1-1-2007

A framework for life cycle assessment of concrete bridge decks

Fouad Taki
Ryerson University

Follow this and additional works at: <http://digitalcommons.ryerson.ca/dissertations>

Part of the [Civil and Environmental Engineering Commons](#)

Recommended Citation

Taki, Fouad, "A framework for life cycle assessment of concrete bridge decks" (2007). *Theses and dissertations*. Paper 152.

This Thesis is brought to you for free and open access by Digital Commons @ Ryerson. It has been accepted for inclusion in Theses and dissertations by an authorized administrator of Digital Commons @ Ryerson. For more information, please contact bcameron@ryerson.ca.

A FRAMEWORK FOR LIFE CYCLE ASSESSMENT OF CONCRETE BRIDGE DECKS

by

Fouad Taki

M.ASc. Civil Engineering, Baghdad, Iraq, 1991

A thesis

presented to Ryerson University

in partial fulfillment of the

requirements for the degree of

Master of Applied Science

in

Civil Engineering

Toronto, Ontario, Canada, 2007

© Fouad Taki 2007

PROPERTY OF
RYERSON UNIVERSITY LIBRARY

I hereby declare that I am the sole author of this thesis.

I authorize Ryerson University to lend this thesis to other institutions or individuals for the purpose of scholarly research.

I further authorize Ryerson University to reproduce this thesis by photocopying or by other means, in total or in part, at the request of other institutions or individuals for the purpose of scholarly research.

Ryerson University requires the signature of all persons using or photocopying this thesis. Please sign below, and give address and date.

Name and signature	Address	Date

A FRAMEWORK FOR LIFE CYCLE ASSESSMENT OF CONCRETE BRIDGE DECKS

Fouad Taki

Master of Applied Science, Department of Civil Engineering
Ryerson University, 2007

ABSTRACT

The construction industry is the largest contributor to environmental loading, and while development will require more infrastructure to achieve its goals, this will require more construction and hence more pollution. In order to achieve a sustainable development, the construction industry has to reduce its environmental loading and consumption of energy and raw materials. The methodology of Life Cycle Assessment (LCA) can help in quantifying the cradle to grave impact of construction on the environment.

This study was performed to develop a model that uses LCA methodology to estimate the environmental impact of concrete bridge decks in North America. The model traces the emissions during the life cycle of a concrete bridge deck, and then calculates the impact of these emissions on the environment. The model also calculates the energy and raw materials that are consumed during the life cycle of a concrete bridge deck. This model can be used by designers to evaluate alternative bridge deck designs to select the environmentally sound one.

ACKNOWLEDGEMENT

I wish to express my gratitude to my supervisor Dr. M. Lachemi, and my co-supervisors Dr. F. Sadeghpour and Dr. A Hossain. I am deeply grateful for their vital directions, valuable discussions, helpful comments and encouragement during the course of research.

Gratitude is also extended to all friends and colleagues who helped me in a certain way while preparing this thesis. Our discussions and their opinions were very helpful in the production of this thesis.

Finally, special thanks are expressed to my wife and children for their patience, understanding during the course of work.

TABLE OF CONTENT

ABSTRACT	iv
ACKNOWLEDGEMENT	v
TABLE OF CONTENTS	vi
LIST OF TABLES	xi
LIST OF FIGURES	xiii
1. INTRODUCTION	1
1.1 Construction and the environment	1
1.2 Sustainable development	2
1.3 Sustainability of construction and Life Cycle Assessment	3
1.4 Problem statement	4
1.5 Plan of research	5
2. INTRODUCTION TO LIFE CYCLE ASSESSMENT	8
2.1 Life Cycle Assessment	8
2.2 Brief history of LCA	10
2.3 LCA standards	11
2.4 Phases of Life Cycle Assessment	12
2.4.1 Goal and scope definition	14
2.4.2 Inventory analysis	15
2.4.3 Impact assessment	17
2.4.4 Interpretation	19
2.5 LCA Software tools	21
2.6 LCA limitations	22
2.7 LCA and construction industry	24

