LICENTIATE THESIS

Reducing Carbon Dioxide Emissions in Transport Infrastructure Projects

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Construction Engineering and Management

LULEÅ
UNIVERSITY
OF TECHNOLOGY

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REDUCING CARBON DIOXIDE EMISSIONS IN TRANSPORT INFRASTRUCTURE PROJECTS

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Preface

I would like to acknowledge my supervisor, Thomas Olofsson, and co-supervisors, Weizhuo Lu and Johan Larsson, for all of their support leading to this licentiate thesis. I would also like to acknowledge everybody who has helped me during my academic career. Thank you all for supporting me in this journey.

Abstract

On- and off-site construction activities during transport infrastructure projects are major contributors to greenhouse gas (GHG) emissions. The Swedish Transport Administration (STA) has stated the goal of gradually reducing its emissions from transport infrastructure projects to zero by 2050. However, current life cycle assessment (LCA)-based approaches for estimating GHG emissions are static and location-independent, and thus do not account for the dynamics of construction. Some project-based methods have been proposed, but there is little guidance and insight available to facilitate their implementation in real projects during project planning.

This thesis aims to explore how CO_2 emissions can be reduced during different stages of the planning process for transport infrastructure. The analysis focuses on emissions during project execution, i.e. on- and off-site construction activities including material production, and transportation. An exploratory research approach is used to develop practical CO_2 reduction methods that could be implemented during the feasibility studies, the design stage, and the procurement stage of the planning process. These methods and models are developed and demonstrated in case studies. This is a similar to the prototyping method in which early drafts of a new system are developed and tested to enable further development into a finalized system. The findings show that considerable CO_2 reductions can be achieved if project alternatives are evaluated systematically during the planning process. Although most major decisions are made during the early stages of the planning process, later stages should not be ignored because these offer opportunities to include more definitive project data and thereby improve the certainty of the assessments. Future research in this area should look at the entire planning process up to the start of construction.

Contents

List of papers

1.1 Appended papers

Paper I:
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.

Authors’ contributions
Johansson and I formulated the idea of the paper. We collaborated on pre-processing and collecting data. As the main author, I wrote the paper.

Paper II:
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.

Author contribution
The main idea of the paper was conceived by all the authors. As main author, I conducted the data gathering, processing and paper writing. The co-authors contributed during the process by providing feedback and ideas.

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.

Authors' contributions

The idea of the paper was developed by all authors. The model and demonstration were developed jointly with Johan Larsson, while I wrote and compiled most of the paper.

1.2 Peer-reviewed papers

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. 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.

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.

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.

2 INTRODUCTION

The introduction presents the background to the thesis and explains why the conducted research is important. It also describes the thesis' aim and scope.

2.1 Background

Anthropogenic greenhouse gas (GHG) emissions are a serious concern (IPCC 2014) and could potentially drive the Earth system into a new, much less hospitable, state (Steffen et al. 2015). The most important anthropogenic GHG is CO_2, of which an estimated 35 Gton were emitted by human sources in 2012 (Olivier et al. 2012). More than 3 times this amount, an estimated 122 Gton of CO_2, is embodied in the Earth's built environment (Müller et al. 2013). To this number, Sweden alone annually adds an estimated 10 Mton of CO_2, of which 3 Mton is attributed to transport infrastructure (IVA 2014). The Swedish Transport Administration (STA) has stated the goal of gradually reducing CO_2 emissions from transport infrastructure projects, with intermediate goals of a 15% reduction by the year 2020 and 30% by 2030 before becoming entirely climate neutral by 2050 (Trafikverket 2016). There are several important sources of CO_2 emissions in transport infrastructure projects. The on-site work is often characterized by extensive use of heavy-duty diesel (HDD) construction equipment and earthmoving equipment (Hajji and Lewis 2013), often handling large quantities of soil and rock (Kenley and Harfield 2011). Transport infrastructure projects also often require crushed aggregate, asphalt and concrete, all of which are associated with substantial CO_2 emissions (Zapata and Gambatese 2005). Prefabrication of materials such as steel and bridge components can also generate considerable emissions (Du and Karoumi 2013).

The project life cycle of transport infrastructure, shown in Figure 1, consists of project execution together with initiation, planning and closure phases. Early in the planning process, i.e. during the feasibility studies, broad investigations are conducted, often by evaluating various alternative corridors for the planned transport infrastructure (Kim et al. 2014). In the following stage, i.e. preliminary design, the location of the planned infrastructure within the corridor is finalized and its geometric properties are specified. In the next stage, the detailed design is drawn up and the project is planned for construction by the contractors selected for the project.

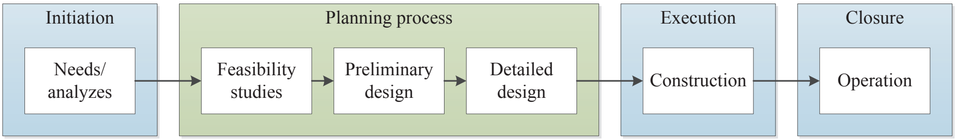

Figure 1. The project life cycle of transport infrastructure projects. Adapted from the work of Larsson (2013).

Previous studies in this area have not provided adequate practical methods for mitigating CO_2 emissions from transport infrastructure projects. Several authors have observed that most existing life cycle assessment (LCA)-based approaches are both static (Thiede et al. 2013) and location-independent (Reap et al. 2008; Ross et al. 2002), and so do not account for the dynamics of real transport infrastructure projects. The CO_2 reduction goals defined by agencies such as the STA (Trafikverket 2016) will only be achieved if project participants are committed to addressing these issues. Despite this, previous publications describing methods for evaluating emissions from construction equipment (Abolhasani et al. 2008; Frey et al. 2010), construction activities (Hajji and Lewis 2013), and entire projects (Melanta et al. 2013) have typically paid little attention to the practical implementation and use of these methods during ongoing projects. Indeed, many studies have only evaluated environmental issues related to transport infrastructure in projects whose construction has already been completed (Kenley and Harfield 2011). Most major decisions and investments in a project are made early in the planning process, leaving only smaller decisions for later planning stages (Paulson 1976). The same is true for decisions affecting CO_2 emissions (Bogenstätter 2000), which suggests that large-scale CO_2 reduction measures must be planned and prepared at a relatively early stage in the planning process if they are to be implemented in the construction phase. Furthermore, by comparing alternatives to a base scenario, reductions and their estimated magnitude can be established (Trani et al. 2016; Fernández-Sánchez et al. 2015). To overcome the aforementioned limitations, CO_2 mitigation approaches should use available project-specific data during the planning process and provide practical implementation guidance to ensure that the predicted CO_2 reductions are actually achieved.

