

Lastly, the energy use and GHG emissions are assessed. In this step, the database is populated with the remaining general data, which includes equipment energy data, load capacities of transportation vehicles, and material energy data, meaning the cradle to factory gate energy use of all the materials included in the construction project. All of these values are listed in Table 2.

Building materials used during construction of the superstructure, besides the prefabricated components, are concrete and reinforcement. Material production, which consists of raw material extraction, transportation, and manufacturing, has Global Warming Potential (GWP) data based on the materials' EPDs from cradle to factory gate [45,46]. The prefabricated components are manufactured by Supplier 1.

Besides energy use data, each type of component in the superstructure has a GWP datasheet listing the emissions from cradle to factory gate. Supplier 1 has used an EPD tool, developed by the Swedish Cement and Concrete Research Institute, to calculate the energy use and GWP associated with the extraction and manufacturing of input materials, transportation to the factory, and the energy used at the factory for manufacturing the components. However, since no actual EPDs of the components manufactured by Supplier 1 have been published, the data has not been verified by a third party. The energy use of the crane and the concrete pump is calculated based on a model that uses the equipment's rated power, brake-specific fuel consumption, and load factor [50].

The building materials, prefabricated components, and on-site facilities need to be transported to the construction site. For each type of transport, the fuel consumption and load capacity is needed. The load capacity is described for each functional unit of the particular goods transported. The diesel use data is based on average values for trucks fully loaded for half of the total distance and unloaded for the other half. The on-site construction process requires a mobile crane and a concrete pump. The workers need two construction site cabins, one with a kitchen and one with shower and dressing room facilities. This assertion is based on discussions with the site manager and observations at site. Standardized productivity values are gathered through observations at the construction site and later validated by the site manager. The productivity of each task is represented with a triangular distribution with each extreme value being 20% higher and lower than the scheduled mean productivity. As all general data is gathered and populated into the relational database, the project-specific data values are used to interrogate the database in order to get the results calculated.

4.2. Results

With the given parameters in this demonstration, the energy use and associated CO_2 equivalent emissions are calculated and divided into three categories, namely *material production*, *transportation* and *construction*. Furthermore, the results from *construction* are divided into the mean, maximum and minimum values, which are a result from the process simulation. The results are presented in Figure 4.

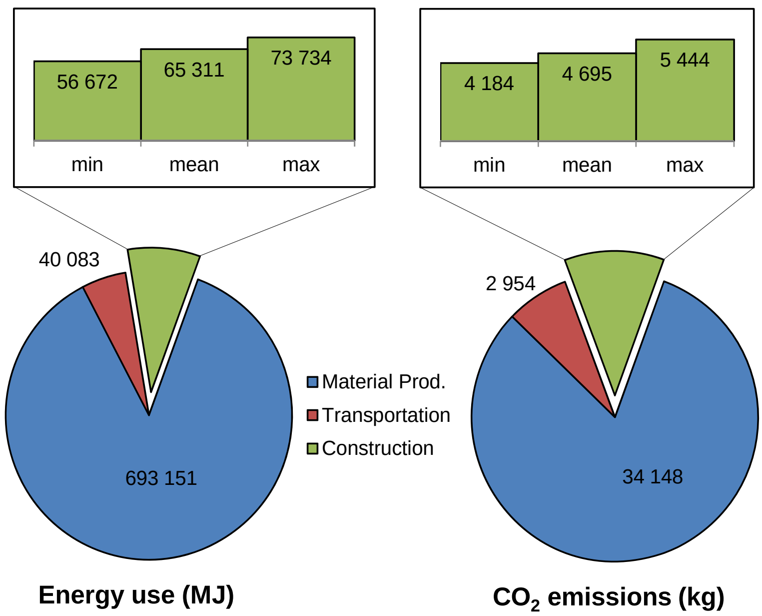

Figure 4. The energy use and CO_2 equivalent emissions of each category.

The energy used for material production is considerably higher than for transportation and construction. Furthermore, the energy use in each category roughly corresponds to the CO_2 equivalent emissions caused. Although the energy use is simply expressed in megajoules (MJ), there are several energy carriers used in the project, both renewable and non-renewable based on the information in the material EPDs.

5. Discussion

If nothing else, the proposed model offers a possibility for mitigating limitations that exist in many of the current LCA-based methods used in construction [12,26] by being adapted for usage in construction projects. The model incorporates both general data and project-specific data into the assessment of embodied energy use and associated GHG emissions of a construction project. BIM is used for efficient generation of input data, such as bill of quantities of components, and material used in the construction process. DES is used to model the on-site construction processes and to generate project-specific schedules. For instance, by including probability distributions for work productivity, material use, and deliveries, on and off-site uncertainties can be addressed [16]. Relational databases are used in several steps during the model implementation. First of all there is short-term storage of project data used in the database-driven simulation process, and secondly, there is the long-term storage of both explicit and experience-based knowledge of product and process data. The proposed process facilitates reuse of the information in multiple projects, as well as comparing alternatives within a project in order to be able to identify and select the most suitable options in the construction stage [3,4]. The case study shows that energy and GHG assessments can be made project-specific, whereas generally accepted LCA approaches often disregard the dynamics of on-site construction [12].

Previous construction management literature has mostly assessed the construction process from the perspectives of time, cost, and quality [51]. The model proposed here contributes by adding an environmental indicator for measuring construction success [2]. Project-specific LCAs, incorporating both project-specific data and general data into the assessment, could allow contractors to develop more environmentally friendly products and processes. As a complement to existing approaches that use time as a factor for assessing project performance [16], this approach allows clients to also consider proposals with respect to energy use and GHG emissions.

In this study, several limitations have been recognized. All may be viewed as possible subjects for future research. Firstly, the model only considers the embodied energy from cradle to gate, *i.e.*, material production, transportation, and on-site construction. While this can be justified in many infrastructure projects, as other life cycle phases have comparatively low energy use and emissions, it cannot be assumed in all cases. Further, if the scope of the model is expanded beyond infrastructure to include e.g., buildings, there are particularly good reasons for including more phases—or indeed the whole life cycle—of these construction projects.

Secondly, the data-gathering process and the generation of input data is a relatively complex and time-consuming process, which can limit the application of this type of model in traditional construction. The standardized product used in the demonstration, however, allows for the reuse of data in multiple projects as products and processes are similar to a large extent. The collected information and input data can be stored in a relational database, which is easily accessible to new projects. The proposed model is therefore more suited for products and processes that are composed of more standardized components.

Furthermore, standardized products and processes offer the possibility to automatize data generation, for instance with sensors on equipment, to provide reference data for future projects. This type of approach can also support a continuous improvement process as knowledge and experience from previous projects can be used to improve future projects. While relational databases are helpful in simplifying procedures by allowing a more automated process, they do not solve all the attendant problems. The data generated using BIM and DES is often project-specific, and cannot be reused in most cases. Consequently, the process becomes time consuming. Part of the problem with data gathering comes from the fact that good data is not readily available. EPDs are still uncommon and quite often they do not exist for all materials and components from a specific supplier, that are used in the construction industry. However, EPDs from other suppliers that might be based in other countries could be used as substitutes, albeit with the effect that these do not completely reflect actual conditions.

Thirdly, the calculation of energy use associated with transportation of materials and equipment needs to consider how many functional units of a given material can be transported on a specific transportation vehicle. While this information could partly be acquired from the material manufacturers directly, it is not specified in EPDs, a situation which then might require some assumptions. A systematization that connects a functional unit of the EPD, or similar material data, with certain options of transportation vehicles would simplify the data gathering further. The main challenge lies in the fact that load capacities of transportation vehicles are often expressed in volume or mass, but materials and products can have more complex units such as areas, length, or number of the specific material or product. The geometric shape of the material and product further complicates how many functional units can fit in a specific transportation vehicle. In addition, the fuel use of the transportation vehicles is dependent on how much material is loaded onto the vehicle, specifically in terms of mass, which needs to be highlighted. By categorizing or classifying material types, functional units and transportation vehicles and defining rules for how these interact, the transportation of materials can be modeled with higher accuracy. This could have implications not only in the field presented in this study, but also in fields dealing with transportation logistics.

Finally, the small-scale and exploratory nature of this study means that some important aspects have been left out. Since the findings have not been validated or compared to those found in related studies, the results of this study must be used with caution. Furthermore, no investigations into appropriate system boundaries have been carried out. However, the findings in this study indicate that the proposed model has the ability to function as an application for producing more project-specific assessments of the increasingly important LCA, especially during the design and planning phases of a project.

6. Conclusions

This study demonstrates, in a small-scale study, a model for assessing the embodied energy and associated GHG emissions in infrastructure construction projects. The model contributes to making these assessments more project-specific by including BIM and DES to generate the necessary input data of material quantities, realistic schedules of work activities, and transportation associated with the construction process. By collecting and storing data in a relational database for future use, the data-gathering process can be simplified. The proposed model is particularly useful in settings where new projects are similar to previous ones, or in projects that use standardized products.

The findings presented in this study may have implications for the advancement of LCAs in general, but particularly within construction processes, as it offers a new approach that can make more project-specific assessments. As environmental concerns are being adopted as an important project evaluation criterion, this study could also have implications within construction management. Ideally, this type of model could provide project managers with a tool to assess construction designs, schedules and supply chains from an environmental perspective. However, further research is needed to integrate the environmental assessment of the project with other important criteria for project success such as time, cost and quality.

Overall, this study demonstrates that there is the potential to generate environmental input data in the design and planning stage of a construction project and therefore make the assessments of embodied energy and associated GHG emissions more project-specific. This is beneficial for the development of more environmentally-friendly products and processes in the project-based construction industry.

Acknowledgments

The authors would gratefully like to acknowledge the Development Fund of the Swedish Construction Industry (SBUF), the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS) and the Swedish Transportation Administration fund for research and innovation (BBT) for their financial support. Finally, it is our pleasure to thank Guest Editor Tanyel Bulbul for the invitation and support, the reviewers for their exacting suggestions, and, of course, the team at MDPI for facilitating this Special Issue "BIM in Building Lifecycle" so professionally.

Author Contributions

The different knowledge and experience of each author has equally contributed to the development and final version of the article. As the main author, Jan Krantz wrote and compiled most of this paper. The proposed model and demonstration were primarily formed and written by Johan Larsson and Jan Krantz. Weizhuo Lu performed the simulation and wrote the section about DES and BIM. Thomas Olofsson supervised and reviewed the work throughout the study. Finally, all authors were involved in all steps of this study.

Conflicts of Interest

The authors declare no conflict of interest.

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Paper IV

‘Eco-Hauling’ principles to reduce carbon emissions and the costs of earthmoving - A case study

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Published in Journal of Cleaner Production, 208, 479-489.

https://doi.org/10.1016/j.jclepro.2018.10.113

January 2019

Journal of Cleaner Production 208 (2019) 479–489

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

‘Eco-Hauling’ principles to reduce carbon emissions and the costs of earthmoving - A case study

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ARTICLE INFO

Article history:
Received 8 June 2018
Received in revised form
6 September 2018
Accepted 10 October 2018
Available online 11 October 2018

Keywords:
Earthworks
Eco-driving
Mass-hauling
Off-road dump truck
Discrete-event simulation
Articulated hauler

ABSTRACT

Mitigating emissions of carbon dioxide and other greenhouse gases is critical if we are to meet the increasing threats posed by global warming. Previous studies have shown conclusively that a substantial part of all carbon dioxide emissions comes from transportation, and that Eco-Driving principles based upon strategic, tactical, and operational decisions have the potential to reduce these emissions. However, these well-established principles have been neglected within the construction industry despite the large number of transport-related activities that attend most construction projects. This paper therefore aims to increase awareness and understanding within the industry of the potential reductions of both carbon dioxide emissions and the costs of earthmoving activities that could be achieved through the use of Eco-Driving principles. A new concept labeled ‘Eco-Hauling’, which extends the Eco-Driving concept to earthmoving, is proposed. A case study of a road project has been conducted and used to demonstrate the new concept. Discrete-event simulation is used to support the data analysis as it enables modeling of the dynamic interactions between equipment and activities of multiple different construction scenarios. The presented findings show that a combination of decisions taken from the proposed Eco-Hauling concept can enable earthmoving contractors to substantially reduce carbon dioxide emissions and costs while maintaining productivity. This study has implications for the general advancement of Eco-Driving theory, as well as for project management as it sets out a viable approach for reducing greenhouse gas emissions in construction projects.

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1. Introduction

To meet the threats posed by global warming it is critical that resolute efforts to mitigate emissions of CO_2 and other greenhouse gases (GHGs) are made (Intergovernmental Panel on Climate Change, 2015). Transportation, which accounts for nearly a quarter of the CO_2 emissions globally (International Energy Agency, 2017) and about 20% of Swedish CO_2 emissions (SCB, 2016), is of prime importance in mitigation efforts. However, expensive measures such as free public transport or increased service frequency are often costly per unit of CO_2 emissions mitigated (International Energy Agency, 2005). On the other hand, low-cost approaches such as campaigns for Eco-Driving based on strategic, tactical, and operational decisions (Sivak and Schoettle, 2012), have proven to be effective (Rutty et al., 2013). Several studies have shown that drivers adopting some form of Eco-Driving can reduce their fuel use and associated CO_2 emissions; these reductions range from a few percent to as much as 40% depending on traffic intensity and other factors (Alam and McNabola, 2014).

Construction of transport infrastructure is also responsible for considerable CO_2 emissions, a fact which has motivated the Swedish Transport Administration (STA) to set the goal of having net zero CO_2 emissions from their projects by 2050 (Trafikverket, 2017). In light of this, contractors need to consider CO_2 emissions as an important performance yardstick alongside the traditionally important indicators of costs, duration, and quality (Alzahrani and Emsley, 2013). Transportation often forms a considerable part of transport infrastructure construction projects, due to extensive hauling of soil and rock materials, i.e., earthmoving (Krantz et al., 2017). Earthmoving operates within a set of similar parameters to that which Eco-Driving attempts to modify (Abbasian-Hosseini et al., 2016), and both drivers and earthmoving contractors share

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https://doi.org/10.1016/j.jclepro.2018.10.113
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the desire to reduce fuel use and associated costs and CO_2 emissions. Yet despite these similarities and the potential for novel solutions and innovation by borrowing concepts between research fields (Franke et al., 2014), no studies have combined Eco-Driving with earthmoving.

The aim of this paper is therefore to study the potential for reducing costs and CO_2 emissions of earthmoving through the use of Eco-Driving principles. We extend the Eco-Driving concept, with its strategic, tactical, and operational decision levels as proposed by Sivak and Schoettle (2012), to earthmoving, and label this new concept *Eco-Hauling*. A case study of an earthmoving task in a road project was conducted using a number of decisions from the Eco-Hauling concept to demonstrate the possibilities of CO_2 and cost reductions. To enable the study of a whole earthmoving task conducted with a large number of different Eco-Hauling decisions and parameters, discrete-event simulation (DES) is used as it enables modeling of dynamic interactions between equipment and activities in a multitude of scenarios (Larsson et al., 2016; Lu and Olofsson, 2014).

The rest of this paper is structured as follows. Literature on Eco-Driving and the characteristics of earthworks are reviewed to introduce its main concepts. This literature is used as a basis for the proposed Eco-Hauling concept in earthmoving. Decisions from the proposed concept are demonstrated in a case study of an earthmoving task where a number of scenarios are considered. Based on the case study results, the contributions and limitations of this study are discussed and conclusions are drawn.

2. Related research

2.1. Earthworks planning and carbon emissions assessments

The term earthworks commonly refers to activities where natural materials are manipulated: excavation, hauling, dumping, crushing, and compacting are all examples of earthworks (Ricketts et al., 2003). Earthmoving deals particularly with the hauling, loading, and dumping of materials, and often constitutes a major part of most transport infrastructure projects due to the large material quantities to be moved within long linear project sites (Mohamed and Osama, 2003). Efficient planning and execution of such activities may therefore have considerable benefits for the overall project success, lowering costs and shortening project duration (Askew et al., 2002). Approaches for improving earthmoving activities range from simple rules of thumb to more sophisticated construction planning and control systems. A common rule of thumb is *cut to fill*, which entails making use of materials onsite as much as possible, thus avoiding costly hauls between the site and external disposal areas or borrow pits (Mawdesley et al., 2002). Some commercial planning software has implemented linear programming-based mass-haul optimization for aiding planners and contractors in minimizing hauling distances (Shah and Dawood, 2011). Location-based scheduling approaches, such as line-of-balance, are particularly useful for linear transport infrastructure projects, as they can represent road line locations in one dimension, and time in another. Based on such approaches, Shah (2014) developed a model that enables identification of time-location congestion, allocation of resources, and monitoring of progress on a weekly basis.