3. PRACTICAL ISSUES OF CONDUCTING LCA STUDY	27
3.1 Goal and scope definition phase	27
3.1.1 Defining the goal(s) of the study	27
3.1.2 Determining specificity of information	29
3.1.3 Determining the functional unit	29
3.1.4 Defining the Scope of the Study	29
3.2 Life cycle inventory phase	30
3.2.1 Preparation of system flow diagram	31
3.2.2 Setting criteria for collection of LCI data	32
3.2.3 Collection of LCI data	34
3.2.4 Allocation of LCI data	34
3.2.5 Setting boundaries of LCI data	35
3.2.6 LCI of energy	38
3.2.6.1 Documentation of energy	38
3.2.6.2 Precombustion of fuels	39
3.2.6.3 LCI of electricity	39
3.2.7 LCI of water	41
3.2.8 LCI of transportation	41
3.2.9 LCI of environmental releases	41
3.2.9.1 Emissions to air	42
3.2.9.2 Effluents to water	43
3.2.9.3 Solid wastes	43
3.2.10 Reporting of LCI results	44
3.3 Life cycle Impact assessment phase	44
3.4 Life cycle interpretation phase	50
 4. LCA MODEL FOR CONCRETE BRIDGE DECKS	 54
4.1 Brief description of the model	54
4.2 System boundaries of the model	56
4.2.1 Construction materials	57
4.2.2 Electricity	58

4.2.3 Construction equipments	59
4.2.4 Transportation	60
4.2.5 Construction stage	61
4.2.6 Operation stage	62
4.2.7 End of life stage	63
4.2.8 Exclusions to the boundary of the system	65
4.3 Source of Data for Life Cycle Inventory	66
4.4 LCI data preparation for the model	68
4.4.1 LCI data for fuels precombustion	70
4.4.2 LCI data for electricity consumption	71
4.4.3 LCI data for Portland cement production	72
4.4.4 LCI data for steel production	74
4.4.5 LCI data for aggregate	75
4.4.6 LCI data for super plasticizer	75
4.4.7 LCI data for plastic fibers	76
4.4.8 LCI data for combination truck transportation	76
4.4.9 LCI data for single unit truck transportation	77
4.4.10 LCI data for diesel fueled construction equipment	78
4.5 Model framework	79
4.6 Input tables	81
4.6.1 Life cycle definition table	81
4.6.2 Construction materials tables	81
4.6.3 Equipment tables	82
4.6.4 Transportation distances table	82
4.6.5 Wastage percentage	83
4.6.6 Electricity consumption table	83
4.7 Managing inventories of the concrete bridge deck	84
4.7.1 Cycles of activities	84
4.7.2 Materials inventory	85
4.7.3 Construction equipment inventory	86
4.7.4 Disposal inventory	87

4.7.5 Electricity inventory	88
4.7.6 Transportation inventory	89
4.8 Calculation of emissions	90
4.8.1 Calculation of construction materials emissions	92
4.8.2 Calculation of electricity emissions	92
4.8.3 Calculation of transportation emissions	92
4.8.4 Calculation of construction equipment emissions	92
4.8.5 Accumulating emissions	92
4.9 Calculation of impact categories	93
4.10 Calculation of energy & raw materials consumption	94
4.10.1 Calculation of construction materials energy and raw materials	95
4.10.2 Calculation of electricity energy and raw materials	95
4.10.3 Calculation of transportation energy and raw materials	95
4.10.4 Calculation of construction equipment energy and raw materials	95
4.10.5 Accumulating energy and raw materials	96
5. PERFORMANCE EVALUATION OF THE MODEL	97
5.1 Base option	97
5.2 Case study 1	101
5.3 Case study 2	108
5.4 Case study 3	116
5.5 Case study 4	122
5.6 Discussion of results	128
6. CONCLUSIONS AND RECOMMENDATIONS	130
6.1 Conclusions	130
6.2 Recommendations for future work	135
REFERENCES	137

APPENDIX (A): EMISSIONS PER UNIT TABLE	A1
APPENDIX (B): ENERGY AND RAW MATERIALS PER UNIT TABLE	B1
APPENDIX (C): Snapshots of input tables of the model	C1