2.2 Aim and scope

The aim of this thesis is to explore and propose project-specific methods to be applied during the planning process for reducing CO_2 emissions during the subsequent construction of transport infrastructure. Each stage of the planning process has a specific character that affects the potential for CO_2 reduction. Therefore, practical methods are proposed for each of the following planning stages:

- Feasibility studies
- Preliminary design
- Detailed design

The thesis focuses exclusively on methods for reducing CO_2 emissions during the construction stages of the project life cycle, and therefore excludes operation, maintenance, and end of life treatment. From an LCA perspective, the thesis covers the upstream activities of transport infrastructure projects, i.e. all the necessary processes prior to the operational stage.

3 RELATED LITERATURE

This chapter presents the main theoretical concepts that the research in this thesis is based on or related to. It first presents related studies that evaluate emissions connected to transport infrastructure construction processes from an LCA perspective and in terms of on-site emissions. The next section focuses on optimization of mass hauls. The last section discusses discrete event simulation (DES) and building information modelling (BIM), and their use in transport infrastructure settings.

3.1 Emissions in transport infrastructure construction

A range of different perspectives have been adopted in literature studies on the estimation of CO_2 emissions and other emissions related to transport infrastructure projects. One common perspective focuses on the vehicles and construction equipment used at the construction site. Previous field studies have measured emissions from construction equipment using portable emissions monitoring systems (PEMS) (Frey et al. 2010; Rasdorf et al. 2010; Abolhasani et al. 2008). Engine dynamometers (Babbitt and Moskwa 1999) and chassis dynamometers (Yanowitz et al. 2000) have also been used to measure emissions from construction equipment in lab environments. Emission inventory models such as MOVES (EPA 2015) and OFFROAD (California Air Resources Board 2011), which include data on construction equipment, have been developed primarily using engine dynamometer measurements (Rasdorf et al. 2010). By using these types of emission inventory models, Avetisyan et al. (2012) developed an optimization model for selecting on-site equipment types and numbers to minimize GHG emissions. Kim et al. (2012) focused on evaluating emissions from on-site equipment by estimating working hours, quantifying energy usage, and calculating GHG emissions. Other studies have emphasised processes and activities such as asphalt pavement production (Lee et al. 2012), pavement rehabilitation (Wang et al. 2016) or earthwork activities (Hajji and Lewis 2013). Several other studies have applied LCA-based approaches to transport infrastructure projects. Barandica et al. (2013) found that on-site earthwork processes were a major source of CO_2 emissions during the life cycle of roads. Conversely, Stripple (2001) concluded that earthworks have a relatively minor impact on total CO_2 emissions. Few studies have covered all life cycle stages. For instance, Melanta et al. (2013) included the whole life cycle except for operation, maintenance, and end of life treatment, while Huang et al. (2009) included operation and maintenance, but not earthworks or end of life treatment, and Stripple (2001) excluded only end of life treatment. By evaluating different material and equipment scenarios for a road project from an LCA perspective, Fernández-Sánchez et al. (2015) showed the potential for significantly reducing CO_2 emissions if the best scenarios are implemented.

3.2 Mass haul optimization

Transport infrastructure projects often depend on large earthmoving operations across long distances. By planning these operations carefully, a project's total transport work and the associated emissions can be reduced (Kenley and Harfield 2011). One planning approach for this purpose is mass haul optimization, which utilizes information from bills of quantities (BOQ) to form a model of the project with routes and weighted nodes (Son et al. 2005). The optimization problem can then be cast as a shortest path problem that can be solved by using linear programming (LP) to optimize (i.e. minimize) the total distance or cost of these mass hauls (Mohamad Karimi et al. 2007). Commercial software packages such as TILOS and DynaRoad have incorporated linear programming-based mass haul optimization into their suites of tools for planning infrastructure projects (Shah and Dawood 2011).

3.3 Discrete event simulation and building information modelling

The dynamic and uncertain nature of construction projects makes it difficult to accurately predict their progress in advance. However, discrete event simulation (DES) is specifically designed to model systems with inherent uncertainties and dynamics, making it useful for construction projects (Lu et al. 2011). Previous studies have evaluated the environmental performance of construction projects by optimizing resource allocation to minimize emissions using DES (González and Echaveguren 2012). The use of static emissions inventory models, such as the NONROAD model (EPA 2005), can be combined with DES to account for the uncertainties and dynamics of equipment usage in projects and the resulting effects on emissions (Zhang et al. 2014). Maintaining and developing simulation models dealing with environmental impacts in construction processes is challenging due to the large amount of data involved (Changbum et al. 2010). BIM can be used to connect the necessary parameters from the transport infrastructure to the DES model, allowing for more project-specific simulations. However, previously reported applications of BIM have mainly focused on integration with material quantification and cost estimation tools (Shen and Issa 2010).

4 RESEARCH METHOD

This section outlines the research methods that were used. It begins with a brief description of the research process adopted during my doctoral studies. Next, the overall research design is discussed, and finally, the case studies that were undertaken are described.

4.1 Research process

My research process started in late 2012 when I began collecting data for my first case study, the Kiruna bypass project, which consists of road E10 and road 870. This case study was initially requested by project managers from the STA, who were interested in evaluating the energy use and associated CO_2 emissions of a set of project alternatives for the construction phase of these roads. This case study became the foundation of my master's thesis, which was presented at the beginning of the summer of 2013. In September 2013, I started my PhD journey in the Construction Engineering group at Luleå University of Technology. My work on the Kiruna bypass case study remained an important part of my research, but my first peer-reviewed journal article (Paper III), which was published in 2015 in the journal *Buildings*, dealt with another case study - the semi-prefabricated bridge. My co-supervisor Johan Larsson conducted most of the data gathering for this case study, starting in 2010. Data and experiences from the Kiruna bypass study were used as the basis for Paper II (published in 2017 in the *Journal of Cleaner Production*) and Paper I (presented at ICCREM 2016, Edmonton, Canada).