Earthworks in transport infrastructure projects often generate considerable carbon emissions from the heavy duty diesel (HDD) equipment used (Hajji and Lewis, 2013). In a study of 24 road projects, Kim et al. (2012) concluded that earthworks generate more than 90% of all equipment GHG emissions onsite. Thus, more efficient use of equipment, such as increasing equipment utilization rates, is one approach to reducing emissions (Jassim et al., 2018). Reducing the idle time of the equipment is another potential approach to reduce GHG emissions. However, if that entails turning off the engine while waiting in a queue, the apparent emissions reduction could be completely negated by a reduction of productivity (Abbasian-Hosseini et al., 2016). Other studies have a wider scope and include, for instance, carbon sequestration lost or gained through deforestation and reforestation caused by the transport infrastructure project (Melanta et al., 2013) or the full life-cycle (Fernández-Sánchez et al., 2015). Hanson and Noland (2015) included the carbon emissions that road construction activities generated through disruption of existing traffic and found that a reduction of such traffic disruption could significantly reduce the overall project carbon emissions.

2.2. Eco-Driving

Adopting a more anticipatory and refined driving style, often referred to as Eco-Driving, has long been understood to enable immediate reductions of fuel use and CO_2 emissions with limited effort (Barkenbus, 2010). While originally encompassing driving styles, Eco-Driving in its broadest sense is now viewed as all of those *strategic*, *tactical*, and *operational* decisions that drivers make to improve their fuel economy (Alam and McNabola, 2014; Sivak and Schoettle, 2012).

Strategic Eco-Driving decisions are those that are made on a long-term basis, and include such things as installing eco-routing navigation systems, selecting an energy-optimal vehicle, and maintaining the vehicle regularly (Sivak and Schoettle, 2012). Indeed, vehicle choice plays a considerable role in determining the energy use per distance covered. In comparison to the worst performing midsize car among those of model year 2018, the best performing hybrid car uses a 75% less miles per gallon gasoline equivalent (MPG-e), whereas the best all-electric car uses a 90% less MPG-e (EPA, 2018a). By keeping the engine tuned, the tires properly inflated, and using the recommended grade motor oil, fuel use can be reduced by an average of 4%, 0.6%, and 1–2% respectively (EPA, 2018b).

Tactical decisions of Eco-Driving are those that can be made at a trip level, and include, among other things, using optimal routes from a fuel use perspective (eco-routes) and limiting the vehicle load (Alam and McNabola, 2014). The shortest route is not always a viable eco-route, even when ignoring road grade and congestion. For instance, in a study of a capacitated vehicle routing problem (VRP) of a delivery vehicle with maximum load capacity and a number of different delivery addresses, it was found that the optimal route with respect to the vehicle load at different instances had 5% lower fuel use than the shortest route (Xiao et al., 2012). Eco-routing for personal vehicles in a realistic traffic environment has the potential for reducing fuel use and associated CO_2 emissions by roughly 5–10% (De Nunzio et al., 2017; Ericsson et al., 2006; Sun and Liu, 2015; Zeng et al., 2016), with extremes of near 25% (Ahn and Rakha, 2008). However, identifying eco-routes can be a major challenge for drivers unless some sort of eco-routing navigation system is used (Alam and McNabola, 2014); those systems that include real-time traffic information are especially useful (Boriboonsomsin et al., 2012).

The *operational* decision level of Eco-Driving is concerned with driving styles, and includes using high gears (low engine RPM), maintaining a steady speed, decelerating smoothly (Beusen et al., 2009), and using fuel-optimal speeds, and minimal throttle (Saboohi and Farzaneh, 2009). This necessitates certain vehicle operator skills, and the anticipation of traffic flows and signals to minimize excessive idling and sudden starts or stops (Barkenbus, 2010). The reported reductions of CO_2 emissions and fuel use of drivers implementing some form of operational Eco-Driving have been near the 5–15% range (Barla et al., 2017; Jamson et al., 2015; Schall and Mohnen, 2017; Zarkadoula et al., 2007), with extremes nearing the 30% mark (Sivak and Schoettle, 2012).

Although a large number of studies have demonstrated the substantial benefits of Eco-Driving, the effects on the transport system as a whole have been more ambiguous. For instance, the effects of operational Eco-Driving decisions have been reported to cause both system-wide increases (Qian and Chung, 2011; Wang et al., 2012) and reductions (Xia et al., 2013) of fuel use and CO_2 emissions, depending on traffic intensity, Eco-Driving penetration among drivers, and the characteristics of the particular traffic system under study. Despite the large number of studies on Eco-Driving, none have yet addressed it as a possible approach for reducing CO_2 emissions and costs in other transport-intensive activities, such as earthmoving in transport infrastructure projects. Our paper seeks to fill this gap in the literature.

3. Proposed concept

In this study we propose an extension of the three decision levels of Eco-Driving, i.e., the *strategic*, *tactical*, and *operational* (Alam and McNabola, 2014; Sivak and Schoettle, 2012), into earthmoving. Details of this concept, which we label *Eco-Hauling*, can be seen in Table 1. Those we suggest are intended to implement Eco-Hauling are earthmoving contractors and their equipment operators. To be useful for earthmoving contractors, the Eco-Hauling concept tries to identify CO_2 and cost reduction potentials. Productivity indicators such as task or project duration are additional key aspects which cannot be ignored if earthmoving contractors are to remain viable. However, costs and CO_2 emissions may be reduced with productivity levels maintained or even increased (Ng et al., 2016). An important *strategic* decision for earthmoving contractors is therefore to acquire an optimal equipment fleet based on fuel use and productivity (Barati and Shen, 2017).

On the *tactical* level, equipment from the fleet is assigned to different tasks in the project according to optimal equipment configurations on the basis of fuel use and productivity. Optimization of the earthmoving plan seeks to minimize the hauling distances within the project, and can be conducted mathematically using linear programming-based planning software (Shah and Dawood, 2011). On a task level it is also important to consider which hauling distances are optimal for the available equipment assigned for that task. By further determining a base speed of hauling vehicles, productivity and fuel use tradeoff can be optimized.

Eco-Hauling on the *operational* level comprises those decisions that equipment operators make; they are similar to those *operational* decisions that drivers make in regular Eco-Driving. An important distinction is, however, that the decisions which equipment operators make should consider productivity, cost, fuel use, and CO_2 emissions of the earthmoving task as a whole, and not just of the individual equipment.

4. Methodology

A case study approach was used to gather data and to investigate the potential for reducing CO_2 emissions of earthmoving in road projects using the proposed Eco-Hauling concept. Case studies have previously been used to study earthmoving and earthworks activities; these have been conducted using DES and other simulation approaches (Ming, 2003; Mohamed and Osama, 2003; Rekapalli and Martinez, 2011; Vahdatikhaki and Hammad, 2014). The case study approach was chosen here since it enabled us to look at the potential of Eco-Hauling within a real-life project context (Yin, 2013). The procedure of the conducted research is shown in Fig. 1.

4.1. Project selection

A conventional road project in Sweden, seen in Fig. 2, was selected for the case study. The project has a total road length of 17 km and is scheduled to be constructed from 2017 to 2019. The road project contains traffic interchanges, bridges, and several smaller passages for nearby land owners, wildlife, etc. This project was particularly suitable for studying the potential of Eco-Hauling as it was planned and scheduled using a linear programming-based planning software called DynaRoad. This provided an earthmoving plan containing hauling distances, quantities, and work order, and enabled us to form an Alternative earthmoving plan to study.

An earthmoving task was selected as a sample from the case project as it was deemed sufficiently separate from other activities to be conveniently studied but realistic enough with regard to its complexity. The earthmoving task, which contains one cut area, one fill area, and a bridge construction area in between, can be seen schematically in Fig. 3, and its location in the project can be seen in Fig. 2.

The work starts within the 500-m-long cut area at the current cut location as determined by the earthmoving plan. An excavator excavates and loads earth onto articulated haulers. Once an

Table 1
Characteristics and possible decisions to be made within each decision level of Eco-Driving and Eco-Hauling.

Eco-Driving	Eco-Hauling
General characteristics - For individual drivers. - Reduces costs, fuel use, and CO_2 emissions at vehicle level.	General characteristics - For earthmoving contractors and equipment operators. - Reduces costs, fuel use, and CO_2 emissions at fleet level. - Maintains or increases productivity.
Strategic (long-term decision level) - Acquire energy-optimal vehicle. - Regular vehicle maintenance. - Install energy-optimal navigation system.	*Strategic* (company level) - Acquire fuel/productivity-optimal equipment fleet. - Regular equipment maintenance.
Tactical (trip level) - Optimal route choice (eco-routing). - Eliminate excess load from the vehicle.	*Tactical* (project and task level) - Optimize equipment assignments. - Optimize earthmoving (mass-haul) plan. - Determine optimal speed for equipment in earthmoving task. - Select fuel types.
Operational (driver behavior level) - Use fuel-optimal speed. - Anticipate upcoming obstacles to maintain even speeds. - Use high gears while cruising. - Minimize throttle.	*Operational* (equipment operator behavior level) - Anticipate upcoming obstacles to maintain even speeds. - Use decided optimal speed.

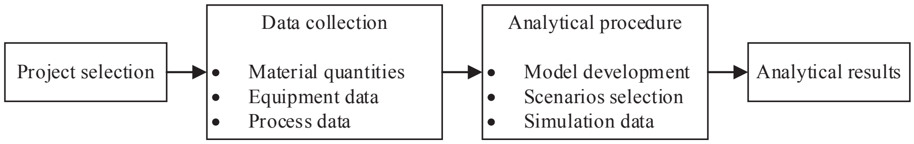

Fig. 1. Research framework.

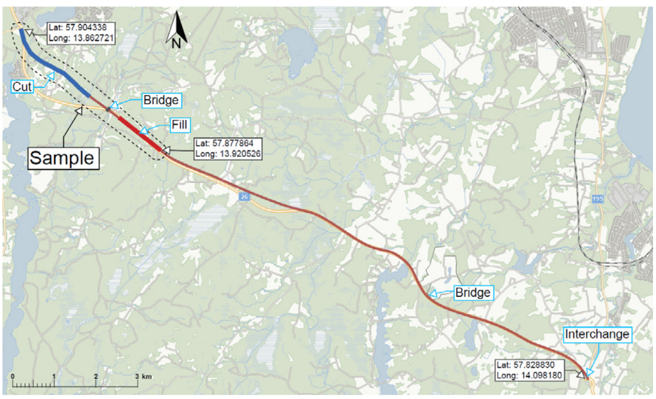

Fig. 2. The road project and the selected sample of the case study.

articulated hauler is loaded it advances towards the fill area along the road line being constructed. The hauler will enter an active bridge construction area where the work activities will sometimes cause a stoppage for haulers trying to pass, in which case the haulers will queue until they can continue advancing to the fill area. The hauler will unload its earth at the current fill location within the 1802-m-long fill area, according to the earthmoving plan. After unloading the material at the fill, the hauler will return through the bridge construction area where it again is subject to the aforementioned possible stoppages. Once it returns to the cut, the articulated hauler will queue if another hauler is being loaded by the excavator. The cut and fill locations move within the cut and fill areas according to the earthmoving plan as the task progresses. The earthmoving loop is continued until the earthmoving task is finished.

4.2. Data collection

The bulk of data collected in this case study consisted of documentation related to the project (e.g., notes of material quantities, equipment, and scheduling information), and interviews with the contractor to ensure that the details of the project were correctly understood. Complementary data about material properties, fuel use of the equipment, and the construction process was gathered from scientific literature (Krantz et al., 2014, 2017; Rylander et al., 2014; Zhang et al., 2014), and also from the equipment manufacturers' documentation, and estimations and assumptions made by the contractor.

4.2.1. Material quantities

A bill of quantities (BOQ) of the full project was acquired from the contractors during the construction phase. The BOQ presents the type and quantity of material that needs to be added (filled) or excavated (cut) per distance (section) interval in the road project. The quantities and properties of the materials to be excavated in the selected earthmoving task can be seen in Table 2. The quantity is stated in bank cubic meters (BCM), and describes the material in its natural state prior to excavation. Data of the material composition and estimated density was gathered from the contractor. The estimated swelling of material excavated and loaded onto a truck was based on the swelling factor for earth material determined by Krantz et al. (2014). In its loosened state the material is expressed in loosened cubic meters (LCM).

4.2.2. Equipment data

A list of available equipment in the project was collected from the contractor. For the earthmoving task a Caterpillar 336DL excavator was selected as loading unit and a number of Volvo A25F articulated haulers were selected as hauling vehicles. The relevant equipment specifications and data used in this study are presented in Table 3. Data of load capacities for the excavator bucket and the

Table 2
Material quantities and properties of the earthworks task.

Property	Quantity	Unit
Material quantity	6646	(m^3, BCM)
Material composition	Earth (silty and gravelly sand)	
Density	2.0	(tonnes/BCM)
Swelling	1.2	(BCM to LCM)

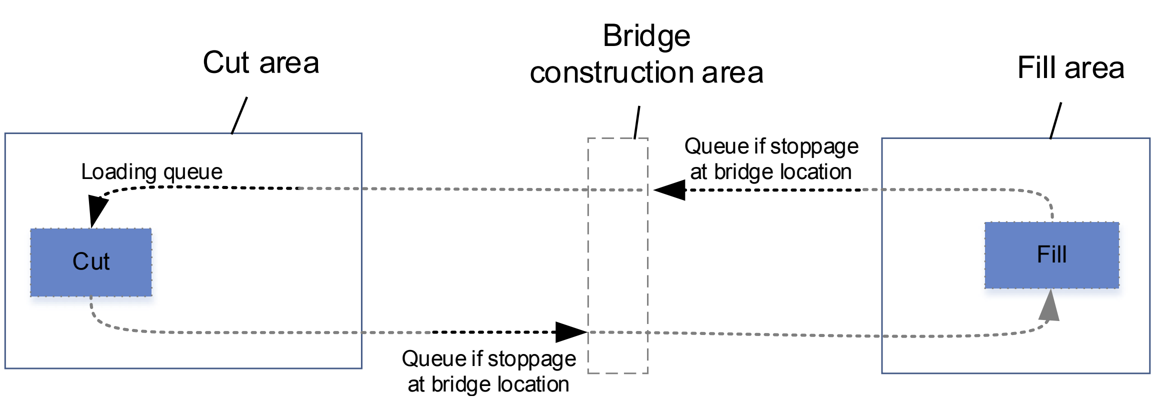

Fig. 3. Schematic illustration of the earthmoving task.

Table 3
Specifications of equipment in the earthmoving task.

Type	Load capacity	Non-idle fuel use	Idle fuel use	Fuel use of increased speed by:	
				1 km/h	5 km/h
Volvo A25F articulated hauler	10 LCM				
- Loaded		0.5241 l/km (at 28 km/h)	4.6 l/h	0.0041 l	0.0205 l
- Empty		0.4193 l/km (at 28 km/h)	4.6 l/h	0.0033 l	0.0164 l
Cat 336DL excavator	2.0 LCM	32 l/h	6.6 l/h	–	

articulated haulers was gathered from the specification documents produced by the equipment manufacturers (Caterpillar, 2009; Volvo, 2015). The load capacity of the articulated hauler is a rounded number and is based on a fill factor of 0.9, i.e., the proportion of the maximum load capacity filled at an average (Zhang et al., 2014).

The average fuel use during non-idle activity was based on estimates from the contractors, and for the Volvo A25F it was 18 l/h. However, to account for the difference in fuel use between a loaded and an empty articulated hauler field data from Rylander et al. (2014) was used. The articulated haulers were assumed to be full half the time and empty the other half of the time. Data of CO_2 emissions of idling and non-idling was based on data from Abbasian-Hosseini et al. (2016), and was used to determine the fuel use of idling since it is expected that the ratio between idling and non-idling is the same whether it concerns fuel use or CO_2 emissions. Finally, the fuel use related to increasing the speed was based on field data collected by Rylander et al. (2014), who found that each stop per km of driving on a quarry track added about 10% to the fuel use just to bring the vehicle speed back to normal. Although we estimate that the terrain conditions during earthworks in a road project are worse than the normal conditions in a quarry environment, we do not expect that the relative effect on fuel use per stop and subsequent speed increase will significantly change.

To account for the fuel use at different speeds, a speed curve was created based on field measurements from Rylander et al. (2014) of a Volvo A40FS articulated hauler. These field measurements contained five data points in a graph with a lap time for a specified lap and relative fuel use per lap where the fastest lap, with an average speed of nearly 37 km/h, was used as reference, i.e., the 100% mark. This data enabled a regression analysis where a quadratic relationship between speed and relative fuel use was assumed due to the shape of the data. The resulting relationship is seen in equation (1) and its R^2 is seen in (2):

$$Y = 0.0017X^2 - 0.0866X + 1.825 \quad (1)$$

$$R^2 = 0.9402 \quad (2)$$

where Y = relative fuel use and X = speed of articulated hauler. To translate the fuel use from relative into absolute, a base speed during normal operation was assumed to be 28 km/h. The fuel consumption of the Volvo A25F of 18 l/h (20 l/h when full and 16 l/h when empty) equals 0.524 when fully loaded and 0.419 when empty. Other speeds have a fuel consumption based on the relationship provided by equation (1).