LIST OF TABLES

Table 2.1: Life Cycle Assessment Standards	12
Table 2.2: Phases of LCA	13
Table 3.1: Commonly used life cycle impact categories	46
Table 4.1: Embodied energy in raw materials of fuels	69
Table 4.2: Contributors to emissions and their units	91
Table 4.3: GWP emission equivalents	93
Table 4.4: AP emission equivalents	94
Table 5.1: dimensions of the bridge deck	96
Table 5.2: Distances of transportation	98
Table 5.3: Concrete mix proportions	99
Table 5.4: construction equipments used at construction stage	99
Table 5.5: construction equipments used at operation stage	100
Table 5.6: construction equipments used at end of life stage	101
Table 5.7: Case study 1, changes in mix proportions of 35% slag replacement	102
Table 5.8: Case study 1, changes in mix proportions of 50% slag replacement	102
Table 5.9: Case study 1, reduction in consumption of raw materials	103
Table 5.10: Case study1, reduction in energy consumption	105
Table 5.11: Case study 1, reduction in GWP	106
Table 5.12: Case study 1, reduction in AP	107
Table 5.13: Case study 2, changes in mix proportions of 50 MPa mix	109
Table 5.14: Case study 2, changes in construction equipment	110
Table 5.15: Case study 2, reduction in consumption of raw materials	111
Table 5.16: Case study 2, reduction in energy consumption	113
Table 5.17: Case study 2, reduction in GWP	114
Table 5.18: Case study 2, reduction in AP	115
Table 5.19: Case study 3, the changes in transportation distances	117
Table 5.20: Case study 3, reduction in consumption of raw materials	118

Table 5.21: Case study 3, reduction in energy consumption	119
Table 5.22: Case study 3, reduction in GWP	120
Table 5.23: Case study 3, reduction in AP	121
Table 5.24: Case study 4, reduction in consumption of raw materials	123
Table 5.25: Case study 4, reduction in energy consumption	125
Table 5.26: Case study 4, reduction in GWP	126
Table 5.27: Case study 4, reduction in AP	127
Appendix (A): Emissions per unit table	A1
Appendix (B): Energy and raw materials consumption per unit table	B1

LIST OF FIGURES

Fig. 2.1: Life cycle stages of a system	9
Fig. 2.2: Framework of LCA study	13
Fig. 2.3: Framework of LCA study	14
Fig. 3.1: Example of unit process for LCI	31
Fig. 3.2: Relation between interpretation phase and other phases	51
Fig. 4.1: Life cycle stages of a concrete bridge deck	55
Fig. 4.2: System boundary of construction materials	58
Fig. 4.3: System boundary of electricity	59
Fig. 4.4: System boundary of construction equipments	60
Fig. 4.5: System boundary of transportation	61
Fig. 4.6: Flow diagram of the bridge deck showing system boundary (Construction stage)	62
Fig. 4.7: Flow diagram of the bridge deck showing system boundary (Operation stage)	64
Fig. 4.8: Flow diagram of the bridge deck showing system boundary (End of life stage)	65
Fig. 4.9: Flow chart of LCI data preparation	68
Fig. 4.10: General flowchart of the model	80
Fig. 5.1: Case study 1, contributors to coal consumption	104
Fig. 5.2: Case study 1, contributors to crude oil consumption	104
Fig. 5.3: Case study 1, contributors to natural gas consumption	105
Fig. 5.4: Case study 1, contributors to energy	106
Fig. 5.5: Case study 1, contributors to global warming potential	107
Fig. 5.6: Case study 1, contributors to acidification potential	108
Fig. 5.7: Case study 2, contributors to coal consumption	112
Fig. 5.8: case study 2, contributors to crude oil consumption	112
Fig. 5.9: Case study 2, contributors to crude oil consumption	113
Fig. 5.10: Case study 2, contributors to energy	114
Fig. 5.11: Case study 2, contributors to global warming potential	115