4.2 Research design

To investigate the current state of knowledge about methods for reducing CO_2 emissions in transport infrastructure projects, a literature review was conducted. This review encompassed publications on BIM, inventory models, construction equipment emissions, mass haul optimization techniques, and applications of LCA and DES in construction. It was found that the existing literature provided little guidance on reducing CO_2 emissions in transport infrastructure projects, and that there were no standardized approaches for this type of research. As a result, the research in this thesis is exploratory. Exploratory research often pursues discovery beyond established methodological contexts (Stebbins 2001), and is commonly performed during preliminary phases of research where further development is expected (Yin 2013). Fieldwork such as case study research is suitable for scientific fields at a nascent and exploratory stage of development because it allows problems and phenomena to be examined in their real-world settings (Edmondson and McManus 2007). Case studies are therefore a major method used in this thesis to develop and demonstrate models for reducing CO_2 emissions. The approach resembles a system development method (SDM) called prototyping, in which a prototype is developed and then later reworked and developed into a finalized system or product (Encyclopedia of Information Technology 2007). The use of case studies in this thesis has some similarity to the concept of “the evolving case”, where empirical language dominates the process and the theoretical language follows as a product of the case study. Two case studies that contributed to three papers form the basis for this thesis, as can be seen in Table 1.

Table 1. Research design

Case study	Contribution to papers	Data collection
The Kiruna bypass	Paper I and Paper II	Interviews, archival records, documentation
The semi-prefabricated bridge	Paper III	Site observations, interviews, archival records, documentation

4.3 Conducted case studies

The Kiruna bypass

The Kiruna bypass case study, which focuses on the roads E10 and 870, was conducted in late 2012 and early 2013. Its purpose was to examine two alternative supply chains for the construction phase of the bypass in terms of their energy use and associated CO_2 emissions. The projects were in their preliminary planning stages when the case study was conducted, and the real-world project setting made it possible to gain important insights into ways of implementing CO_2 reduction approaches in real projects.

The samples examined in this case study were two separate but related road projects that are collectively known as the Kiruna bypass. The gathered data included a BOQ for each project and project maps. Knowledge regarding factors such as access roads, borrow pits, disposal areas, planned crushing plant locations, possible equipment, and a digital terrain model (DTM) was also collected. Most of the data used in the analysis were acquired from documentation, archival records, personal communications, and interviews with the project managers at the STA, consultants, previous contractors, and experts. This case study was presented and analysed in Paper II. Data from the case were also used in Paper I, which evaluated CO_2 emissions from alternative road alignments of road E10. The case study has also been presented in a conference paper (Krantz et al. 2014).

The semi-prefabricated bridge

The semi-prefabricated bridge is the second case study used in this thesis. Initially the case study was conducted to explore the on-site construction process of an industrialized bridge concept. However, for this thesis the case was used to develop a framework that enables more project-specific evaluations of embodied energy. The framework was demonstrated in Paper III using the semi-prefabricated bridge as an example.

Johan Larsson gathered the data for the case study in 2010. The data gathering process included interviews, site observations, and collecting archival records and documentation (Larsson 2016). Site observations were performed to gain knowledge about the product and the process used to construct and assemble the bridge. Interviews were conducted with the manager of the bridge concept and the site manager to further increase understanding of the product and process. The documentation and archival records included drawings, calculations, and construction schedules.

This case study subsequently formed the basis of several publications (Larsson et al. 2016) and conference articles (Larsson et al. 2014; Larsson and Simonsson 2012), including Paper III of this thesis. In Paper III, the data from the case was used to develop and demonstrate a model for assessing the embodied energy and associated emissions of the bridge's superstructure. The project and process data were used in combination with BIM and DES to conduct a more project-specific analysis than would previously have been possible.

5 SUMMARY OF APPENDED PAPERS

This section presents the aims, samples, data collection and findings of each appended paper in this thesis.

5.1 Paper I

Title: Evaluating Construction-based Greenhouse Gas Emissions of Alternative Road Alignments

Road infrastructure planning is a process of making decisions and gradually refining and developing data. During the early stages, such as the feasibility studies, project data is limited and many major decisions remain to be made, for instance regarding the location of the road. This paper explored how on-site CO_2 emissions can be evaluated during feasibility studies examining alternative road alignments. An adapted version of the mass flow emissions (MFE) model (presented in Paper II) was used to describe the workflow for evaluations of this kind. Three alternative road alignments for the E10 project were evaluated using data from the Kiruna bypass case study including a DTM and information on possible borrow pit and disposal area locations.

The three road alignments were first modelled onto a DTM using Quantm, which is a program designed for evaluating alternative alignments based on costs. The roads' geometric properties, which were dictated by the STA, were specified in the software to ensure that the generated alignments complied with the applicable standards. Quantities for each alignment were imported into the mass-haul optimization program DynaRoad, which was used to construct mass hauling plans. The mass haul plan was then combined with equipment data to calculate GHG emissions.

The paper provided insights into the application of a modified MFE model during feasibility studies to evaluate and compare alternative road alignments or corridors. It showed that one can begin addressing CO_2 emissions in the early planning stages of a project, providing additional decision support in the process. This is important because many large decisions remain to be made during the early planning stages, and using the proposed model gives project managers and planners important information for decision support. Although data from the Kiruna bypass case study was used, the study was conducted separately from the E10 project, which imposed some limitations in terms of practical implementation. It was therefore considered important to perform further studies within real projects.

5.2 Paper II

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

This paper presents the mass flow emissions (MFE) model, which is outlined in Figure 2. It is a step-by-step model designed for assessing CO_2 emissions based on how masses “flow” in a project. The MFE model can be used to analyse project alternatives such as potential supply chains, production methods, materials, or alignments. Its applicability was evaluated in a case study on two related road projects during their design stages. In collaboration with the project managers, two large scale supply chain alternatives for the construction of the roads were identified. These were then compared using the MFE model, revealing that the CO_2 emissions for one alternative were around 37% lower than those for the other.

The main discovery from Paper II were that careful analysis of alternatives in the design phase can reduce projects’ CO_2 emissions during the upcoming construction phase. The results obtained by evaluating the two alternatives contradicted the project managers’ intuitions, which may also be the case in other projects. This demonstrates the importance of systematic and careful analysis. Because the alternatives were evaluated during the design phase, there was plenty of time to prepare and practically implement the superior alternative during construction.