The fuel use data in Table 3 is used for the articulated hauler in different activities. The non-idle fuel level is used when driving. Depending on the target base speed, going from a standstill to that base speed uses a multiple of the fuel use of accelerating to a 1 km/h higher speed. Time spent in queues is subject to idle fuel use and an additional fuel use for advancing in the queue. Each step that an articulated hauler advances in the queue is estimated to equal 20 m reaching 5 km/h.

4.2.3. Process data

Data related to the earthmoving process can be seen in Table 4. The time required for the excavator to load one articulated hauler with material, i.e., the loading time, depends on, among other things, the load capacities, fill factors, and the productivity of the excavator. Based on random distributions, Zhang et al. (2014) modeled the loading time for their equipment configuration at between 2.24 and 3.28 min. Krantz et al. (2015) used 2.5 min as loading time and 0.5 min as unloading time for an excavator–hauler configuration. We estimate that these loading and unloading times are similar to what we can expect from the excavator and articulated haulers in our case. To account for inherent variations, we use random distributions for the loading and unloading time. Furthermore, the construction processes of the bridge construction area are estimated to cause blockages for articulated haulers 20% of the time, with a duration expressed as a triangular distribution.

4.3. Analytical procedure

To study Eco-Hauling in a realistic manner, consideration must be given to the dynamic conditions under which the earthmoving task is conducted. The articulated haulers interact with each other, the bridge construction area, and the excavator which loads them, while the hauling distances change as the work progresses. A DES-model was established to capture these dynamic conditions and task interactions in different scenarios. The DES-model enables the simulation of the independent variables, i.e., the different Eco-Hauling decisions studied in the scenarios, in terms of the dependent variables constituted by CO_2 emissions and costs. An initial scenario and a total of 1536 Eco-Hauling scenarios have been studied in this research.

4.3.1. Model development

In the studied case, one excavator and a fleet of articulated haulers are arranged working in a group to execute the earthmoving task. The Eco-Hauling based earthmoving process is defined as Fig. 4. The excavator will cut soil at the present location until the hauler arrives at the cut location. The excavator then loads the hauler according to the sequence of arrival and moves to the next cut location when the task at the present location has been finished. After being loaded, the hauler can move toward the fill location by passing the bridge construction area. For the Eco-Hauling decision of anticipating obstacles, the hauler passes a checkpoint 500 m before the bridge construction area, where the operator will check its status and determine whether the passage is blocked. If passage across the bridge construction area is blocked, the operator will adjust the hauler speed immediately when passing the checkpoint; otherwise the hauler will maintain its speed. The hauler has to wait at the bridge construction area if the

Table 4
DES-model common parameters for the earthmoving task.

Parameter	Value
Probability of blockage at bridge construction area	20%
Time of blockage at bridge construction area	Triangular (2, 2.5, 3) minutes
Loading time per LCM	Triangular (0.22, 0.25, 0.28) minutes
Unloading time per LCM	Triangular (0.045, 0.05, 0.055) minutes
Distance from bridge blockage or loading queue where hauler operator may adjust speed	500 m

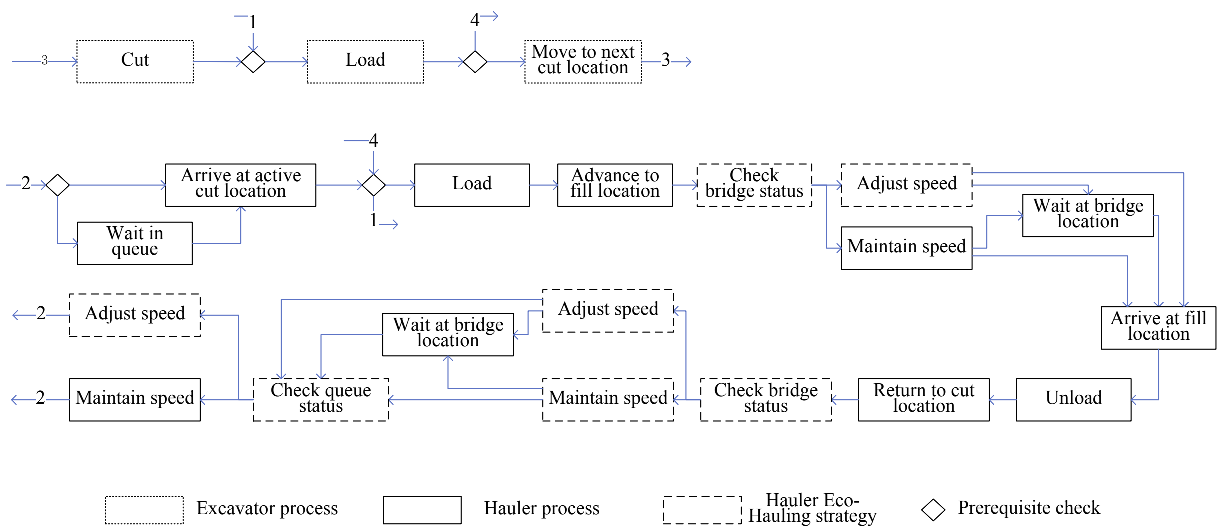

Fig. 4. The earthmoving process logic with Eco-Hauling.

passage remains blocked when arriving at the area. The same actions will be conducted on the return trip from the fill to the cut. This strategy theoretically decreases the possibility of the hauler having to stop, idle, and accelerate to base speed after the bridge passage is no longer blocked. Another checkpoint is set 500 m before the cut location. Similarly, the operator will adjust the speed of the hauler based on the number of vehicles in the loading queue. This too can potentially reduce the idle time and the number of times the articulated hauler has to advance in the queue.

The hauling distance is dynamically changed along with earthmoving tasks performed according to the earthmoving plans seen in Figs. 5 and 6. Furthermore, the influence of the blockages at the bridge construction area on the earthmoving task is uncertain as the blockages occur at variable intervals. These factors demand continuous monitoring of the earthmoving system to determine the effects of Eco-Hauling. The developed DES-model which simulated the earthmoving system considers these dynamic factors; the model also enables a large number of Eco-Hauling scenarios to be simulated and compared.

During the DES, the data about duration and CO_2 emissions of articulated haulers was recorded based on: 1) the distance covered at different speeds; 2) whether the haulers are loaded or empty; 3) the number of times haulers accelerated to different base speeds; 4) the idle time when waiting in the queue for loading or at the bridge construction area; and, 5) the number of steps advanced in a queue. The number of simulated replications should ensure stability of output variance. A trial-and-error method was employed to determine the appropriate replication number (Lorscheid et al., 2012). Stability of output variance was achieved at 50 replications, hence 50 runs was selected as the number of replications for each scenario.

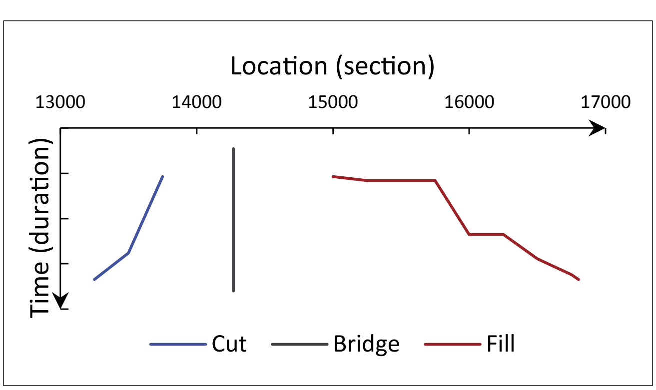

Fig. 5. The earthmoving plan of the initial scenario.

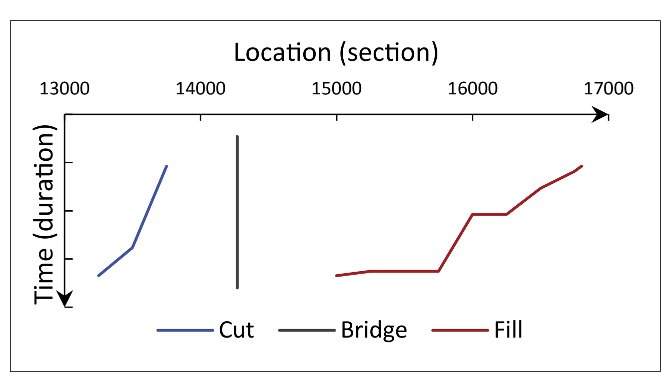

Fig. 6. The Alternative earthmoving plan of Eco-Hauling.

4.3.2. Initial scenario

The parameters of the initial scenario are based on information received from the general contractor of the project, together with estimates and assumptions. The earthmoving plan (represented as a line-of-balance schedule in Fig. 5) has an increasing hauling distance with time, starting at 1250 m and finishing at 3552 m. The vertical and horizontal axes of the line-of-balance schedule denote time and location respectively, and detail the order to which the cut and fill quantities of the BOQ are worked. The cuts are executed simultaneously with a fill to allow a steady flow of material from cuts to fills using articulated haulers. This scenario is also subject to interaction with the bridge construction area located between the cut and the fill. The bridge construction processes are not considered as part of the earthmoving task, but interactions with the earthworks task are included in the study since these happen within the same time-location window. Additional parameters of the initial scenario are shown in Table 5.

4.3.3. Eco-Hauling scenarios

A total of 1536 Eco-Hauling scenarios, consisting of the parameters set out in Table 6, were studied in this paper. Several of the same parameters of the initial scenario seen in Table 5 were included in the Eco-Hauling scenarios, since some parameters were not studied in isolation. For instance, number of haulers, base speed, and anticipation of upcoming obstacles will all influence each other, and it is possible that for some of these parameters, the base value has the best performance. The strategic level of Eco-Hauling was excluded since those aspects are beyond the scope of available options in the selected case study. In the Alternative earthmoving plan the fill work starts at the high section and progresses towards the low section, as is the case with work at the cut area. This results in more uniform hauling distances throughout the earthmoving process. Operational Eco-Hauling with regard to anticipation of obstacles depends on the behavior of articulated hauler operators. 500 m was deemed as a realistic distance at which the operator is able to identify obstacles (such as queuing vehicles) or see if construction works at the bridge location, e.g., material deliveries, etc., are likely to prevent passage. When the articulated hauler reaches the 500 m checkpoint before an obstacle, the operator adjusts the speed depending on the type of obstacle ahead. The three obstacles considered are: 1) one vehicle in queue (or ahead); 2) two or more vehicles in queue (or ahead); and 3) the bridge passage blocked.

4.3.4. Simulation data

Based on duration and fuel (diesel and HVO) use data from the scenarios modeled with the DES, the CO_2 emissions and costs were calculated. Diesel emits 2.62 kg CO_2 per liter of diesel combusted (Ji et al., 2014). HVO used in Sweden in 2016 has roughly 86% lower CO_2 emissions than diesel, i.e., 0.39 kg CO_2 per liter of HVO combusted (Energimyndigheten, 2016). However, due to the lower density of HVO, the volumetric fuel consumption is 2% higher than for conventional diesel (Omari et al., 2017). The costs were estimated based on the fuel use and equipment rental costs. Diesel costs € 1.47/liter whereas HVO costs € 1.49/liter in one of Sweden's main filling station chains (Preem, 2018). The rental costs for the equipment were estimated at € 150/h for the excavator and € 100/h per articulated hauler.

4.4. Results and discussion

The results of the case study show that our proposed Eco-Hauling concept has the potential to reduce CO_2 emissions by a total of 6.94% (85.87% using HVO) or costs by 15.63%, as can be seen in Table 7. These results can be achieved by selecting the best combination among those parameters defined for Eco-Hauling (Table 6 and Fig. 6), and the parameters of the initial scenario (Table 5 and Fig. 5). Of the individual Eco-Hauling decisions, seen in Table 8, HVO was naturally the decision with the highest impact on CO_2 emissions due to it not containing any fossil fuels. The selection of fuel type is independent of other Eco-Hauling parameters as it does not impact the earthmoving process. Reducing the number of haulers from 4 to 3 is another individual Eco-Hauling decision with a notable effect on both CO_2 emissions (−5.57%) and costs (−12.62%).

A negligible effect on costs was achieved by implementing the individual Eco-Hauling decisions of adjusting speed due to anticipated obstacles and by changing base speed, but in terms of CO_2 emissions these decisions enabled a reduction by 1.07% and 2.40% respectively. If both parameters are combined, part of the CO_2 emissions reduction for the speed adjustments due to anticipated obstacles is offset by already having a more advantageous base

Table 5
The parameters of the initial scenario.

Parameter	Value
Number of Volvo A25F Articulated hauler	4
Base speed	28 (km/h)
Earthmoving plan	Cut: high to low station; fill: low to high station (see Fig. 5)
Fuel type	Diesel

Table 6
The parameters constituting the Eco-Hauling decisions addressed in the study.

Parameter	Value
Tactical Eco-Hauling	
Alternative number of haulers	3, 4
Alternative base speeds	25, 28, 31 (km/h)
Alternative earthmoving plan	Cut: high to low station; fill: high to low station (see Fig. 6)
Fuel type	Hydrogenated vegetable oil (HVO)
Operational Eco-Hauling	
Anticipate obstacles and adjust speed if:	
One vehicle in queue	16, 19, 22, 25 (km/h)
Two vehicles in queue	16, 19, 22, 25 (km/h)
Bridge passage blocked	16, 19, 22, 25 (km/h)

Table 7
The best performing combination of Eco-Hauling decisions (parameters) in terms of CO_2 emissions and costs compared to the initial scenario.

	Parameters	CO_2 emissions (kg)	Parameters	Costs (€)
Base speed	25 km/h	1907 (−85.87%)	31 km/h	40 702 (−15.63%)
Anticipate obstacles:	–	12 561 (−6.94% excl. HVO)	–	
One vehicle in front	22 km/h		25 km/h	
Two vehicles in front	16 km/h		19 km/h	
Bridge passage blocked	25 km/h		25 km/h	
Earthmoving plan	Initial		Alternative	
Number of haulers	3		3	
Fuel type	HVO		Diesel	

Table 8
The best individual Eco-Hauling decisions (parameters) in terms of CO2 emissions and costs compared to the initial scenario.

	Parameters	CO_2 emissions (kg)	Parameters	Costs (€)
Base speed	25 km/h	13 174 (−2.40%)	25 km/h	48 253 (Initial)
Anticipate obstacles:	–	13 354 (−1.07%)	–	48 172 (−0.17%)
One vehicle in queue	19 km/h		19 km/h	
Two vehicles in queue	16 km/h		19 km/h	
Bridge passage blocked	22 km/h		22 km/h	
Earthmoving plan	Initial	13 498 (Initial)	Initial	48 253 (Initial)
Number of haulers	3	12 746 (−5.57%)	3	42 164 (−12.62%)
Fuel type	HVO	2049 (−84.82%)	Diesel	48 253 (Initial)

speed in place. Thus, the combined CO_2 reduction does not equal the sum of reduction for both parameters, but reaches a total reduction of 3.15%. If the excavator is excluded, as it does not conduct any operational Eco-Hauling, the reduction of CO_2 emissions reaches 5.85%. This is within the 5–15% reduction range as reported in studies on operational Eco-Driving (Barla et al., 2017; Jamson et al., 2015; Schall and Mohnen, 2017; Zarkadoula et al., 2007). Table 8 also shows that as an individual Eco-Hauling decision, the Alternative earthmoving plan could not outperform the Initial earthmoving plan, neither in terms of CO_2 emissions nor costs.

Fig. 7 and Fig. 8 highlight the performance of all Eco-Hauling scenarios (HVO excluded) in terms of costs, CO_2 emissions, and duration. The number of haulers, different base speeds, and the particular earthmoving plan show distinct clusters in both Figures. The variations within each cluster are a result of the specific speed parameter combinations used with respect to how obstacles are anticipated.