Fig. 5.12: Case study 2, contributors to acidification potential	116
Fig. 5.13: Case study 3, contributors to crude oil consumption	118
Fig. 5.14: Case study 3, contributors to energy	119
Fig. 5.15: Case study 3, contributors to global warming potential	120
Fig. 5.16: Case study 3, contributors to acidification potential	121
Fig. 5.17: Case study 4, contributors to coal consumption	124
Fig. 5.18: Case study 4, contributors to crude oil consumption	124
Fig. 5.19: Case study 4, contributors to natural gas consumption	125
Fig. 5.20: Case study 4, contributors to energy	126
Fig. 5.21: Case study 4, contributors to global warming potential	127
Fig. 5.22: Case study 4, contributors to acidification potential	128
APPENDIX (C): Snapshots of input tables of the model	C1

1. Introduction

1.1 Construction and the environment

Human activities of every day practices have a negative side due to emission of harmful substances that contribute to environmental changes along the globe. One of the activities in human life today, which has the largest contribution to environmental changes is construction. Construction is the largest consumer of earth resources and generates air emissions, water pollutants, and solid wastes more than any other human activity. The construction industry has the greatest impact on global environment and therefore has a greater obligation to improve its environmental performance.

Building construction, renovation and operation consumes as much as 40% of raw materials and energy in the world each year [1]. A study submitted to The National Renewable Energy Laboratory [2] on 500 sectors of the US economy revealed that the construction sector produces the most CO₂ emissions through the manufacture, transport and use of materials alone. The construction industry created 300 million tons of upstream CO₂ emissions, more than the direct total fossil CO₂ emissions of all electricity generating utilities in the United States. It is estimated that the production of 1 ton of cement produces 1 ton of CO₂. Although production of other materials may produce more CO₂, the high consumption of cement makes it an important factor. The operation and use of civil engineering structures contribute more to emissions and solid wastes. For example 38% of the US primary energy consumption is related to building operations, which are also responsible for 65% of all 1997 Municipal Solid Wastes [3, 4].

The concentration of greenhouse gases (like carbon dioxide and methane) and toxic substances (like mercury and persistent organic pollutants) are increasing continuously in the atmosphere and sensitive ecosystems. The increase in population and demand for goods and services has offset the improvement in efficiency per unit of production. "At current patterns of consumption and

population growth, by 2100, we will need the resources of *four* planets to sustain us at decent living conditions [5]”.

1.2 Sustainable development

“The problems we have created cannot be solved at the level of thinking that created them” --*Albert Einstein*

The effects of mankind development on the environment, with the construction industry as a main tool in this development, force the adoption of a more eco-friendly development – a sustainable development.

Sustainable development is typically defined as the development that meets the needs of the present without compromising the ability of future generations to meet their own needs. Decision-makers on different levels in public and private sectors wanted a clear way to steer their organizations on the path of sustainable development, and in this line, the recommendations of the World Commission on Environment and Development in the Tokyo meeting in 1987 [6] was to:

1. Revive Growth: “economic growth must be stimulated, particularly in developing countries, while enhancing the resource base”.
2. Change the Quality of Growth: “revived growth must be of a new kind in which sustainability, equity, social justice, and security are firmly embedded as major social goals”.
3. Conserve and Enhance the Resource Base: “sustainability requires the conservation of environmental resources such as clean air, water, forests and soils; maintaining diversity; and using energy, water and raw materials efficiently”.
4. Ensure a Sustainable Level of Population: “population policies should be formulated and integrated with other economic and social development programmes”.

5. Reorient technology and manage risks: "the orientation of technology development must also be changed to pay greater regard to environmental factors".
6. Integrate Environment and Economics in Decision-Making: "the ability to anticipate and prevent environmental damage will require that the ecological dimensions of policy be considered at the same time as the economic, trade, energy, agricultural and other dimensions".

The degree of adherence to these principles is not uniform along the globe. Conserving and enhancing the resource base and achieving a sustainable development is lagging behind development that was achieved in other principles, but in any case, sustainable development is now almost an everyday term.