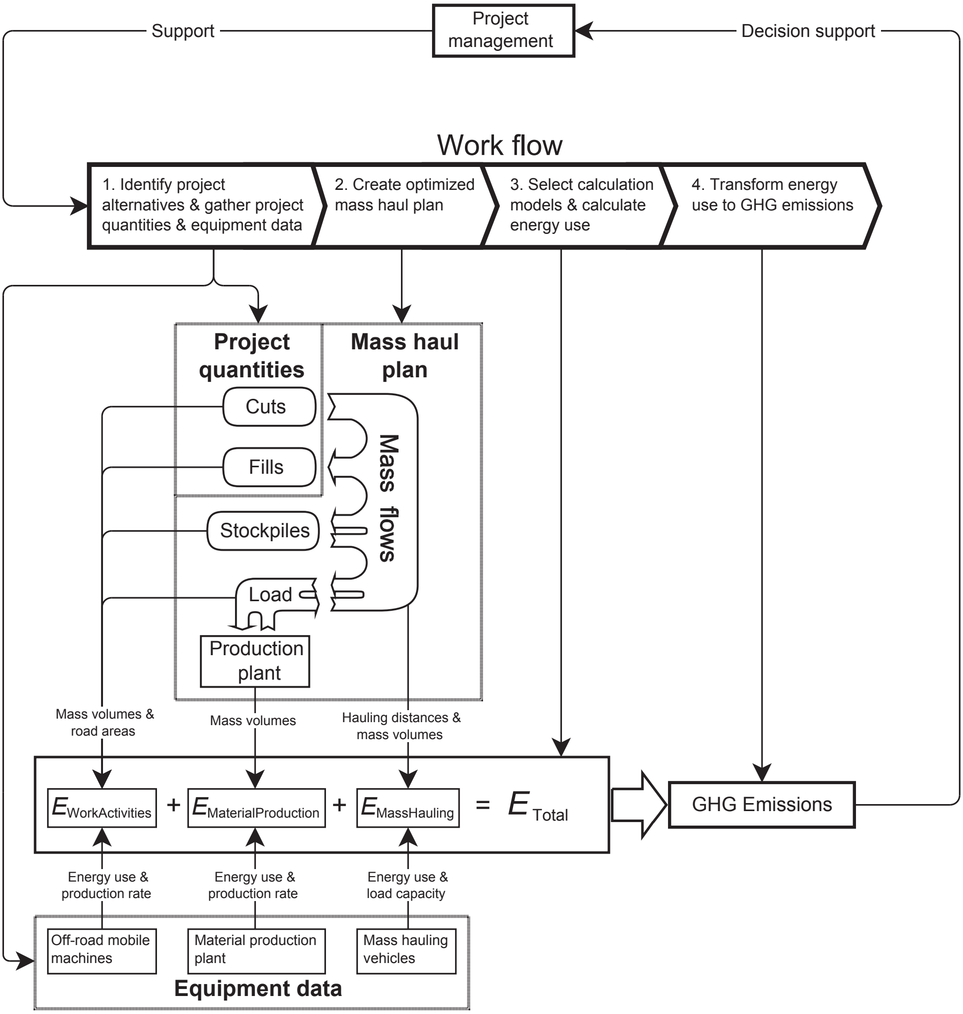

Figure 2. The mass flow emissions (MFE) model.

5.3 Paper III

Title: Assessing Embodied Energy and Greenhouse Gas Emissions in Infrastructure Projects

Paper III proposed a model for estimating energy use and GHG emissions in infrastructure construction projects. The model, which is outlined in Figure 3, uses BIM-based material quantity take-offs to estimate the embodied energy of materials and their transportation requirements. These quantities are then used in a database-driven simulation to account for the required work activities. The generated BIM and simulation data are combined with information on the equipment for the required work activities and environmental product declaration (EPD) data to account for the energy used in the materials as well as during transportation and on-site construction work. The model was demonstrated by applying it to the superstructure of the semi-prefabricated bridge considered in the second case study. The demonstration included the upstream phase of the superstructure, but the location of the project was hypothetical.

Unlike many existing LCA approaches, the proposed model can be used to perform more project-specific GHG assessments which can provide decision support during later project planning stages, such as when procuring contractors. The use of BIM gives detailed lists of the quantities and types of materials and components that will be used, while DES makes it possible to model the project and address some of the inherent uncertainties of the on-site and off-site construction processes. The proposed model adds an environmental indicator to the existing cost and time indicators used to measure project success, and thus allows clients to consider both the embodied energy and the associated GHG emissions of their proposals.

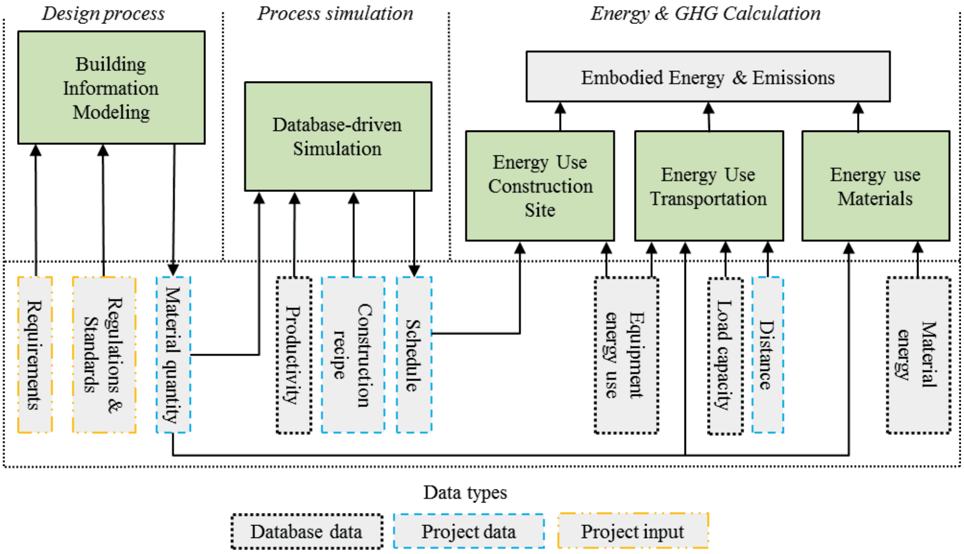

Figure 3. Embodied energy and associated emissions model.

6 DISCUSSION

This section discusses how and to what degree the thesis project's research aims were fulfilled. This is followed by a discussion of the proposed models.

6.1 Aim fulfilment

The aim of this study was to explore and propose methods to be applied during the planning process of transport infrastructure projects to reduce the CO_2 emissions of the subsequent construction process. The key stages of interest during the planning process stages were the feasibility studies, the preliminary design, and the detailed design. Two models were proposed, which were demonstrated in three papers as shown in Figure 4. The MFE model proposed in Paper II and the related model used in Paper I demonstrated practical usefulness in the preliminary design stage and for evaluating alternative road alignments, which is commonly done during feasibility studies. Paper III also demonstrated a model for assessing embodied energy and associated emissions, which is practically relevant in project settings. The proposed methods therefore covered all the targeted planning stages. However, the models were not applied to railways, asphalt, or tunnels. Furthermore, the models were not applied to concrete and bridges during the feasibility studies or preliminary design stages, and the only detailed design stage application focused on the superstructure of a bridge. Therefore, the models need to be tested on a wider scale including more transport infrastructure types and their life cycles.