As was mentioned previously, the Alternative earthmoving plan was outperformed by the Initial earthmoving plan in terms of CO_2 emissions and costs as an individual Eco-Hauling decision. However, in combination with other Eco-Hauling decisions, the clusters of the Alternative earthmoving plan often outperform their counterparts in the Initial earthmoving plan both in terms of duration

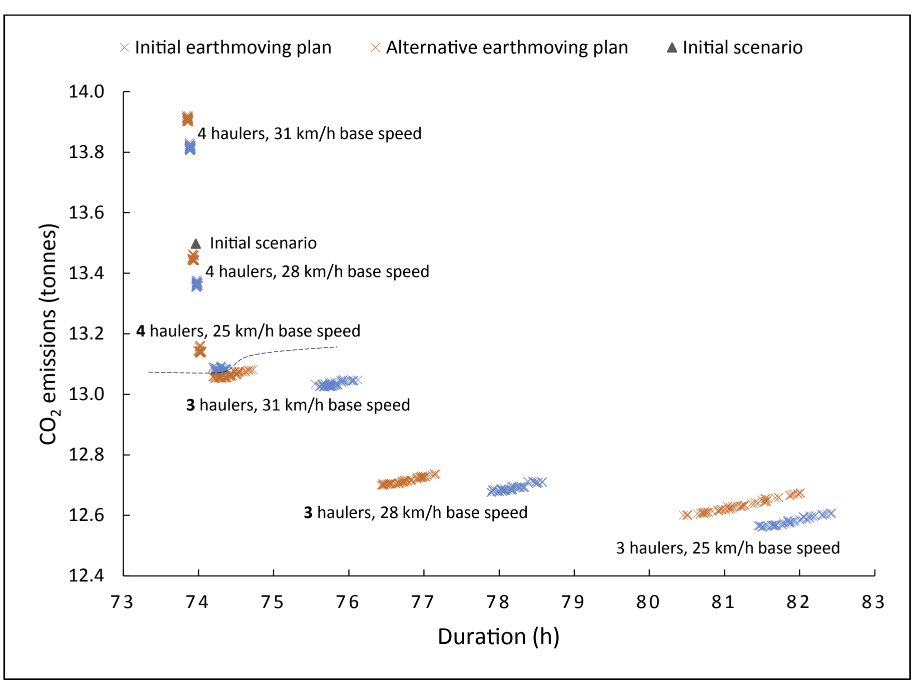

Fig. 7. Diesel-based CO_2 emissions and duration of the initial scenario and Eco-Hauling scenarios relating to number of vehicles, base speed, and anticipation of obstacles for the Initial and Alternative earthmoving plans.

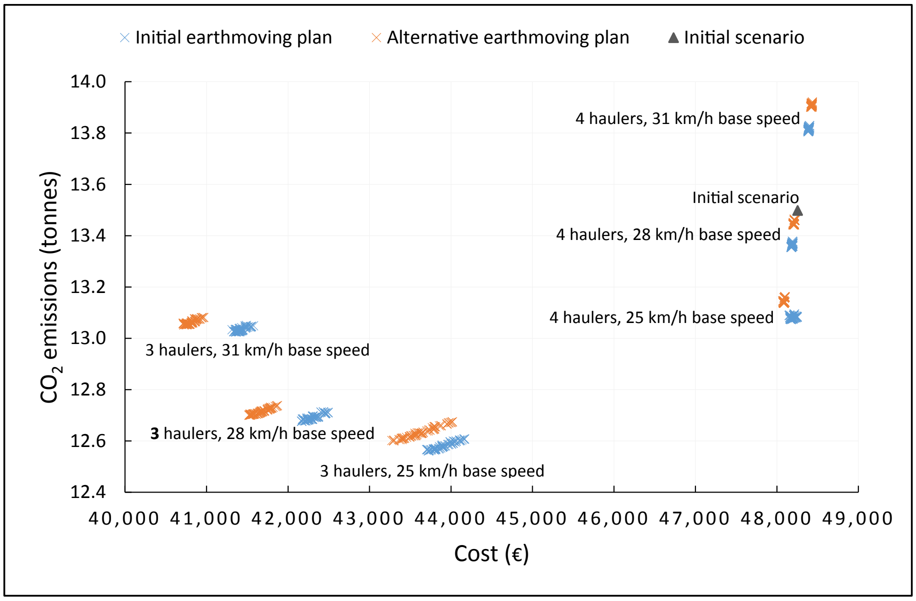

Fig. 8. Diesel-based fuel use and costs of the initial scenario and Eco-Hauling scenarios relating to number of vehicles, base speed, and anticipation of obstacles for the Initial and Alternative earthmoving plans.

(Fig. 7) and costs (Fig. 8). In fact, due to the generally shorter durations, some clusters of the Alternative earthmoving plan can compete with clusters of the Initial plan with a higher number of haulers. Highly competitive Eco-Hauling scenarios are those in the cluster of the Alternative earthmoving plan with 3 haulers and a base speed of 31 km/h (which is a far from fuel optimal base speed). The best scenarios of the cluster are able to compete with the cluster of the Initial earthmoving plan using 4 haulers and a base speed of 25 km/h. Both have similar durations but the Alternative plan has lower CO_2 emissions, as seen in Fig. 7. In fact, they are almost able to compete with the initial scenario in terms of duration, which has 4 haulers and a base speed of 28 km/h. Incidentally, the same cluster (Alternative earthmoving plan, 3 haulers and a base speed of 31 km/h) has the lowest costs of all studied scenarios at under 41 000 €, while costs for any scenarios using 4 articulated haulers stand at over 48 000 € as seen in Fig. 8. This difference is primarily caused by lower rental costs, as 3 instead of 4 haulers were used, while the total duration was only marginally higher than for any of the scenarios using 4 articulated haulers.

The utilization rates of the equipment are presented in Fig. 9. The utilization rate of the excavator was calculated based on the percentage of the total duration spent non-idle, i.e., when loading haulers. For articulated haulers the utilization rate is the percentage of the total duration not spent in queues. Using 3 haulers and low base speeds results in a low utilization rate of the excavator, which causes longer durations. If 4 articulated haulers are used instead,

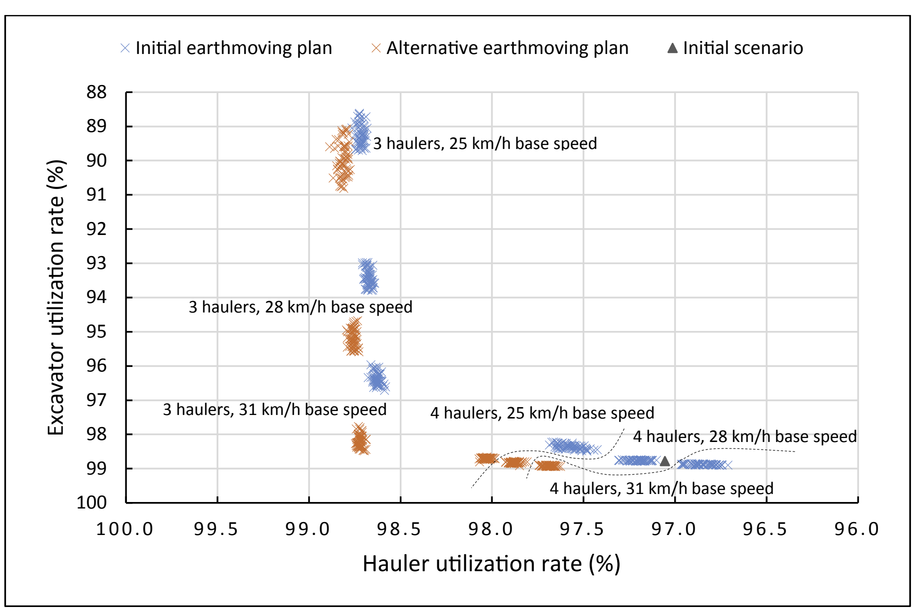

Fig. 9. Utilization rates of used equipment in the initial scenario and Eco-Hauling scenarios relating to number of vehicles, base speed, and anticipation of obstacles for the Initial and Alternative earthmoving plans.

the utilization rates of the haulers are reduced due to more time spent in queues. The previously mentioned competitive scenarios with the Alternative earthmoving plan – 3 haulers and a base speed of 31 km/h – are able to balance high utilization rates both for the excavator and the articulated haulers.

The results of the case study show that rational selections of Eco-Hauling decisions can achieve both considerable reductions of CO_2 and costs with maintained or nearly maintained productivity. Thus, in real-world decision making, earthmoving contractors could use the Eco-Hauling concept to conduct a tradeoff between costs, CO_2 emissions, and productivity to meet duration-based constraints while saving money and reducing their carbon emissions.

5. Conclusions

This study contributes to the ongoing discussion about the impact of Eco-Driving on different system levels (Alam and McNabola, 2014; Xia et al., 2013), by applying our proposed Eco-Hauling concept to earthmoving. The results showed that operational decisions of Eco-Hauling can generate similar CO_2 emissions reductions on a hauler fleet-level as operational Eco-Driving achieves on the individual vehicle-level (Barla et al., 2017; Jamson et al., 2015; Schall and Mohnen, 2017; Zarkadoula et al., 2007).

The results of this study also contribute to the construction engineering and management (CEM) field, where discourse has increasingly emphasized the need to reduce carbon emissions from construction practices (Fernández-Sánchez et al., 2015; Krantz et al., 2017). The Eco-Hauling concept may support the management of earthmoving with regard to such emissions as well as costs and productivity. The case study showed that Eco-Hauling has the potential to achieve considerable benefits both with respect to CO_2 emissions and costs without significantly sacrificing productivity in terms of duration. No single combination of Eco-Hauling decisions was, however, able to achieve the lowest costs, CO_2 emissions, and duration. Rational Eco-Hauling implementation therefore necessitates a tradeoff between these three variables. Similar to findings by Jassim et al. (2018), our study indicated that balancing equipment utilization rates can be an effective approach not only to reduce CO_2 emissions, but also to address the tradeoff. The DES-approach used in the case study enabled us to analyze these factors for an earthmoving task by identifying particularly competitive options. The approach developed here could support earthmoving contractors in real projects in their Eco-Hauling implementation.

Although the results clearly indicated the benefits of Eco-Hauling, we concede that actual implementation is more complex and less intuitive than in the case of Eco-Driving. The main reason for this is that earthmoving is a multifaceted task that has to consider more factors than private car driving. Successful Eco-Hauling implementation depends on project-specific factors, such as hauling distances, quantities, site layouts, and equipment types. Successful implementation may also be counterintuitive, e.g., using a non-optimal base speed from a fuel use standpoint may in fact be the best overall decision for an earthmoving contractor when considering CO_2 emissions, costs, and productivity. Reaching an understanding of these subtleties is crucial for Eco-Hauling implementation and requires up-to-date site information, and careful planning and management of the earthmoving operations. One promising approach to facilitate the implementation of Eco-Hauling is the development of digital production control systems which would enable managing production in real time. Such a system could be used to optimize the production flow and to inform equipment operators of changes in, e.g., base speeds.

The single case study approach used in this paper included unavoidable simplifications since all site conditions could not be taken into account. For instance, in modeling the two earthmoving plans, articulated haulers might face differences in rolling resistance between filled fill areas and unfilled fill areas – these are not reflected in our results. Furthermore, the unloading of material may be facilitated by not having to pass filled piles in the Alternative plan. Aspects such as these could be investigated with further studies, particularly by using field experiments with the collection of real-time site information integrated into a digital production control system. Despite these weaknesses, our results show that the proposed Eco-Hauling concept has the potential to reduce CO_2 emissions and help contractors to choose an appropriate alternative for their earthmoving tasks based upon project-specific requirements.

Acknowledgement

This work was funded by the Development Fund of the Swedish Construction Industry (SBUF), the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (Formas), and the National Key Research and Development Program of China (No. 2016YFC0701904).

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Paper V

A Model to Reduce Earthmoving Impacts

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Submitted to Transportation Research Part D: Transport and Environment

February 2019

A Model to Reduce Earthmoving Impacts

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Abstract: Meeting increasingly ambitious carbon regulations in the construction industry is proving particularly challenging for earthmoving operations due to the extensive use of heavy-duty diesel equipment. Planners and contractors need to better plan their operations and balance their efforts between the competing demands of environmental concerns, costs, and duration. However, existing approaches-both theoretical and practical-rarely address all of these objectives in combination, and are often limited to only parts of the earthmoving process. This study proposes a model adapted for contractors to optimize mass flows and to allocate earthmoving equipment configurations with respect to the tradeoffs between duration, cost, CO2 emissions, and energy use. Three equipment allocation approaches are proposed and demonstrated in a case study where the best performing approach in terms of costs, CO2 emissions, and energy use is a rule-based approach which allocates equipment configurations according to hauling distances. The simplicity of such an approach makes it a promising option for facilitating practical adoption at the construction site. In addition, the study also indicates that trucks are a major contributor to the costs and environmental impacts of earthmoving operations.

Keywords: Earthmoving operations; Optimization framework; Optimum configuration; Tradeoff duration; Cost; Emissions.

1. Introduction

1.1 Background

Climate change poses significant threats to, among other things, human health (McMichael et al., 2006), economic development (Ciscar et al., 2011), and species survival (Fordham et al., 2012). To mitigate such threats, increasingly ambitious policies and regulations on carbon and other greenhouse gas (GHG) emissions are being introduced; the global Paris Agreement to limit global warming to under two degrees Celsius above pre-industrial temperatures (UNFCCC, 2015), various national carbon tax schemes (Lin and Li, 2011), and the European carbon trading scheme for energy generation and energy intensive industries (European Commission, 2003) now form a complex legislative framework for attempts to deal with the problem. In line with this general picture, carbon reduction policies are increasingly being implemented within the construction industry. For instance, the Swedish Transport Administration (STA) is imposing carbon reduction goals on contractors delivering road projects with the goal of a net zero carbon transport infrastructure no later than 2045 (Trafikverket, 2017). Extensive use of heavy-duty diesel (HDD) equipment is a main contributor to GHG emissions in transport infrastructure projects (Hajji and Lewis, 2013). Earthmoving equipment alone represents approximately 90-95% of the onsite emissions in some projects (Hwang et al., 2000; Kim et al., 2012). Reducing emissions from earthmoving equipment is therefore important, which we in this paper set out to address by proposing a model to support the management of earthmoving processes and equipment.

Previous research has focused on field studies regarding emissions related to the operational and equipment characteristics of HDD equipment (Abolhasani et al., 2008; Frey et al., 2010; Lewis et al., 2011). Other studies have looked at the impacts that ambient humidity and air temperature have on emissions (Lindhjem et al., 2004). Although there are promising alternatives to diesel, such as biofuels (Love and Nejadhashemi, 2011) and electrified equipment, these are unlikely to become mainstream in the near future (Lajunen et al., 2018). Regardless of the availability of such technologies, some emissions reductions may be achieved by using existing equipment more efficiently (Marshall et al., 2012), such as through increasing their utilization rates (Jassim et al., 2018a, 2018b). This necessitates viewing equipment as interconnected components in a process, which in turn requires careful planning of earthmoving operations (Ahn et al., 2009). In fact, to avoid excessive emissions, assessment of climate impacts needs to be an integral part of the project planning (Grann, 1997). Any such assessments need methods for quantifying the impacts (Sihabuddin and Ariaratnam, 2009), for instance using emission inventories created through measuring equipment emissions in field conditions (Lewis et al., 2009). Despite this clear need, most assessments are currently conducted during construction, or even after project completion (Dongier and Lovei, 2006).

Contractors have a major responsibility for the equipment usage onsite, but reducing emissions is generally not a primary concern unless accompanied by reduced costs or shortened project duration (Jukic and Carmichael, 2016). Developers also extensively select contractors offering the lowest bid rather than taking other factors into account (Ariaratnam et al., 2013). A number of modern approaches which have the potential to reduce the GHG emissions of earthmoving and other construction processes in transport infrastructure projects have been proposed. One such approach is the minimization of earthmoving haul distances (or costs) using linear programming (LP) on the earthmoving system treated as a shortest path problem (Son et al., 2005). Such techniques have also shown potential in reducing fuel use and associated emissions of earthworks (Sanchez et al., 2015). LP-based optimization techniques have been incorporated in commercial planning software for the transport infrastructure construction industry (Shah and Dawood, 2011). Improving equipment combinations to optimize productivity and reduce idle time may also use LP to reduce both costs and emissions (Kaboli and Carmichael, 2014). Discrete event simulation (DES) is capable of capturing variability and the complex dynamic interactions between equipment and the earthmoving environment, and is therefore suitable for determining equipment performance in greater detail (Kim and Kim, 2016). Intelligent approaches for optimization are becoming increasingly used for a wide array of applications across several fields (Nabaei et al., 2018). For instance, using a number of operational parameters, a machine learning system based on an artificial neural network to predict the fuel use and associated emissions of earthmoving equipment has been put together (Jassim et al., 2018b; Siami-Irdemoosa and Dindarloo, 2015). Evolutionary optimization is another intelligent approach which may be adapted for allocating earthmoving equipment based on a tradeoff between costs and duration (Parente et al., 2015).

1.2 Knowledge gap and aim

Although the aforementioned literature clearly signals the potential for reducing GHG emissions, further theoretical development is necessary to better enable implementation in earthmoving projects (González and Echaveguren, 2012; Liu et al., 2013). Firstly, to be of interest for contractors, GHG reduction measures should be practical both in terms of cost and project duration (Jukic and Carmichael, 2016, Shi et al., 2013). However, only a limited number of studies have considered those aspects in earthmoving projects (Ahn et al., 2009; Kim and Kim, 2016), although Ahn et al. (2009) specifically acknowledged the need to explore the tradeoff between GHG emissions, costs, and duration when developing new methods. Secondly, developed methods should be comprehensive enough to encompass several components, or indeed, the full process (Akadiri et al., 2012). Kim and Kim (2016), and Ahn et al. (2009) considered only the impact of different equipment configurations in small or hypothetical earthmoving cases under specific conditions.