1.3 Sustainability of construction and Life Cycle Assessment

The use of life cycle approaches in dealing with environmental impacts of human activities will contribute to environmental protection, is essential in the path to sustainability and will help to overcome global challenges. The use of life cycle thinking in dealing with a product (or a system) expands the focus from the localities that are associated with a product to the whole product life cycle. Life cycle thinking can widen the scope of any study on a product to incorporate various aspects associated with a product over its entire life cycle which is sometimes called a "cradle to grave" concept. The study in these cases will generally produce recommendations to improve performance in all phases of the product life cycle.

The main goal of life cycle thinking is to optimize usage of resources and reduce emissions to the environment. Life cycle thinking will avoid shifting a problem from one life cycle stage to the other and from one environmental media to the other. Considering life cycle stages will ensure overall environmental benefits and contribute to sustainable patterns of development.

The cradle to grave concept of the life cycle thinking should include all the activities in major stages of the life cycle of a product such as

- Raw material acquisition
- Production of primary materials of a product
- Manufacturing of the product
- Use/ reuse/ maintenance of the product
- Waste management

The construction industry has a major role in environmental impacts and at the same time has a great potential to improve its performance in this regard. The upstream environmental impacts of construction are highly significant and as such, they offer important opportunities for environmental improvements leading to a sustainable construction industry. The use of wastes as a fuel in the production of cement and the use of slag, silica fume and fly ash as a binder replacement for a part of cement content is increasing and new applications are emerging. The use of new or improved construction materials and the recycling in the construction industry have opened the door for evaluation of environmental impacts of these new practices. The utilization of a life cycle approach in these evaluations will insure that these evaluations are inclusive and can be verified on solid bases for compliance with the requirements of sustainable developments.

1.4 Problem statement

Civil engineering structures are very complex systems that can have a long life, with many construction activities (such as periodical maintenance) that are performed through this life time, with many stakeholders on the play. Little work has been done to facilitate the use of Life Cycle Assessment (LCA) in civil engineering structures, mainly due to the complexity of these systems and its long life with the great uncertainty that is expected to shadow the use of the structures. Designers and engineers are not expected to become LCA experts in order to incorporate environmental decision-making in their design process. Therefore, the objective of this research is to develop a model that is flexible

enough to cover most aspects of Life Cycle Assessment of Concrete Bridge Decks. Such a model is valuable for civil engineering practitioner to establish the environmental loading of a concrete bridge deck along its life cycle and can be used to make comparison between different designs, or to address environmental regulations.

1.5 Plan of research

The first step in every LCA study is to define the goal of the study and then collect the required Life Cycle Inventory (LCI) data that are related to the subject of the study. In this research, a great deal was given to collecting LCI data that represent the North American industrial set. The proposed model incorporated the real world scenario for different activities in the life cycle of a concrete bridge deck and traced the emissions of these activities to establish an inventory of these emissions, and then tabulate the emissions according to the source of the emission and according to the different stages of the life cycle. The model can be used as a tool to facilitate a full LCA study for a concrete bridge deck by using the emissions inventory established by the model.

The literature review spans over two chapters of the thesis. Chapter two includes an introduction into Life Cycle Assessment, history, fundamentals and the limitations of Life Cycle Assessment. A brief description of available Life Cycle Assessment software tools is provided in chapter two. A brief description of earlier works in Life Cycle Assessment of engineering structures is also included.

Chapter three is the second part of the literature review and is aimed at providing a description of practical issues of conducting a study by using the fundamentals of Life Cycle Assessment. The preparation of chapter three depended heavily on the report "Life Cycle Assessment: Principles and Practice" [7]. The chapter follows the four phases of the Life Cycle Assessment study and expands on the practical issues associated with performing every step in every phase of the study.

Chapter four contains detailed information about the framework of the model including the detailed steps followed to collect the LCI data. A detailed description of every part of the model, calculations steps and requirements of every part are included also in chapter four. The model can give indicators of two impact categories on the environment, namely the Global Warming Potential (GWP) and Acidification Potential (AP). Chapter four also describes the calculations of these indicators. The model calculates the energy and raw materials consumption, electricity consumption, transportation and construction equipments along all stages of the life cycle of a concrete bridge deck and these calculations are explained in chapter four.

Chapter five is aimed at introducing the flexibility of the model by estimating the environmental loading of an assumed concrete bridge deck and compares it with different alternatives to determine the option with the least environmental loading.