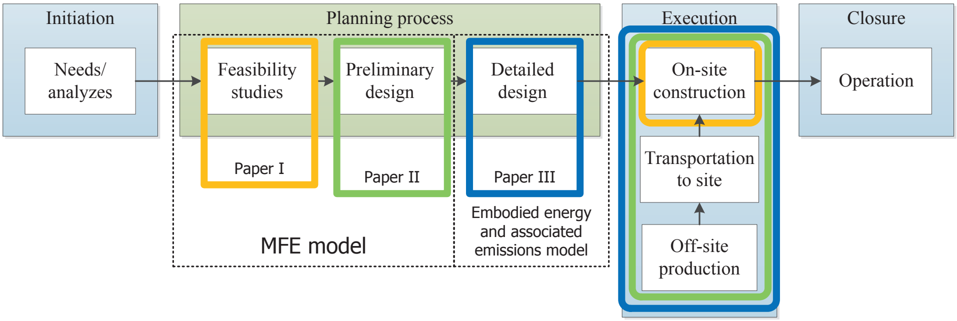

Figure 4. The planning stage in which each model was implemented, and the proportion of the execution stage covered by each paper.

6.2 The MFE model

The MFE model provides a practical way of reducing CO_2 emissions from on-site construction activities, off-site production, and transportation to the site. As demonstrated in Papers I and II, these reductions are achieved and substantiated by comparing project alternatives to a base alternative. Key project data such as hauling distances and quantities to be hauled are generated by modeling the project of interest using mass haul optimization tools. The success of this approach substantiates the arguments of Kenley and Harfield (2011), who stressed the importance of mass haul optimization tools for addressing environmental issues. The early application of the model allows planners and project managers plenty of time to prepare and implement the superior alternative, as was demonstrated in Paper II when the Kiruna bypass case study was conducted. Results from Paper II showed that considerable reductions of CO_2 emissions can be achieved by analyzing relevant project alternatives. This is consistent with the findings of Paulson (1976) and Bogenstätter (2000), who demonstrated that the potential impact of decisions in early planning stages could be orders of magnitude greater than that of late stage decisions. Not only were considerable reductions of CO_2 emissions achieved in Paper II, the results were unexpected and counterintuitive for the project managers, demonstrating the importance of performing systematic analyses of this kind rather than relying on managers' instincts and assumptions. Unlike the approaches presented by e.g. Abolhasani et al. (2008), Frey et al. (2010), Hajji and Lewis (2013), and Melanta et al. (2013), the MFE model provides a practical step-by-step approach for reducing CO_2 emissions.

6.3 The embodied energy and associated emissions model

The embodied energy and associated emissions model presented in Paper III provides project-specific evaluations for the upstream processes of transport infrastructure projects. Previous LCA-based approaches have lacked this type of project applicability due to their inability to capture uncertainties (González and Echaveguren 2012); most previously reported approaches are both static (Thiede et al. 2013) and location-independent (Reap et al. 2008; Ross et al. 2002). In contrast, the embodied energy and associated emissions model outlined in Paper III uses DES to model the inherent project uncertainty on the construction site. Furthermore, BIM is used to extract accurate material quantities. The model's practical application was greatly facilitated by its application to the semi-prefabricated bridge concept because this product and the associated design and construction processes are highly standardized, and large amounts of information concerning its constituent materials and supply chains have already been compiled. In other contexts the amount of available data may be more limited, so one way to increase the model's applicability and simplify its use would be to incorporate a database of generally useful information on materials and processes. In addition, the model was developed in the context of a bridge concept owned and developed by a contractor, at a point in the planning process at which contractors had already been procured. It is thus applicable at later stages of the planning process, such as the detailed design stage (see Figure 4).

7 CONCLUSION

This section provides concluding remarks to the thesis. First the theoretical and practical contributions of the research are presented. This is followed by an assessment of the research quality and a discussion of some promising future research directions based on the work's identified limitations.

7.1 Contributions

This thesis offers both theoretical and practical contributions relating to CO_2 emissions and methods for reducing them during transport infrastructure projects. The main theoretical contribution is the connection of the proposed models to the planning process of transport infrastructure, allowing their use as tools for minimizing CO_2 emissions. This is practically relevant to clients because it allows them to reduce their projects' emissions, and to contractors because it allows them to develop more sustainable processes and products.

Related works by authors such as Melanta et al. (2013) and Hajji and Lewis (2013) have proposed methods and approaches, but their practical applicability for reducing CO_2 emissions from real construction projects has not been elaborated upon. Instead, many studies have evaluated the emissions of projects after construction has been completed, when it is no longer possible to mitigate emissions (Kenley and Harfield 2011). The MFE model was adapted for use during the planning process, and was demonstrated in the case of the Kiruna bypass, showing that real reductions in CO_2 emissions could be achieved and substantiated by systematically evaluating relevant project alternatives. Although the results of this evaluation went against the project managers' intuitions, they followed the model's recommendations. This highlighted the importance of conducting such systematic evaluations during project planning. The results obtained contribute to the literature on project-based evaluation of emissions by stressing the connection between project planning, when major decisions are made, and the subsequent construction stage, when emission mitigation efforts are implemented.

Most previously reported LCA approaches are ill-suited to construction projects because they are often static (Thiede et al. 2013) and location-independent (Reap et al. 2008; Ross et al. 2002). The main theoretical contribution to LCA literature made by this thesis comes from the development of an embodied energy and associated emissions model that can be used to conduct more project-specific evaluations. The model combines DES and BIM to generate more project-specific data to facilitate estimation of the embodied energy and the associated CO_2 emissions on a project basis. The resulting model is an LCA-based approach that is useful in certain projects, as was demonstrated by its application to the semi-prefabricated bridge case. The main practical contribution resulting from the model's development relates to its applicability in project settings, which makes it easier for managers to comply with CO_2 mitigation goals such as those drawn up by the STA (Trafikverket 2016).

7.2 Research quality

This thesis is largely exploratory and is based on case studies, which were conducted in line with the concept of the "evolving case" as described by Dubois and Gadde (2002). This means that the end product of the case study cannot be known in advance and the analysis of the process is largely based on empirical discussions, while the end product is evaluated in more theoretical terms. The quality of the case study research presented in this thesis was evaluated by drawing on the criteria described by Yin (2013). The repeatability of the case studies was addressed by ensuring that the data and calculation models used are clearly presented in the appended papers so that the process can be followed and the calculations can be verified. Furthermore, multiple data sources were used, including project documentation, archival records, direct observations, and interviews, which is seen as a way to strengthen the validity of the findings. However, it is important to remember that all case studies are of unique character and their findings cannot be generalized far beyond the scope of the studied cases. For example, the proposed approaches were implemented in specific project settings that did not include all major aspects of transport infrastructure projects. Further research is needed to improve the generalizability of the findings, as discussed in the following section.