Therefore, the overall aim of this study is to propose a comprehensive model to reduce GHG emissions, costs, and the duration of earthmoving projects. The model is implemented in several stages, comprising both optimization of earthmoving mass flows and the allocation of equipment configurations to different project locations according to a number of operational parameters. Parameters considered include equipment engine loads, material density, slope of haul roads, and the hauling distances at different project locations. A case study of several major earthmoving tasks in a road project is conducted to demonstrate the applicability of the model. Outputs from the model may assist contractors when allocating equipment to earthmoving tasks or projects in the short term, and also help them to acquire an optimal equipment fleet in the long term. Furthermore, a particularly competitive approach for allocating equipment configurations was a simple distance rule-based approach. The simplicity of an approach such as this may facilitate the practical implementation and understanding among operators and site managers. A valuable twofold contribution from this research can be therefore discerned: firstly, it results in a practical approach for decision support regarding earthmoving operations, and secondly, it has produced theoretical insights into automating the evaluation of earthmoving operations with regard to cost, duration, and environmental impacts.

2. Proposed model

To meet the aforementioned aims, we propose the use of a Planning, Simulation, Estimation, and Decision making (PSED) model, which provides a set of equipment configurations. The PSED model consists of three interconnected successive stages: project documentation, modern planning techniques for selection and estimation, and different approaches to decision-making based on equipment allocation (see Figure 1).

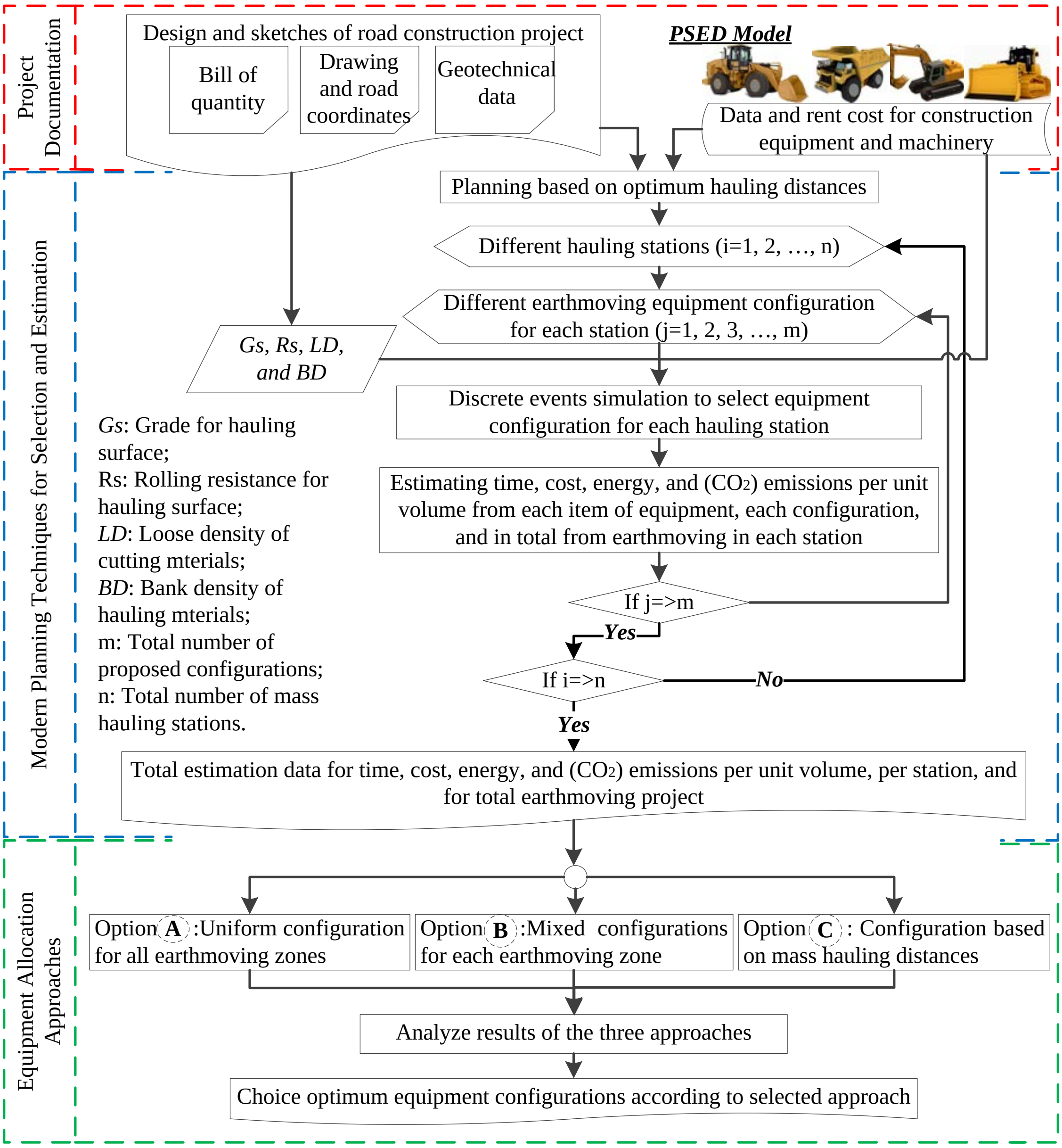


Fig. 1. Outline of the Planning, Simulation, Estimation, and Decision making (PSED) model.

2.1 Project documentation

In the first stage, the collection and extraction from infrastructure projects of data and information relevant to the planning and execution of earthmoving operations is conducted. These data and information are mainly classified into two parts; the first part is connected to design details and sketches consisting of bills of quantities, drawings, topographical information showing elevations between earthmoving work areas, and material type and density data. The second part comprises performance data for the construction equipment that is available for the contractor-basic operational characteristics and hire costs. This stage is considered important for planners because it provides knowledge about the entire scale of the project and the conditions and constraints that should be planned for. Therefore, this stage can be considered as a preparation stage that extracts all of the essential data and information to be used as input data for the following stages of planning earthmoving operations.

2.2 Modern planning techniques for selection and estimation

In this stage, the hauling distances are optimized and the earthmoving process simulated, to produce a plan that can meet two objectives: optimum mass haulage distances and the best equipment configurations based on utilization rates (i.e. work efficiency with limited resources available) against constraints and work conditions (i.e. time, budget, and environmental impact), as well as evaluation of all targets values. Thus, this step is performed by:

Mass haul optimization tool (e.g. DynaRoad): This is a program designed to manage earthwork operations in linear construction projects, providing a mass haulage plan based on optimum mass hauling distances between different earthmoving stations in road construction projects. In this study, an earthmoving station is defined by one or two cutting or loading areas that are closely spaced together coupled with one or more dumping areas. However, earthmoving may comprise a number of stations, all of which may be located close together to create a large area called an earthmoving zone (i.e. each zone includes a number of earthmoving stations). Therefore, the earthmoving plan in infrastructure projects may consist of several zones within which earthmoving takes place. In other words, the main output of this step can be described as identifying the optimum distances in a road construction project to haul earthwork materials on-site or off-site.

Simulation technique: The best combination of earthmoving equipment to be allocated in a project can be determined using DES to model real work conditions. The choice of equipment configuration in each work station and/or zone is based on duration and cost constraints. Additionally, the utilization rates of each item of equipment in combination are also considered when selecting type, number, and capacity of each piece of equipment within overall configurations. Utilization rates are also used later to determine the weighed percentages of the cost and emissions for each piece of equipment against total cost and emissions of the earthwork operations as a whole. The output from this stage represents the integrated earthmoving plan (i.e. locations and their equipment configurations), which can be described as the optimal hauling distances, with a balance between cost and duration, that provide a high level of equipment utilization rates.

Estimation of target values (i.e. time, cost, energy, and (CO_2) emissions): The time and cost for each configuration to perform earthmoving in each station are computed within the simulation based on cycle time and capacity for each piece of equipment, distances to hauling materials, and hourly rental costs. This stage also entails estimations of energy use and CO_2 emissions for all of the equipment configurations that have been nominated to work within each station from the DES. Energy use and CO_2 emissions estimates are based on Equations 1-4 developed by Jassim et al. (2018a, 2018b); these are considered the actual productivity rates of earthmoving equipment and load factor values based on the density of hauling materials to estimate energy use and emissions (CO_2) per unit of volume-based fuel consumption. Equations 1 and 3 are used to estimate energy use (MJ/m^3) and CO_2 emission (kg/m^3) from excavators, wheel-loaders, and bulldozers, while Equations 2 and 4 are used for trucks to consider rolling resistance and grade for hauling surface.

$$An = \left(\frac{SFC\ .H_p.L_f.C_{nf}}{\rho_{fuel}.P_{ra}}\right) \tag{1}$$

$$Tn = \left(\frac{SFC\ .H_{pt}.C_{nf}}{\rho_{fuel}.P_{ra}}\right) \tag{2}$$

$$Dm = An\ .C_{mf} \tag{3}$$

$$Tm = Tn\ .C_{mf} \tag{4}$$

Where *An* represents energy used per cubic meter of material hauled by operating the excavator "*En*", or wheel-loader "*Ln*", or bulldozer "*Bn*" respectively, at a specific station of the earthmoving operation. *Tn* is energy used per cubic meter of material hauled by operating the trucks. *SFC* is specific fuel consumption (0.22 kg/kW.h), to be set to a suitable value for engines with power in the range of 28.8 to 370 kW (Hunkeler and Rebitzer, 2005; Klanfar et al., 2016). H_p is the maximum design horsepower of the equipment used (kW). ρ_{fuel} is the specific gravity of the diesel fuel to be consumed (0.85 kg/L), ranging between 0.83 and 0.87 kg/L. C_{nf} is the conversion factor between fuel and energy, and C_{mf} is the conversion factor between energy and CO_2. P_{ra} is the actual productivity rate (m^3/h) of the equipment for each level of utilization in the earthmoving operations as simulated in the DES. *Dm* is emissions (CO_2) per cubic meter of material hauled by operating the excavator "*Em*", the wheel-loader "*Lm*", or the bulldozer "*Bm*" respectively, at a specific station of the earthmoving operation; in addition, *Tm* represents emissions (CO_2) per cubic meter of material hauled by operating the trucks. L_f is the engine load factor (decimal) for equipment (i.e. excavator, wheel-loader, and bulldozer) that was estimated based on Equation 5 developed by Jassim et al. (2017):

$$L_f = 0.0366e^{0.00136B_D} \tag{5}$$

Where B_D represents the materials densities (kg/m^3). H_{pt} is the grade engine horsepower of trucks (see Eq. 6) accounting for the effect of the total resistance (i.e. grade and rolling resistance), and G_s is the hauling road grade (decimal), which is denoted by a positive sign (+) for an up gradient and a negative sign (-) for a down gradient. The surface grade is estimated from longitudinal profiles of the road project by dividing the difference between the average elevations between cutting/loading area and filling/dumping area with the hauling distance.

$$H_{pt} = \left(\frac{G_{wt}.(G_s + R_s).S_{av}}{cc}.C_{hp}\right) \quad (6)$$

Where R_s is the rolling resistance of the hauling surface that is selected based on the surface type of the haulage route (decimal), S_{av} is the average hauling speed of the truck (km/h), cc represents a constant value (273.75), C_{hp} represents the conversion factor (0.7457) for converting the energy from HP to kW. G_{wt} is the total weight of a truck that consists of chassis weight (kg), body weight (kg), and total payload of a truck (kg) based on the loose density of the materials being hauled (kg/m^3), and the truck's heaped capacity (m^3).

The amount of energy used (En_{conf}, MJ) and CO_2 emitted (Em_{conf}, kg), (Eqs. 7 and 8) is estimated by the equipment configurations in each station where the contributions from the different equipment used are summarized (e.g. energy use and CO_2 emissions of excavator, wheel-loader, bulldozer, and trucks). In addition, the energy consumed (En_{total}, MJ) and CO_2 emissions (Em_{total}, kg) from all earthmoving zones can be computed by using Equations 9 and 10.

$$En_{conf} = \left[\sum_{i=1}^{n}(En)_i + \sum_{i=1}^{n}(Ln)_i + \sum_{i=1}^{n}(Bn)_i + \sum_{i=1}^{n}(Tn)_i\right].V \quad (7)$$

$$Em_{conf} = \left[\sum_{i=1}^{n}(Em)_i + \sum_{i=1}^{n}(Lm)_i + \sum_{i=1}^{n}(Bm)_i + \sum_{i=1}^{n}(Tm)_i\right].V \quad (8)$$

$$En_{total} = \sum_{j=1}^{m}\left(En_{conf}\right)_j \quad (9)$$

$$Em_{total} = \sum_{j=1}^{m}\left(Em_{conf}\right)_j \quad (10)$$

Where En_{conf} is energy used by equipment configuration in each station of the earthmoving operation, and *En*, *Ln*, *Bn*, and *Tn* are energy used by operating the excavator, wheel-loader, bulldozer, and trucks respectively, in a specific station of the earthmoving operation (where i = 1, 2, 3, …, n; n = total number of each type of equipment in configuration at each earthmoving station in a road project). Em_{conf} is (CO_2) emitted from the equipment configuration in each station of the earthmoving operation, and *Em*, *Lm*, *Bm*, and *Tm* are (CO_2) emitted from operating the excavator, wheel-loader, bulldozer, and trucks respectively, in a specific station of the earthmoving operation (where i = 1, 2, 3, …, n; n = total number of each type of equipment in configuration at each earthmoving station in a road project). V is the volume of materials in each mass hauling station of the earthmoving operations. En_{total} is the amount of energy used by all equipment configurations in the earthmoving operations, and Em_{total} is (CO_2) emitted from all equipment configurations in the earthmoving operations, where j = 1, 2, 3, …, m; m = total number of earthmoving stations in a road construction project. After estimating the energy use and CO_2 emissions of different earthmoving units, the final total data for all earthmoving configurations are calculated. A three-dimensional matrix is thereby produced consisting of time, cost, and environmental impacts (energy use and CO_2 emissions). These are the three target objectives that all earthmoving equipment configurations in each workstation are subject to.

2.3 Equipment allocation approaches

In the final stage of PSED the best equipment configurations on the basis of the three aforementioned target objectives are selected through analyzing the results of the earthmoving operations for each station. The equipment configurations are allocated according to the following approaches:

Uniform configuration: One configuration allocated for the whole earthmoving process.

Mixed configurations: One configuration allocated per earthmoving station, resulting in mixed configurations throughout the project site.

Hauling distance configuration: Configuration allocated according to hauling distance range per earthmoving station.

Approach A is a suitable selection when equipment allocation needs to be kept simple. Approach B enables more detailed planning of equipment allocation as the process is divided per earthmoving section. A simple planning method that enables different equipment configurations to be selected for different zones is to consider hauling distances as the selection criteria, as was done in approach C.

3. Model application in case study

A case study is conducted to demonstrate the efficiency of the PSED model in producing optimum earthmoving equipment configurations that can manage the tradeoffs between time, cost, and environmental impacts. Models with similar applications have been demonstrated in other case environments (Carmichael et al., 2014; Kim and Kim, 2016). Figure 2 shows an overview of our case which consists of three earthmoving zones selected from a road project in southern Sweden of 17 km, containing a cut volume of about 151 000 m^3. The project is being undertaken by NCC, a large Swedish construction company. The bidding cost of each unit volume of earthmoving is (55 SEK/m^3), which includes all tasks required to execute the earthmoving tasks (e.g. cutting, transporting, filling, distributing, and leveling to the required level for each layer). The case was selected due to its extensive earthmoving operations and its detailed documentation of equipment which facilitated our analysis. The structure of the conducted case study is outlined in Figure 3.

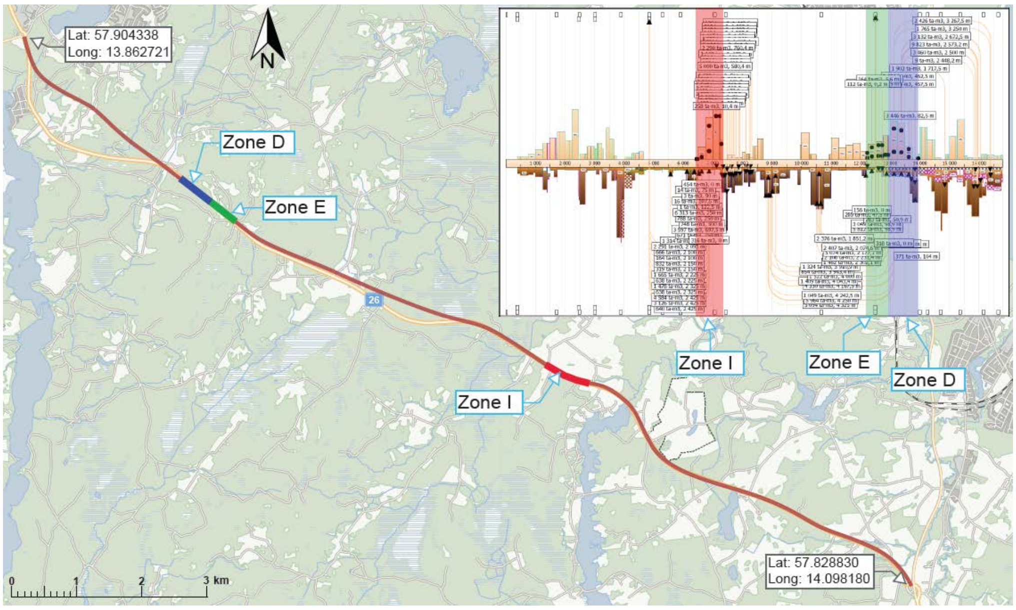


Fig. 2. Project map containing earthmoving zones and coordinates.

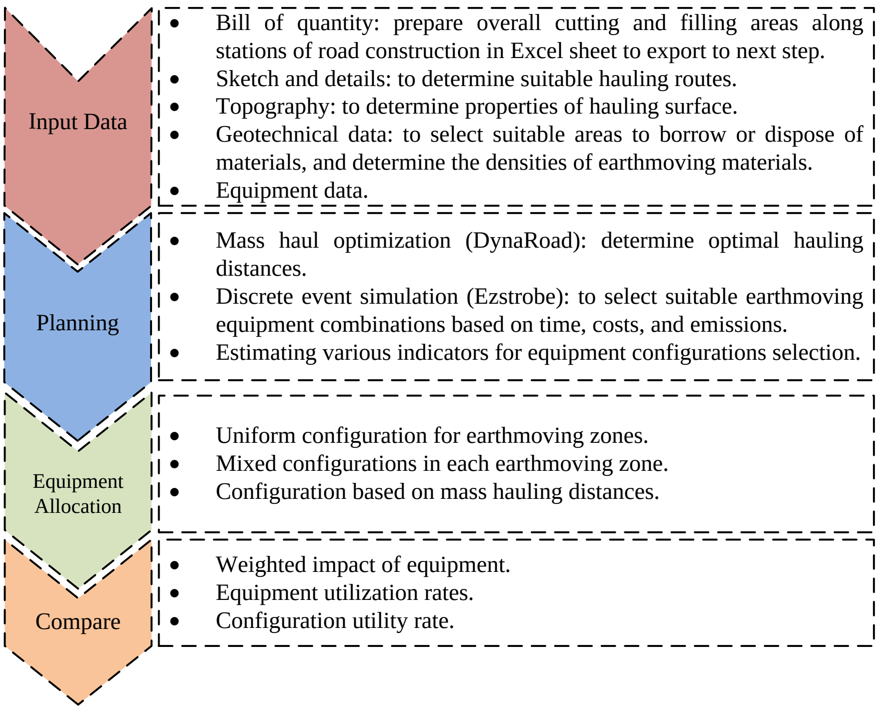


Fig. 3. The case study process.

3.1 Input data

The first step of implementing the PSED model is to gather and organize the necessary input data. This data is mainly gathered from the project, and include the bill of quantities for the earthmoving operations, a drawing for the main line of the road construction (i.e. a longitudinal profile), geotechnical data and topography, and data of the earthmoving equipment available (see Table 1). The average bank density of materials excavated is 1886, 1835, and 1943 kg/m^3 for zones D, E, and I respectively. A surface grade of 2% for hauling operations is estimated in zones E and I, and 3% for hauling operations in zone D. The rolling resistance is estimated at 3% based on the type of haulage surface.

Table 1. Equipment available for the selected project.

Type of equipment	Model	Number of units	Heaped capacity of unit (m^3)	Engine horsepower (kW)	Hourly rental cost (SEK)
Articulated truck	Cat. 725	5	14.3	230	800
Off-highway truck	Cat. 770	5	25.0	381	900
Off-highway truck	Cat. 772	5	30.0	446	1000
Excavator	319DL	2	0.802	94	700
Excavator	329D	2	1.101	152	900
Wheel-loader	924Hz	1	2.1	55	800
Wheel-loader	930H	1	2.5	113	1000
Bulldozer	D7R	1	--	179	1000
Bulldozer	D10T2	1	--	447	1200

3.2 Planning

3.2.1 Mass haul optimization

In the first planning step of the PSED model implementation, the hauling distances between cuts and fills are optimized. A bill of quantities in an Excel format, which specifies the cut and fill quantities and locations along the road line, are imported into the DynaRoad platform. Additional locations of borrow pits and disposal areas necessary to compensate for a lack of filling materials, or to dispose of surplus or non-useful materials, are specified manually. DynaRoad summarizes material quantities along the road line into intervals of 50 meters, with some exceptions due to the distribution of different material types. We define such an interval as an earthmoving station, and DynaRoad calculates hauling distances from the center of such stations. DynaRoad calculates the optimal hauling distances automatically using linear-programming, and a simple visualization of the planned hauls can be generated (see Figure 2). In this step we also combine the earthmoving stations into larger zones according to their material characteristics and quantities where it can be expected that the same equipment configurations can conduct the work in sequence. A step like this is commonly conducted in large earthmoving projects to divide the work into more manageable chunks. Three of the zones, seen in Figure 2, were selected to demonstrate the model in this case study.

3.2.2 Discrete event simulation

The next planning step of the PSED model focuses on selecting suitable equipment configurations for each earthmoving station based on the optimum mass haul plan that was produced in the preceding step. Ezstrobe, a DES tool to represent earthmoving operations, was used to propose the best equipment configurations for each earthmoving station. The simulation implemented the following constraints:

Equipment: The items of equipment used cannot exceed in number the items of equipment available.

Duration: The working hours cannot exceed the total time allocated to earthmoving operations.

Operating cost: The equipment operating costs cannot exceed the budget allocated to earthmoving operations.

Utilization rates: Utilization rates should be in harmony with realistic equipment utilization in earthmoving operations, or with the improved utilization rate based on rational applicable ideas.

Typically, a simulation template for each earthmoving scenario consists of a number of components and elements that mimic real-world earthmoving operations in road projects (see Figure 4). In addition, the description and distribution function for each item in the template is shown in Table 2.

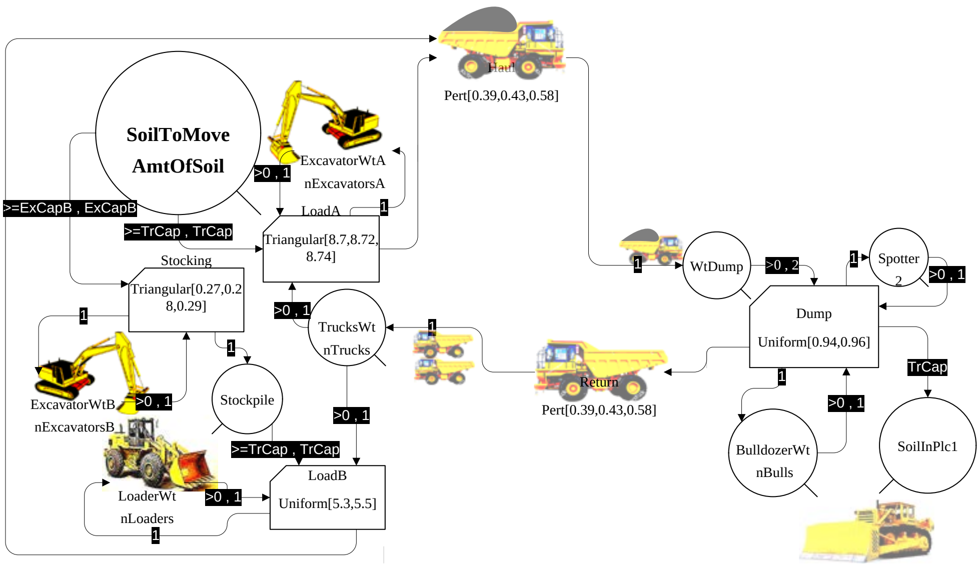
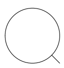
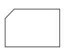
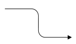


Fig. 4. Example of earthmoving simulation template used.

Table 2. Main items of the DES template.

Symbol	Name	Description	Relation/Function
	Queue	This is a place for waiting until the start of an activity (buffer) requiring these resources. Queues might involve generic or characterized resources (e.g. trucks, excavators, bulldozers, and spotters), which are logically ordered depending on their function.	Logical relation with boundary conditions.
	Combination Activity	This describes a specific type of activity to be performed over a known (distribution probabilistic) duration, from start to end. The activity always requires a specific combination of resources, and is fed from the preceding queue(s).	Triangular distribution function for excavator activities; Uniform distribution for wheel-loader and bulldozer/truck activities.
	Normal Activity	This describes a specific type of activity to be performed over a known (distribution probabilistic) duration, from start to end, for a single resource.	Pert distribution function for truck activities (i.e. hauling and retuning).
	Link	This shows the flow of logic. For example, links indicate the sequence of activities. Activities with occurrence depending on other activities are also shown.	Logical relation with boundary conditions.

Based on the equipment and machinery available and drawing on planners' experiences, a number of configurations are proposed for the earthmoving activities project. Table 3 shows five suitable configurations that are proposed to test overall earthmoving zones in terms of offering higher productivity rates within earthmoving operations and the lowest cost within time constraints across all zones. The configurations V and VI are used in earthmoving operations in real road projects (identified from project documents).

Table 3 . Suggested equipment configurations.

Configuration No.	No. of trucks	No. of excavators	No. of wheel-loaders	No. of bulldozers
I	5 (Cat. 770)	2 (319DL)	1 (924Hz)	1 (D10T2)
II	3 (Cat. 772)	2 (319DL and 329D)	1 (930H)	1 (D7R)
III	5 (Cat. 772)	2 (329D)	1 (924Hz)	1 (D10T2)
IV	5 (Cat. 770)	2 (319DL)	1 (924Hz)	1 (D7R)
V	3 (Cat. 725)	1 (319DL)	–	1 (D7R)
VI	5 (Cat. 725)	1 (319DL)	–	1 (D7R)

3.2.3 Estimation and computation of time, cost, energy, and emissions

The cost and time required for each hauling operation were computed within the DES model; in the case of cost estimating, the model considers a total hourly hire cost for each configuration at each station that is based on the hourly hire cost for each item of equipment involved in earthmoving, then divided by the actual level of productivity for the specific configuration in workstations of each scenario, in order to calculate cost per unit of the hauled materials; in other words, varied values at each station were mainly dependent on the type of equipment combination used and the hauling distances between loading and dumping areas. Meanwhile, time is computed from each scenario based on a cycle time interval (minimum and maximum values) with a suitable kind of distribution that can mimic real-world behavior of each piece of equipment used in each configuration at each station, plus waiting times for each item of equipment in different areas through the scenario. In addition, the time taken to haul materials from the loading area to the dumping area was computed by dividing the hauling distance from each scenario by the assumed speed interval within specific distribution to produce a hauling time and then summed with dumping time. Equations 1–6 described above in section (2) are used to estimate energy use and CO_2 emissions per cubic meter of earthmoving for all equipment and machinery used. The energy consumption and CO_2 emissions are computed for each station by equations (7, 8), and over all earthmoving zones in the road project by equations (9, 10). At the end of this step, the values of time, cost, energy, and emissions (CO_2) for all mass hauling in each zone are computed. The results are then exported to MATLAB platform in the form of data matrices in order to start the last stage of the PSED model that focuses on providing an optimum alternative of equipment configurations to reduce earthmoving impacts. The earthmoving zones selected involved a large number of cutting and filling activities within various hauling distances to cover all variations in earthmoving conditions and requirements over the entire road project.

3.3 Equipment allocation

The results of the preceding stages are analyzed with approaches A, B, and C, with the goal of allocating equipment configurations to the earthmoving project according to the defined objectives. The results of each approach are presented in the following sections.

3.3.1 Approach A: Uniform configuration for all earthmoving zones

The first approach entails allocating one equipment configuration to the whole earthmoving process; the results of the values for time, cost, energy, and emissions (CO_2) from using different equipment configurations in three earthmoving zones are shown in Table 4. These results were computed from the simulation outputs for each configuration for conducting all earthmoving operations within each station in the three zones. The total results from the earthmoving zones (D, E, and I) show that configuration III has the lowest execution time, costs, energy use and CO_2 emissions. The individual results obtained from zones D and E show the same indicators for configuration selection that appeared in all earthmoving zones, whereas in zone I, although configuration III has the lowest execution time, there are slightly higher costs, energy use and CO_2 emissions than for configuration II. This difference is due to the difference in engine size for the equipment used in each configuration, which affects the amount of energy used and emissions (for example, the different ratios of sensitivity to increased emissions from the equipment against the change in the gradient of the haulage surface and increase density of materials excavated/hauled that basically effects on engine load). The result shows that configuration (III) in the studied zones had the lowest time, cost, energy use, and CO_2 emissions. It is therefore considered to be the first option (A) suggested when planning earthmoving operations according to approach A.

Table 4. Results by earthmoving zones and in total possible impact reduction comparison with configuration III.

Zone	Configuration	Time		Cost		Energy use		CO_2 emissions	
	No.	hour/m^3	hours	SEK/m^3	(1000*SEK)	MJ/m^3	(1000*MJ)	kg/m^3	(1000*kg)
D	I	0.0037	183.3	27.81	1539.8	66.36	3334.3	4.83	242.8
	II	0.0044	212.3	28.03	1486.1	75.37	3770.0	5.51	275.2
	III	**0.0026**	127.9	**26.46**	1215.3	**65.17**	3240.5	**4.72**	233.9
	IV	0.0037	183.5	27.16	1504.6	59.69	2991.9	4.36	218.6
	V	0.0082	413.2	36.34	1818.3	75.73	3775.9	5.39	268.9
	VI	0.0061	298.6	36.92	1791.5	78.37	3841.9	5.62	274.1
E	I	0.0032	101.2	24.01	849.8	50.84	1642.5	3.71	118.7
	II	0.0036	110.6	22.94	773.9	54.05	1642.9	3.93	118.6
	III	**0.0022**	67.8	**21.74**	644.5	**48.56**	1555.7	**3.50**	111.0
	IV	0.0032	101.1	23.41	828.9	52.08	1681.7	3.80	121.6
	V	0.0065	208.4	28.91	916.9	53.90	1702.0	3.86	120.5
	VI	0.0059	191.3	35.75	1147.6	63.21	1993.4	4.61	144.8
I	I	0.0031	210.2	23.37	1765.5	49.34	3467.9	3.57	250.1
	II	0.0028	191.0	**17.91**	1337.1	**43.192**	2946.5	**3.11**	211.4
	III	**0.0021**	138.3	21.36	1313.9	46.99	3209.6	3.39	229.3
	IV	0.0031	210.2	22.83	1723.7	50.54	3667.9	3.66	265.0
	V	0.0059	416.7	26.15	1833.7	46.30	3262.7	3.32	233.3
	VI	0.0059	416.9	35.68	2501.8	53.73	3796.6	3.88	273.6
Total	I	0.0033	494.7	24.76	4155.1	54.44	8444.6	3.95	611.6
	II	0.0034	513.9	21.90	3597.2	54.69	8359.4	3.97	605.3
	III	**0.0023**	334.1	**22.87**	3173.7	**52.43**	8005.7	**3.79**	574.3
	IV	0.0033	494.8	24.17	4057.3	53.457	8341.6	3.89	605.3
	V	0.0067	1038.	29.64	4568.8	56.28	8740.7	4.02	622.7
	VI	0.0059	906.8	36.04	5440.9	62.81	9631.9	4.54	692.6
Approach (A)	I		32%		24%		5%		6%
	II		35%		12%		4%		5%
	III		---		---		---		---
	IV		32%		22%		4%		5%
	V		68%		31%		8%		8%
	VI		63%		42%		17%		17%

3.3.2 Approach B: Mixed configurations per earthmoving zone

The second approach selects configurations based on each studied station and on the total impacts of earthmoving zones, thus providing a mixed configuration in every earthmoving zone. This mix is achieved through a multi-objective particle swarm optimization (MOPSO) method in order to find all possible tradeoffs between the conflicting objectives (Goh et al., 2010). Using MOPSO reveals tradeoffs between time, cost, and environmental impact within defined constraints and conditions, thereby finding optimal selection solution(s) in terms of equipment configurations, together with their related impacts. The optimum results are known as non-dominated solutions because in such cases there are no other solutions superior in all features that can represent a set of non-dominated solutions lying along a surface called the "*Pareto front*" (Horn et al., 1994). The Pareto concept is also commonly termed the Pareto optimal set, or efficient points and admissible points (Fonseca and Fleming, 1993). Kalyanmoy (2001) showed that Pareto solutions are non-dominated with output matrices, but they are better than other non-Pareto options in multi-objective problems. However, tradeoffs among conflicting objectives through moving between Pareto solutions always lead to a sacrifice in one objective to achieve a gain in (an)other (Konak et al., 2006). According to Lavin, (2015) there are two general methods that produce multi-objectives optimization: (i) a single, composite function that combines the individual objectives, and (ii) determining a Pareto optimal solution set, which is the approach adopted in this study. The discrete variables in the input matrices represent various equipment configurations in respect of our target values from each configuration, with a maximum value against earthmoving quantities in every station.