7.3 Limitations and further research

The models and approaches presented in this thesis have shown some advantages over those previously reported in the literature. However, they still have drawbacks and limitations that will require further research to overcome. The MFE model was only demonstrated in the early planning stages, in a case that did not involve any consideration of bridges, tunnels, vegetation and top soil removal, asphalt, or concrete surfaces. Some of these factors can have considerable impacts on CO_2 emissions. The model presented in Paper III for assessing embodied energy and associated emissions was demonstrated in a later planning stage, and relied on the fact that a contractor had already been selected. Furthermore, it was only applied to the superstructure of the studied bridge; its applicability to larger transport infrastructure projects is unexplored. Implementing different models during the project planning stage can be costly and time consuming. Future research should therefore try to combine existing models or develop new ones to be used throughout the planning phase. A model of this type should also be broad enough to account for the major components of most transport infrastructure projects.

Another limitation of this study is that the thesis only briefly discusses the actors involved in project planning and their potential roles in addressing the project's CO_2 emissions. The role of the contractors in particular warrants further study because they are responsible for the actual construction processes and thus play an important role in implementing CO_2 mitigating measures. Any such study should address the specific conditions that the contractors must operate under based on the client's requirements. The impact of early contractor involvement in transport infrastructure projects is another important topic for further study. Despite these limitations, the results presented in this thesis shed new light on an increasingly important global issue by outlining some practical ways of reducing the CO_2 emissions from construction projects.

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Paper I

Evaluating Construction-based Greenhouse Gas Emissions of Alternative Road Alignments

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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.

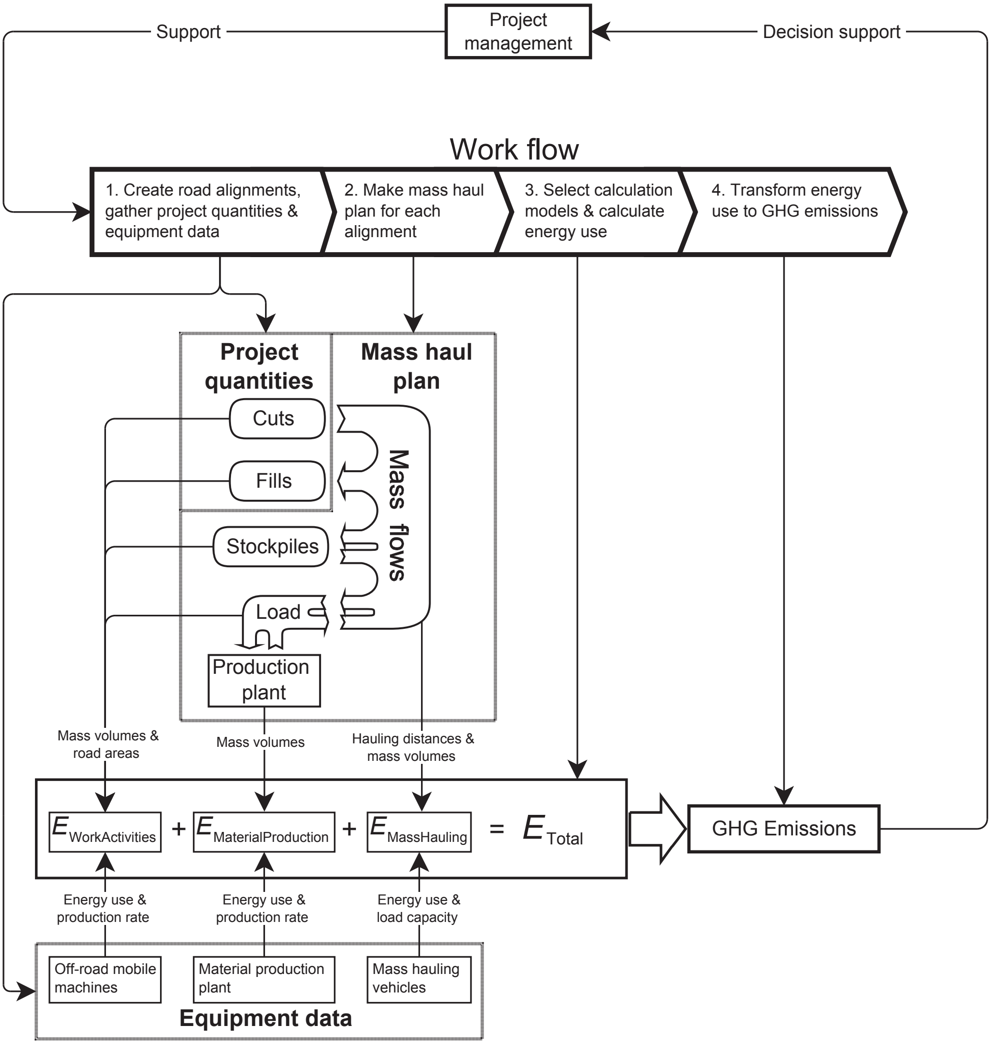

Figure 1. The proposed model containing its four implementation steps.

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).

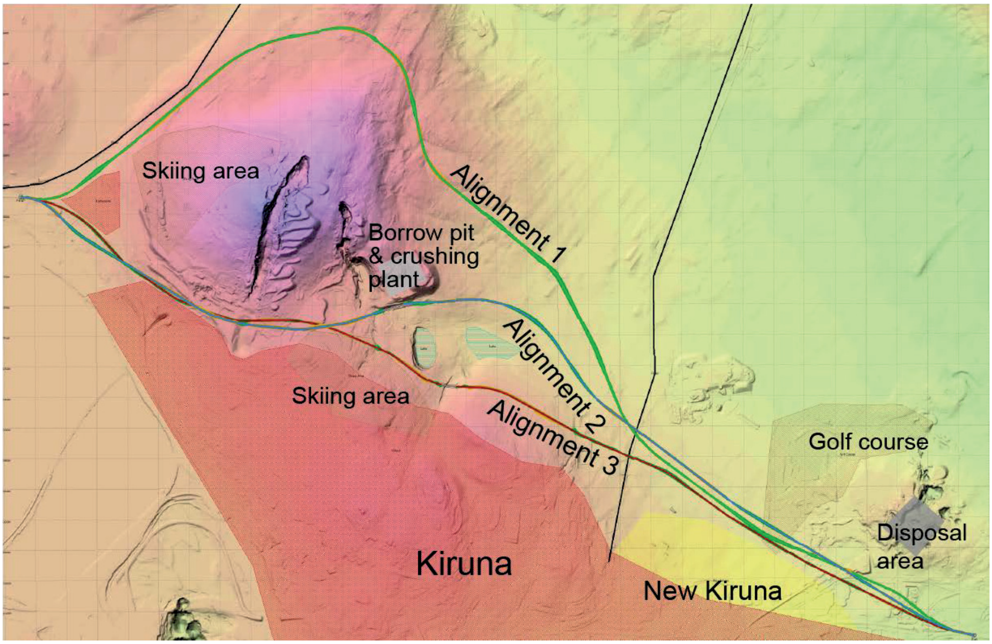

Figure 2. The demonstrated case encompassing alignments and area features.

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.

$$E_{\text{hauler}} = \sum_i (L_t / L_c \cdot C_t \cdot F_c)_i \tag{1}$$

$$E_{\text{crushing}} = \sum_i (E_c \cdot M_t)_i \tag{2}$$

$$E_{\text{offroad}} = \sum_i (A \cdot P \cdot L_f \cdot B_e)_i \tag{3}$$

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.

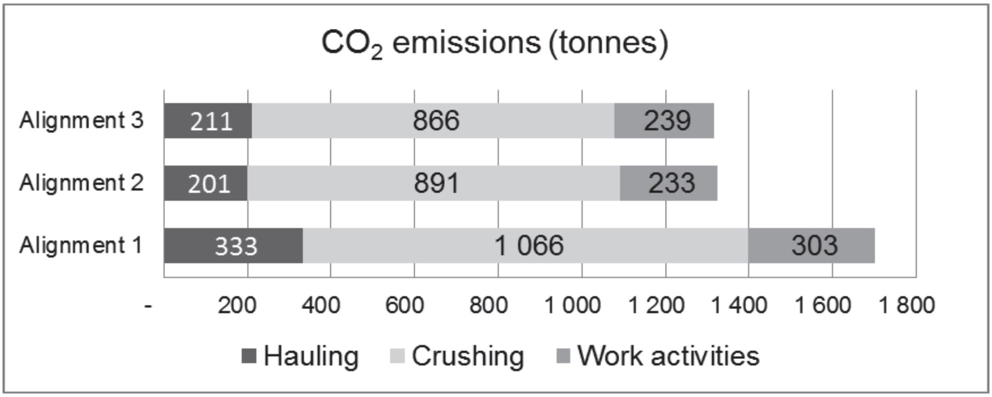

Figure 3. Case study results with CO_2 emissions of each alignment.

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.

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Paper II

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

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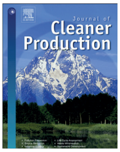

Analysis of alternative road construction staging approaches to reduce carbon dioxide emissions

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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.

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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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,

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[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.

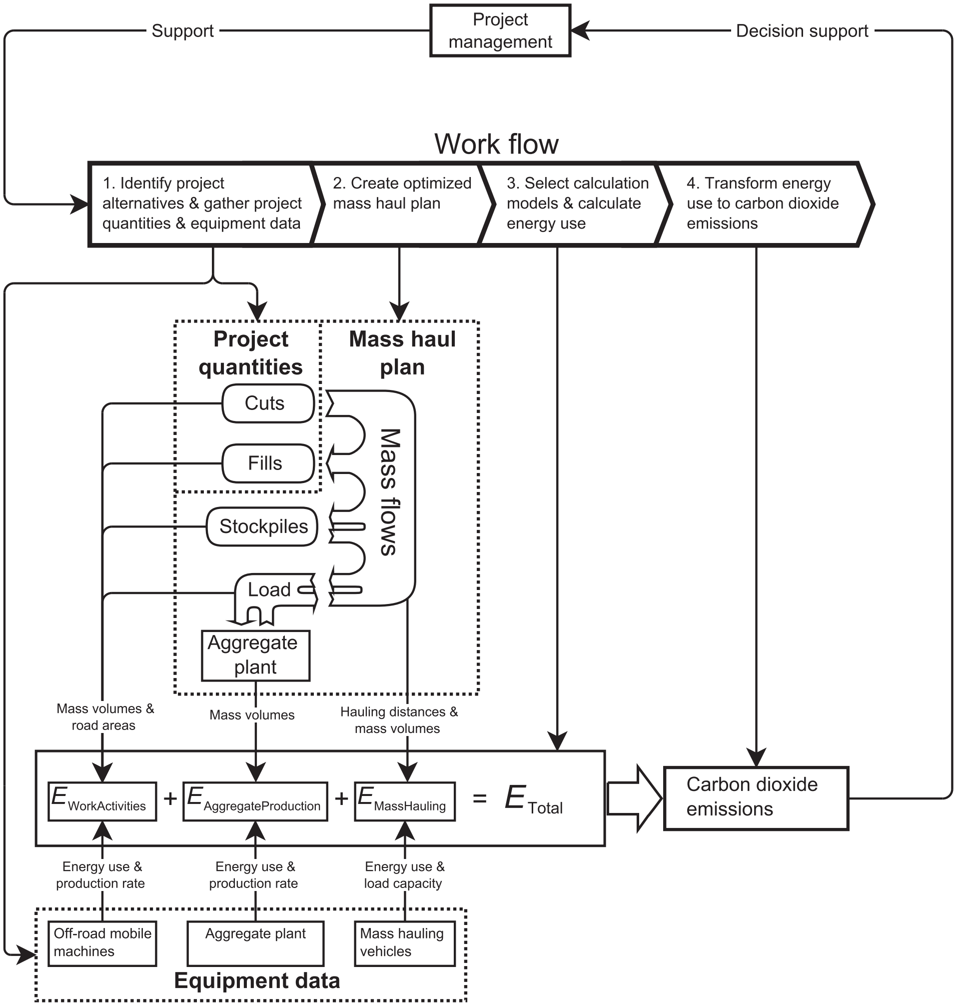

Fig. 1. The mass flow emissions (MFE) model.

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.