In order to increase the dominance tournaments among the competing outputs of MOPSO, the input data of 50 earthmoving configurations (i.e. random configuration selections from simulations with higher impacts) was included with the existing six configurations selected previously so as to investigate the ability of approach (B) to reduce total earthmoving impacts. MOPSO was automatically processed for 70 runs (i.e. repetition for PSO running time) to improve the algorithm performance and thereby to increase the accuracy of optimization. Thus, the matrices of earthmoving impacts for the proposed equipment configurations were entered into the MATLAB platform to perform PSO optimization that was employed to manage the tradeoff between time, cost, and environmental impact over all equipment configurations and throughout all stations within the three zones.

Although for optimization purposes 50 earthmoving configurations were tested over 43 earthmoving stations throughout the three zones, the useful outputs were only four Pareto options (shown in Table 5a) that were produced in 42.0 seconds. These options represent the number of configurations obtained as optimum solutions within the set of Pareto feasible solutions (i.e. number of points that draw an imagined surface of limited area of optimization). Thus, based on the project considerations and preferences, planners can select from any of these Pareto options, which are non-dominated with each other on all entered options (i.e. the metrics of input impacts). In this case, mitigating the environmental impact of the earthmoving operations with the lowest effect on the execution costs estimated in the previous step is the criterion used to select the configuration-mix within options shown in Table 5b. Thus, when compared to approach (A), approach (B) can reduce the environmental impact (7% and 6% respectively) for energy use and CO_2 emissions, with approximately the same cost and only a longer duration ~ 21%.

Table 5a. Total amount of time, cost, and emissions for four optimum outputs within the Pareto feasible solution.

Pareto Optimal Output	Time (hours)	Cost (1000*SEK)	CO_2 (1000*kg)
Optimal Output 1	439.5	3265.5	560.0
Optimal Output 2	406.8	3205.9	534.7
Optimal Output 3	**412.9**	**3177.8**	**539.6**
Optimal Output 4	408.9	3083.6	574.9

Table 5b. Configuration selection based on MOPSO by earthmoving station.

Zone	Station	Quantity (m^3)	Hauling Distance (m)	Configuration No.	Zone	Station	Quantity (m^3)	Hauling Distance (m)	Configuration No.
D	12950-13958	2426	3267.5	IV	I	6435-7325	1815	1885	III
		1765	3250	IV			1524	1393.6	III
		405	2823.2	III			1636	1250	III
		7006	2500	IV			288	1154	II
		2122	1717.5	IV			2407	1005.4	III
		8054	462.5	II			5034	801.3	III
		2548	197.5	V			2290	760.4	II
		1396	107.5	II			1478	685.4	III
		3901	4000	IV			7582	580.4	II
		3901	4092.5	IV			1629	510.4	II
		6086	4215	III			3500	440.7	II
		8565	4325	IV			7218	362.9	II
E	12199-12950	2407	2074.6	III			258	130	II
		5074	2177.1	III			3402	117.9	II
		2059	2231.4	IV			7101	250	III
		2411	2302.1	IV			748	500	II
		2685	4043.4	III			4268	697.5	II
		2790	125.5	II			707	1302.5	II
		7959	98.9	II			145	1462.5	II
		522	1701	III			17920	1575.5	III
		952	1851.2	III			408	1750	V
		5600	1945	III					

3.3.3 Approach C: Configuration based on mass hauling distances

A third approach to decision-making in the final stage of the PSED is achieved by analyzing the effects of changing haulage distances for each equipment configuration at each station in each zone against the target parameters in the final earthmoving plan. The results in Figures 5-10 show that equipment configuration (II) can be considered a more suitable configuration to use in earthmoving operations in the project when hauling earth/materials over distances of less than 1.5 km (where all other project conditions remain constant). Configuration (III) is superior for minimizing earthmoving impacts at haulage distances of between 1.5 km and 5.0 km. The results show an incremental cost and emissions (CO_2) per each cubic meter of earth moved with increasing haulage distances for different sizes of earthmoving operations in each zone. The non-linear behavior of the increase in the target parameters in Figures 5-10 is due to variations in the operational characteristics for configurations and project conditions for every station.

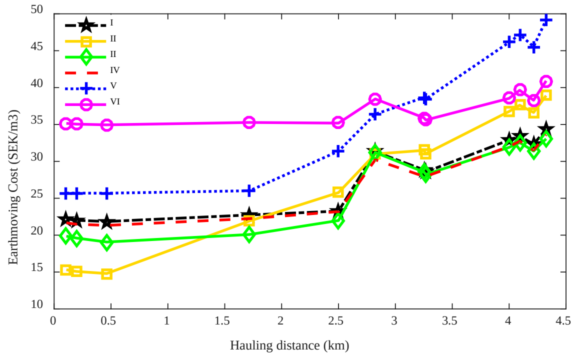


Fig. 5. Cost per unit of mass hauling by configuration in zone D.

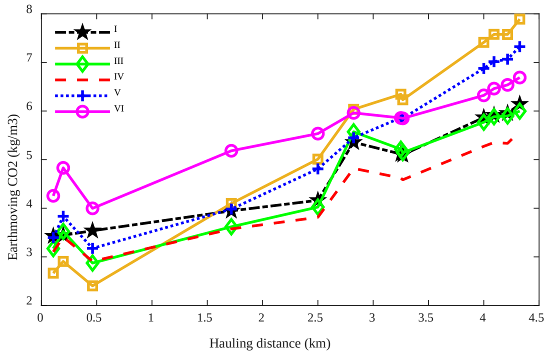


Fig. 6. CO_2 emissions per unit of mass hauling by configuration in zone D.

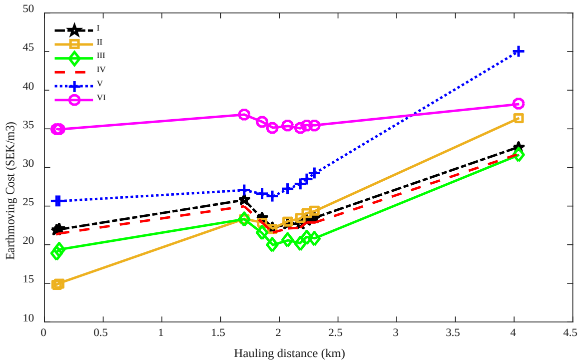


Fig. 7. Cost per unit of mass hauling by configuration in zone E.

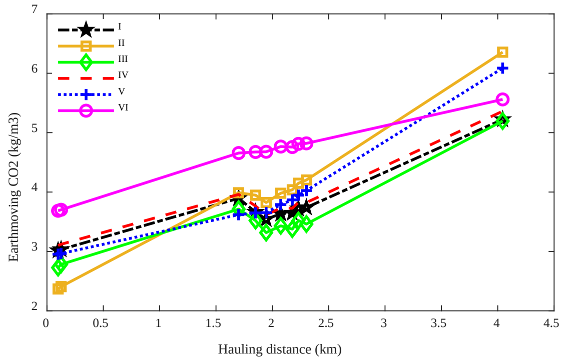


Fig. 8. CO_2 emissions per unit of mass hauling by configuration in zone E.

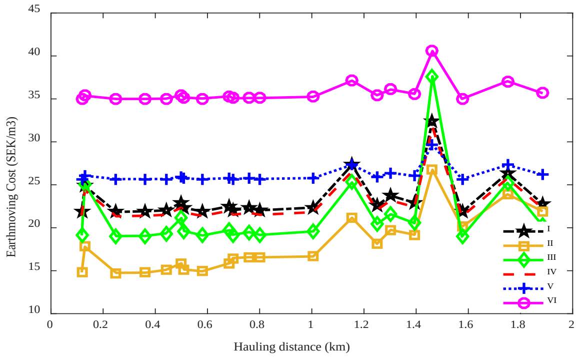


Fig. 9. Cost per unit of mass hauling by configuration in zone I.

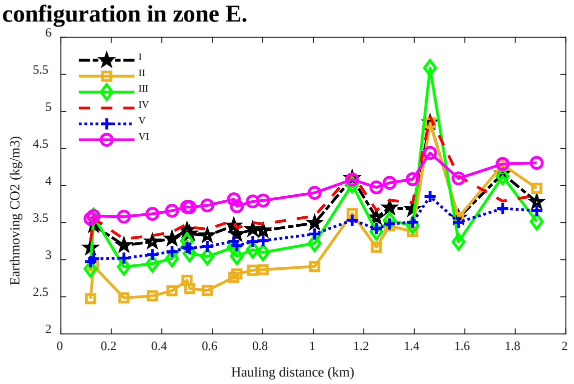


Fig. 10. CO_2 emissions per unit of mass hauling by configuration in zone I.

3.4 Comparisons with other technical terms/concepts

To ensure that the results of the aforementioned equipment allocation approaches are realistic and in agreement with findings from other researches some additional data are introduced to enable comparisons. The idea was to test the realism of our proposed/adopted approaches vis-à-vis different indications of earthmoving equipment/configurations by comparing them to other studies that have used similar elements or terms. Therefore, this study chose three terms frequently used in earthmoving operations management to support decision-making in cases of equipment selection: (i) weighted impact of equipment, (ii) equipment utilization rates, and (iii) utility rates of equipment configurations.

3.4.1 Weighted impact of equipment

In the context of evaluating the effects of each type of equipment on the total performance of earthmoving projects, this subsection specifically shows the major impacts of the main equipment used in the earthmoving operations. These impacts are figured in terms of cost and emissions (CO_2) as an indication or benchmark for selecting equipment combinations that are more suitable for operating in earthmoving in road and infrastructure projects when compared to other similar types of equipment. There are two particularly significant factors that emerge regarding equipment operations that can be used as indicators to guide planners considering the primary impact of the use of each equipment type in earthmoving projects. These are represented by a cost weighted ratio for each piece of equipment against total cost, and by an emissions weighted ratio for each piece of equipment against total emissions. The weighted ratios for each piece of equipment in the entire earthmoving operation are calculated in the last stage of the PSED model because all values of earthmoving operations needed to calculate these indicators should have been accounted for at the end of stage three of the PSED. Each factor is computed by dividing the sum of the total multiplying cost or emissions for each type of equipment throughout the earthmoving project by the total cost or emissions of the earthmoving equipment. Above all, the fundamental idea of this subsection is to demonstrate the degree of agreement between the final outputs of this study and real-world operations; in other words, the aim is to show its planning strength by mimicking and representing real-world operations that had been measured or estimated by other studies. The weighted ratios of equipment are calculated by using Equations 11 and 12:

$$C_{wr} = \frac{\sum_{i=1}^{n} C_i \,.\, T_i}{\sum_{j=1}^{m} \sum_{i=1}^{n} (C_i \,.\, T_i)_j} \tag{11}$$

$$E_{wr} = \frac{\sum_{k=1}^{l} E_k \,.\, V_k}{\sum_{q=1}^{r} \sum_{k=1}^{l} (E_k \,.\, V_k)_r} \tag{12}$$

Where C_{wr} is the cost weighted ratio for the specific type of equipment against total cost of earthmoving operations (decimal) (see Table 6), C_i represents the hourly hire cost of a specific item of equipment used in earthmoving operations, T_i represents the time of operating a specific item of equipment in each earthmoving station (where i = 1, 2, 3, …. n; n = number of total stations in a road project. and j = 1, 2, 3, …. m; m = total different types of equipment used in the earthmoving operation), E_{wr} is the energy or emissions weighted ratio for the specific type of equipment against total energy or emissions of the earthmoving operation (decimal) (see Table 6), E_k is energy or emissions per cubic meter of matter produced from operating a specific type of equipment in each station (MJ or kg/m^3), and V_k is the volume of earthmoving in each station (m^3) (where k = 1, 2, 3, …. l; l = number of mass haul stations in earthmoving operations. and q = 1, 2, 3, …. r; r = total different types of equipment used in the earthmoving operation). Table 6 represents weighted ratios in terms of cost and emissions for each type of equipment used in each configuration throughout the earthmoving zones.

Table 6. Cost and emissions weighted ratios of different equipment in the earthmoving project.

Zone	Conf. No.	Weighted ratio of total cost				Weighted ratio of total emission			
		Truck	Loader	Exc.	Bull.	Truck	Loader	Exc.	Bull.
D	I	0.595	0.095	0.1667	0.143	0.751	0.057	0.102	0.109
	II	0.471	0.143	0.243	0.143	0.578	0.071	0.192	0.159
	III	0.579	0.084	0.211	0.126	0.741	0.058	0.115	0.107
	IV	0.609	0.097	0.171	0.122	0.699	0.064	0.113	0.146
	V	0.545	---	0.227	0.227	0.792	---	0.048	0.159
	VI	0.667	---	0.167	0.167	0.851	---	0.034	0.115
E	I	0.595	0.095	0.167	0.143	0.711	0.072	0.117	0.123
	II	0.471	0.143	0.243	0.143	0.561	0.092	0.164	0.182
	III	0.579	0.084	0.211	0.126	0.701	0.070	0.134	0.118
	IV	0.609	0.097	0.171	0.122	0.694	0.0696	0.115	0.144
	V	0.545	---	0.227	0.227	0.765	---	0.057	0.178
	VI	0.667	---	0.167	0.167	0.819	---	0.043	0.137663
I	I	0.579	0.084	0.211	0.126	0.686	0.077	0.142	0.119
	II	0.471	0.143	0.243	0.143	0.552	0.104	0.166	0.178
	III	0.595	0.095	0.167	0.143	0.701	0.077	0.124	0.124
	IV	0.609	0.097	0.171	0.122	0.683	0.076	0.120	0.145
	V	0.545	---	0.227	0.227	0.749	---	0.063	0.187
	VI	0.667	---	0.167	0.167	0.863	---	0.054	0.083

The results show that trucks have a large impact on the total costs and CO_2 emissions, ranging from 47%-67% and 55%-85% respectively, across all studied equipment configurations. Configurations using one loading area (i.e. V and VI) or a greater number of trucks (i.e. I, III, IV, and VI) have higher weighted ratios for trucks overall. In addition, the cost weighted ratio for excavator and bulldozer was the same in configurations V and VI due to each piece of equipment having one unit being operated in the configuration but with the same hourly rental costs and total operating times. Differences in weighted ratios for CO_2 emissions are due to equipment power, load factors, and project conditions. Figure 11 and Figure 12 presents the mean weighted ratios of cost and CO_2 emissions respectively, for all studied equipment configurations. The weighted ratio for CO_2 emissions are in close agreement with those presented by Li and Lei (2010), with the exception for wheel-loaders, where our numbers are about three percentage points higher. This disparity can likely be explained by differences in engine sizes.

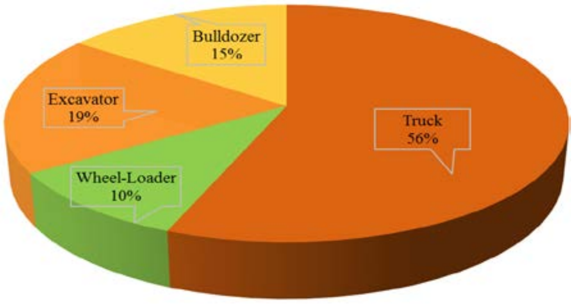


Fig. 11. Cost weighted ratio for each equipment type.

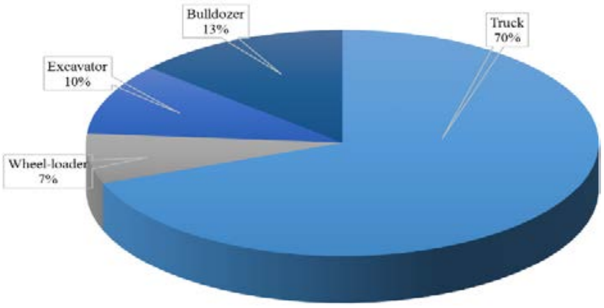


Fig. 12. Weighted ratio of CO2 emissions by equipment type.

3.4.2 Equipment utilization rates

Operational efficiency measures such as the utilization rate of earthmoving equipment often correlates to lower CO_2 emissions, costs, and duration (Krantz et al., 2019). Since Ezstrobe records utilization data of equipment, we are able to investigate whether our studied earthmoving operations display similar patterns. The utilization rate is the time spent non-idle as a percentage of total work time. Thus, the idle time considered may be conveniently summarized as queuing trucks, no trucks to load, and no material to spread. Table 7 shows average utilization rates for each equipment type by configuration and earthmoving zone.

Table 7. Total average utilization rates of equipment in different configurations and zones.

Zone	Conf. No.	Utilization Rate				Zone	Conf. No.	Utilization Rate			
		Truck	Loader	Exc.	Bull.			Truck	Loader	Exc.	Bull.
D	I	0.802	0.660	0.804	0.197	E	IV	0.762	0.721	0.921	0.225
	II	0.912	0.498	0.605	0.158		V	0.856	---	0.909	0.178
	III	0.792	0.679	0.757	0.209		VI	0.573	---	0.978	0.192
	IV	0.804	0.656	0.803	0.197	I	I	0.574	0.715	0.951	0.229
	V	0.852	---	0.751	0.147		II	0.836	0.623	0.857	0.223
	VI	0.707	---	0.949	0.186		III	0.590	0.769	0.919	0.253
E	I	0.762	0.719	0.921	0.225		IV	0.575	0.716	0.951	0.229
	II	0.894	0.537	0.687	0.179		V	0.658	---	0.981	0.192
	III	0.783	0.770	0.893	0.247		VI	0.395	---	0.981	0.192

The utilization rates correlate with the performance of uniform equipment configurations in terms of the earthmoving impact objectives in Table 4. Configuration III, which was seen as a particularly competitive configuration, balances the truck and excavator utilization rates at a high level in zones D and E, while also delivering the highest loader and bulldozer utilization rates. Zone I, which has considerably shorter hauling distances than zones D and E, did not show similar balanced utilization rates for configuration III.

Approach C selected configurations II and III as optimal for hauling distances <1.5km and >1.5km respectively. Table 8 specifically considers the utilization rates according to these hauling distance intervals. The results show that excavators consistently have higher utilization rates than trucks for all earthmoving stations of hauling distances of <1.5km, indicating the significance of excavators to ensure quicker throughput of trucks. This pattern is especially evident in zone I in Table 8, where ~85% of its stations fall below the <1.5km hauling distance threshold.

Table 8. Average utilization rates for each item of equipment per configuration and zones based on haul distances.

Zone	Conf. No.	Utilization rate for hauling distances <1.5km				Zone	Conf. No.	Utilization rate for hauling distances ≥1.5km			
		Truck	Loader	Exc.	Bull.			Truck	Loader	Exc.	Bull.
D	I	0.459	0.757	0.993	0.242	D	I	0.917	0.628	0.741	0.182
	II	0.747	0.697	0.974	0.258		II	0.966	0.431	0.483	0.124
	III	0.480	0.832	0.969	0.270		III	0.896	0.628	0.685529	0.188
	IV	0.461	0.758	0.993	0.241		IV	0.918	0.622	0.741	0.182
	V	0.479	---	0.998	0.195		V	0.977	---	0.669	0.131
	VI	0.287	---	0.998	0.195		VI	0.846	---	0.934	0.183
E	I	0.428	0.763	0.994	0.243	E	I	0.846	0.708970	0.903	0.219
	II	0.694	0.704714	0.982731	0.261		II	0.944	0.494835	0.613	0.159
	III	0.449	0.842	0.988	0.275		III	0.867	0.752521	0.869	0.240
	IV	0.427	0.763	0.994	0.243		IV	0.846	0.711236	0.904	0.220
	V	0.434	---	0.999	0.196		V	0.962	---	0.887	0.174
	VI	0.260	---	0.999	0.196		VI	0.651	---	0.973	0.191
I	I	0.544	0.716	0.955	0.230	I	I	0.754	0.713	0.932	0.226
	II	0.823	0.643	0.885	0.231		II	0.912	0.504	0.688	0.178
	III	0.558	0.775	0.920	0.254		III	0.782	0.735	0.91456	0.249
	IV	0.545	0.716	0.954	0.230		IV	0.753	0.714	0.932	0.226
	V	0.616	---	0.982	0.193		V	0.907	---	0.973	0.191
	VI	0.369	---	0.982	0.193		VI	0.545	---	0.975	0.191

For mass haulage distances ≥1.5km, configuration III exhibits a better balance between truck and excavator utilization rates. Trucks perform especially consistently at a higher utilization rate than for hauling distances <1.5km. Similar to the results in Table 7, the wheel-loader and bulldozer utilization rates in configuration III are consistently the highest among all of the configurations.

3.4.3 Utility rate of earthmoving equipment configuration

Utility theory is used here as decision support by assigning each equipment configuration a numerical index which can be described as the degree of fulfillment of the decision-maker's objectives or preferences. Such "preference" indexes are values between a minimum to maximum limit that consist of quantity units translated into utility units (Keeney and Raiffa, 1993). Utility functions can be represented as graphs, tables, or mathematical formulas (Clement, 1991). Furthermore, mathematical formulas of utility functions can be represented by the linear, logarithmic, or exponential expression (Marzouk and Moselhi, 2003).

Equation (13) is used to represent the utility value based on the average utilization rate, type, number, and cost weighted ratio for each type of earthmoving equipment, total material quantity, and costs. Keeney and Raiffa (1993) recommended that the most desirable scenario corresponds to the highest utility value. In our case the equipment configuration utilization rates of 100% and 10% represent utility values between (0.1–1). The utility values for the four performance measures are calculated as follows:

$$U_{TEC} = \left(\frac{\sum_{i=1}^{n}(U_{ar}.N_e.C_{wr})_i}{T_{NE}\,.r_d}\right).\left(\frac{T_Q}{T_{EC}}\right) \tag{13}$$

Where U_{TEC} = utility rate for earthmoving operations efficiency per equipment configuration, U_{ar} = average utilization rates per equipment type in an equipment configuration, N_e = number of equipment types per configuration, C_{wr} = cost weighted ratio for the specific type of equipment against total cost of earthmoving operations (decimal), and where i = 1, 2, 3, …. n; n = the total different types of equipment used in each earthmoving configuration. T_{NE} = total number of items of earthmoving equipment used in a specific earthmoving configuration, r_d = adjusted factor to the range of utility index distribution (0.037). T_Q = volume of earthmoving materials hauled by earthmoving configuration, and T_{EC} = total cost of earthmoving operations by configuration.

Table 9. Utility rates per equipment configuration in each zone.

Zone	Conf. No.	Utility rate for earthmoving configurations selected in Uniform combination approach (A)	Utility rate for earthmoving configurations selected in approach (C)	
			hauling distances < 1.5km	hauling distances ≥ 1.5km
D	I	0.01411	0.01428	0.01408
	II	0.01369	0.02650	0.01174
	III	0.01763	0.01976	0.01717
	IV	0.01462	0.01477	0.01459
	V	0.01558	0.01897	0.01489
	VI	0.014854	0.01016	0.01630
E	I	0.01703	0.01387	0.01749
	II	0.01796	0.02597	0.01557
	III	0.02284	0.01953	0.02311
	IV	0.01765	0.01430	0.01816
	V	0.02134	0.01841	0.02151
	VI	0.01386	0.00978	0.01482
I	I	0.01562	0.01522	0.01796
	II	0.02328	0.02532	0.01917
	III	0.02132	0.02070	0.02490
	IV	0.01609	0.01566	0.01860
	V	0.01247	0.02065	0.00701
	VI	0.01157	0.01123	0.01360

Table 9 shows that equipment configurations II and III have the highest utility rates for hauling distances (<1.5km) and (≥1.5km) respectively, based on the outputs of approach C. Configuration III has the highest utility rate among uniform equipment configuration in zones D and E, while configuration II has the highest rate in zone I. This is in agreement with the utilization rates and is likely caused by 85% of the hauling distances in the zone being <1.5km. These results show that utility rates may also efficiently support the selection of equipment configurations related to mass hauling distances.

3.5 Summarized results and discussion

In this study, DES can essentially be seen as part of the search for an optimum allocation of equipment in earthmoving projects; the intention is to offer a range of possible solutions that could help in making decisions about the final configurations that can support the most effective mass haulage plan for any major project, all factors considered. It is important to note that certain changes in the configurations of earthmoving equipment will influence project duration, costs, and environmental impacts. Therefore, a proper DES should provide efficient planning techniques for equipment selection in earthmoving operations that have positively improved costs and/or broken other constraints. The environmental impacts are considered as variables in the simulation stage of the PSED and estimated directly from the DES model at each scenario based on the relevant assessment formula for each piece of equipment that has considered machinery characteristics and specific site conditions. Thus, the planner should note the ability of this stage to reduce these impacts, too. The simulation mechanism could provide a result with satisfactory performance outputs without imposing on other objectives, which can be an option for a planner to consider when decision making. Although this step is primarily important in assessing the overall earthmoving project impacts during the planning stage, the outputs of this step can nevertheless be considered as significant references or benchmarks for monitoring and evaluating the performances of these operations during execution stages.

The results of the three alternative approaches for allocating equipment configurations evaluated in this case study are summarized in Table 10, Figure 13 and Figure 14. Approach A, which entails using one configuration for the whole earthmoving process, showed that configuration III was superior to the other configurations with regard to duration, costs, energy use, and CO_2 emissions. Approach B, which uses mixed configurations for each earthmoving zone, showed potential for further reducing CO_2 emissions by ~6%, and energy use by ~7%, but adding ~0.1% in costs and ~21% in duration compared with approach A. Approach C was used to allocate equipment configurations on the basis of hauling distances. It was found that configuration II was superior in terms of costs and CO_2 emissions at distances <1.5km, whereas configuration III was superior at distances ≥1.5km. Compared to approach B, approach C enabled a reduction of CO_2 emissions, energy use, costs, and execution time by 1.4%, 1.1%, 3.6%, and ~10.5% respectively. In comparison with the optimum configuration from approach A (i.e. configuration III), this approach yielded a reduction of ~3.4% in costs, ~8.1% in energy use, and ~7.4% in CO_2, while increasing duration of ~10%. Tables 4 and 10 also show a significant term related to construction operations that is called a function unit of earthmoving impact for each target parameter (i.e. it is used to identify the impact for each target value per cubic meter of material produced from the earthmoving operations), which is important in this study for two reasons; firstly, it can show the consistency of relation between these values and the totality of each impact; secondly, it shows the influence of earthmoving volumes (m3) for each station on the total impacts from a zone, for instance, the situation of earthmoving operations in zone I.

Table 10. Results in terms of time, costs, and environmental impacts of the studied approaches.

Configuration No.	Time		Cost		Energy		Emission (CO_2)		Profit of approach (C) comparing with all configurations proposed			
	hour/ m^3	hours	SEK/ m^3	(1000* SEK)	MJ/m^3	(1000* MJ)	kg/m^3	(1000* kg)	Time	Cost	Energy	Emission
I	0.0033	494.7	24.8	4155.1	54.4	8444.6	3.95	611.6	25.2%	26.2%	12.8%	13.0%
II	0.0034	513.9	21.9	3597.2	54.7	8359.4	3.97	605.3	28.0%	14.7%	11.9%	12.1%
Approach (A)	**0.0023**	334.1	22.9	3173.7	52.4	8005.7	3.79	574.3	-10.7%	3.4%	8.0%	7.5%
IV	0.0033	494.8	24.2	4057.3	53.5	8341.6	3.89	605.3	25.2%	24.4%	11.7%	12.1%
V	0.0067	1038.4	29.6	4568.8	56.3	8740.7	4.02	622.7	64.4%	32.8%	15.8%	14.6%
VI	0.0059	906.8	36.0	5440.9	62.8	9631.9	4.54	692.5	59.2%	43.6%	23.6%	23.2%
Approach (B)	0.0028	412.9	21.7	3177.8	49.7	7443.3	3.80	539.6	10.5%	3.5%	1.1%	1.4%
Approach (C)	0.0025	370.15	**20.6**	3068.0	**49.3**	7361.5	**3.57**	532.0	---	---	---	---

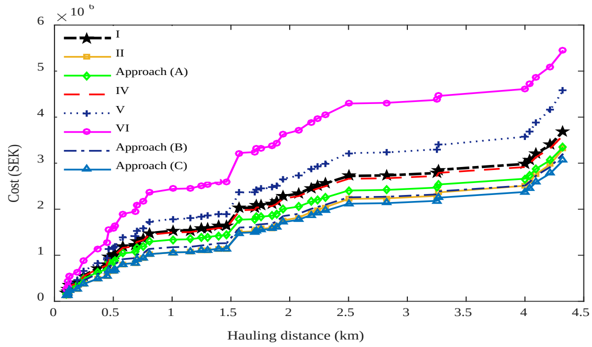


Fig. 13. Cumulative earthmoving costs per configuration.

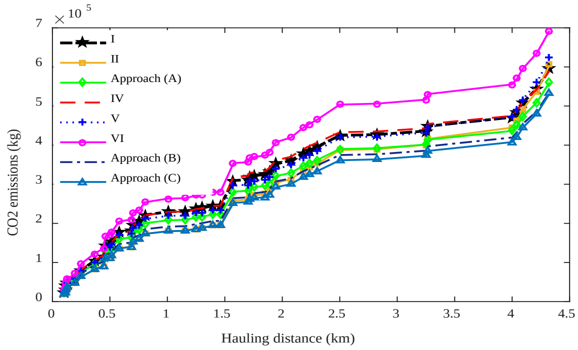


Fig. 14. Cumulative earthmoving CO_2 emissions per configuration.

4. Conclusions and implications

This study set out to propose a comprehensive model, called PSED, to help reduce the duration, costs, and GHG emissions of earthmoving processes undertaken during major construction/infrastructure projects. The model was used to identify and allocate suitable equipment configurations to an earthmoving project and its different earthmoving zones. A case study consisting of 43 earthmoving stations of varying character was conducted to demonstrate the ability of the model to quantify the aforementioned objectives. Earthmoving equipment configurations were allocated based on their performance according to the following approaches: (A) earthmoving zones, the more detailed (B) earthmoving stations, and (C) hauling distances.

The results of approach A showed considerable differences between the initially identified configurations in terms of costs, duration, CO_2 emissions, and energy use. Thus, the approach may be powerful if allocating one equipment configuration to a given earthmoving project or single zone. Approach B could potentially generate further savings in terms of all objectives, although our case study only showed reductions in terms of CO_2 emissions and energy use, with the same range of costs and *increased* duration compared to approach A. Approach C investigated the results by hauling distance, and provided in our case study an intersection point between configuration II and III at hauling distances of around 1.5 km both with regard to costs and CO_2 emissions. Furthermore, this approach turned out to be superior to the other approaches in terms of costs, energy use, and CO_2 emissions. Functional units of earthmoving operations' impact can play an important role in providing the simplest way to allocate equipment for earthmoving zones that have stations with harmonic earthmoving characteristics (e.g. quantity and hauling distances).

To substantiate the case study results, we studied the overall impact of equipment types, the utilization rates by equipment type, and the utility of each configuration. Utility theory is widely used to support decisions in construction management and should indicate the performance level of each configuration in terms of the objectives considered. In our case the highest utility rates corresponded with the best performing equipment configurations. The interaction between truck and excavator utilization rates is another potentially significant indication to consider for the overall performance of equipment configurations. The results of configurations II and III indicated that high and balanced truck and excavator utilization rates may be a powerful way of reducing adverse project impacts. Increased truck utilization rates are particularly important in decreasing negative project impacts, especially in the case of hauling distances of <1.5km, demonstrated by the performance of configuration II. The importance of trucks was further demonstrated by their overall cost and CO_2 emissions impact as seen in Figure 11 and Figure 12, indicating the necessity of putting more effort into the primary selection of configurations. Worth noting here is the considerably higher cost than environmental impact of the excavator both when single and double loading areas are used. This suggests that the choice of excavator may be particularly important when managing project costs. Bulldozers also display a significant effect on the configuration performance as high utilization rates correlate with higher overall performance.

The model may be attractive for contractors seeking to manage impact reductions and the necessary tradeoff decisions (Ahn et al., 2009), particularly since costs were included as an objective (Jukic and Carmichael, 2016). Given that approach C was superior to the other approaches, the simple rule-based results derived from it may simplify implementation and increase understanding among equipment operators, site managers, and others at the construction site. Indeed, simplicity is crucial since construction projects are often burdened with onerous cost and time constraints, severely limiting the ability of the project organization to adopt novel and complex guidelines or approaches (Jacobsson and Linderoth, 2010). But, even though the results derived are simple, running the PSED model is complex, and consequently usage of the tool may be most suitable mainly for central organizations of construction companies rather than those on the ground. In the short term it may be used to appoint equipment configurations to projects (together with the simple rule-based guidelines); in the longer term it could also support strategic decisions regarding equipment acquisitions and management of the equipment fleet.

In a nutshell, the equipment weighted impacts (cost and emissions) and utilization rates, and configuration utility rate are typically considered the important terms of such projects; as stated earlier, these factors were incorporated here for the following reasons: (i) to validate the planning outputs of PSED by comparison with impact ratios for earthmoving equipment in other researches, as well as the significance of the utilization rate to mitigate impacts; and (ii) to support the adopted approach in this study of selecting configurations that show agreement with utility theory.

The case study considered a wide range of various effects on earthmoving operations, for example, the density of materials excavated/hauled, payload, grade, and rolling resistance for trucks, as well as the haulage distance from different points into/from/to the road construction project. However, to enable the approach to be applied more generally, more cases studies are needed, particularly involving a greater number of equipment configurations and alternative fuels. Such studies may be useful in identifying additional simple rule-based equipment allocation approaches to enable wider implementation among organizations involved in planning and executing major construction projects.

Acknowledgement

This study was funded by the Development Fund of the Swedish Construction Industry (SBUF), and supported by NCC AB.

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