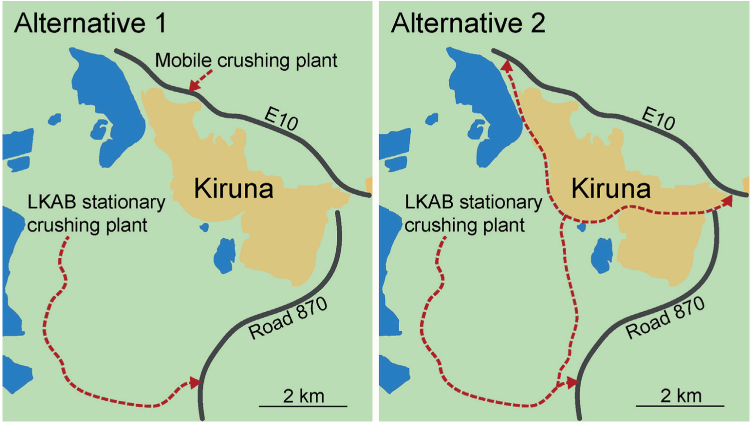

Fig. 2. Alternatives 1 and 2 with their crushing plant locations and hauling routes (marked in red) for crushed aggregates. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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:

$$\min \sum_{jk} Q_{jk} D_{jk} \tag{1}$$

$$\sum_{j} Q_j = \sum_{j} B_j \tag{2}$$

$$\sum_{k} Q_k = \sum_{k} B_k \tag{3}$$

$$Q_{ij} \geq 0 \tag{4}$$

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.

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

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).

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

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.

$$E_{\mathrm{crushing}} = \sum_i (E_{\mathrm{c}} \cdot M_{\mathrm{t}})_i \tag{7}$$

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:

$$E_{\mathrm{offroad}} = \sum_i \left(A \cdot P \cdot L_{\mathrm{f}} \cdot B_{\mathrm{e}}\right)_i \tag{8}$$

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 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.

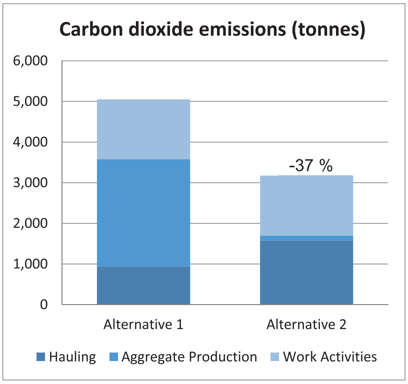

Fig. 3. Results of the two alternatives in terms of carbon dioxide emissions.

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

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Paper III

Assessing Embodied Energy and Greenhouse Gas Emissions in Infrastructure Projects

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Article

Assessing Embodied Energy and Greenhouse Gas Emissions in Infrastructure Projects

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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

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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.

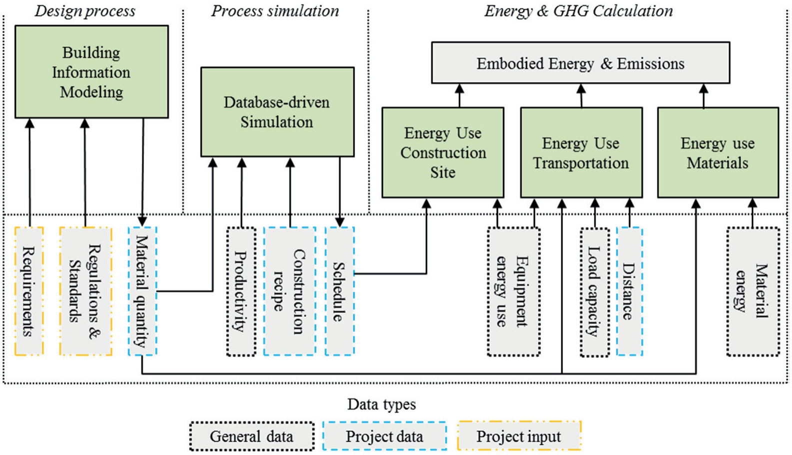

Figure 1. The model for assessing embodied energy associated emissions.

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.

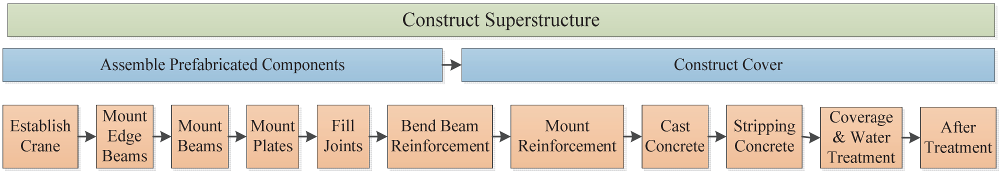

Figure 2. Construction process of the bridge superstructure.

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.

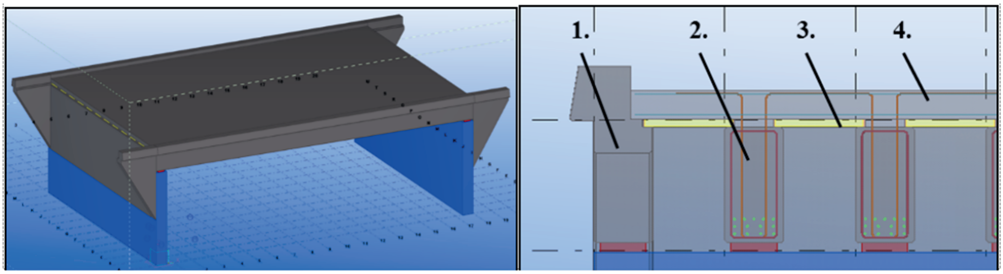

Figure 3. (**Left**) BIM of the bridge; (**Right**) superstructure components 1 = Edge beam, 2 = Beam, 3 = Plate, 4 = Cover.

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.

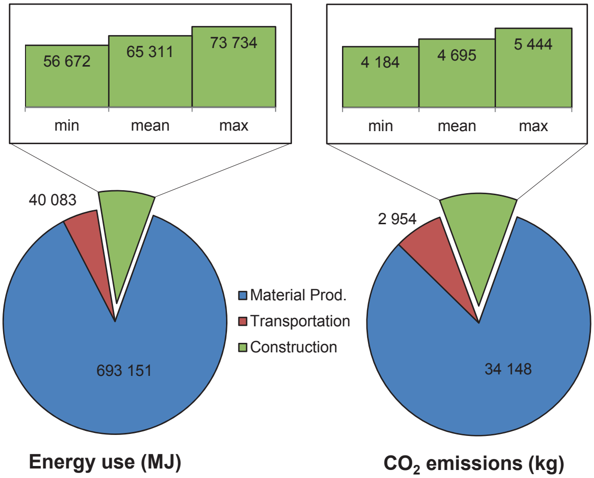

Figure 4. The energy use and CO_2 equivalent emissions of each category.

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.

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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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