The case studies propose multiple alternatives by:

- Changing the mix proportions to reduce the content of Portland cement.
- Increasing the strength of concrete and use post-tensioning to reduce the thickness of concrete, using two methods of construction.
- Shifting the batch plant closer to construction site to reduce transportation emissions.
- Continue to use the old bridge deck with reducing the intervals of periodical maintenance.

A brief discussion of the results is included in chapter five.

Chapter six includes the conclusions of the thesis on the need for LCA to estimate the environmental loading of a concrete bridge deck to select the best design option that is in line with the requirements of a sustainable construction in reducing the consumption of energy and raw materials and reducing the impact on the environment. Chapter six provided recommendations on some topics of

interest for future research, particularly for the type and quality of life cycle inventory data.

2. Introduction to Life Cycle Assessment

Life Cycle Assessment (LCA) is a tool to estimate the environmental loading of a system during its life cycle. The term “system” can refer to a product, a service or a technological system (such as a concrete bridge deck). This chapter is aimed at providing an introductory review of the fundamentals of LCA. There are many existing software tools to conduct LCA, and some of them are mentioned here. LCA has some limitations, and these limitations are briefly presented. LCA application to construction industry has been a new subject with little work done in this regard compared with the application of LCA in industrial products. Some of the earlier applications of LCA in construction industry are also mentioned.

2.1 Life Cycle Assessment

Life Cycle Assessment (LCA) is an analytical tool for the systematic evaluation of the environmental loads of a product, a service or a system through all stages of its life cycle. Life Cycle Assessment principles and procedures used in analyzing the environmental interactions of a system (throughout its life cycle) with the environment makes LCA an adequate instrument to take an informed environmental decision. Therefore LCA is considered an important tool for environmental management [8].

The methodology of LCA is a comprehensive one, whereby all (in and out) flows of a system (materials, energy, emissions and products) are first qualified and then quantified. Typically, all flows of a system are inventoried along the stages of the life cycle of the system starting with raw materials (extraction, transportation and processing), production, use or operation of the system, and ending with the end of life of the system (decommissioning and disposal) as shown in Fig. 2.1.

Fig. 2.1: Life cycle stages of a system [7]

The environmental loads of the system are subsequently calculated based on the inventories of materials, energy and other processes that are within the system. The environmental loads include emissions to air, effluents to water and the generation of solid wastes. This methodology of LCA is sometimes called a “cradle-to-grave” approach because the analysis begins with the gathering of raw materials from the earth to create the system and ends at the point when all materials are returned to the earth as environmental loading. The emissions of the system contribute to some of the environmental phenomenon (called impact categories) such as global warming, ozone depletion and acidification.

LCA unique methodology of accounting emissions from all stages of a system can help decision-makers compare all major environmental impacts caused by a system and can help when deciding between two or more alternatives to select the one with the overall least environmental loading, without transferring the environmental loading from one media to the other, or from one stage of the life cycle to the other. The ability to quantify and record environmental loadings and the transfer of environmental impacts from one media to the other and the shifts

in environmental impacts can help decision makers and managers fully characterize the environmental trade-offs associated with the system under study or between the alternatives. LCA can be used to establish recommendations for action for decision makers for product procurement or purchases. LCA can be used to weigh the impacts from discrete systems and materials to select the optimum one [9]. Conducting an LCA study on a system can:

- Evaluate the environmental consequences associated with the system.
- Explain the environmental trade-offs associated with a system or to compare between two different systems to help stakeholder to take an informed decision.
- Quantify environmental loading to air, water, and land from each stage of the life cycle of the system and/or the major activities in the life cycle that contribute to the environmental loading. It can help in monitoring environmental loading of the system on a specific environmental area of concern.
- Evaluate the effects of environmental loading of the system to the local community, the region and the world.

LCA study can help in making an informed decision regarding the environmental impact of the system subjected to study, while other tools will be required to evaluate cost and effective performance of the system. Hence LCA study is only one component of a more comprehensive decision process assessing overall performance of the system and deciding the trade-offs between environmental impacts, cost and performance of the system.

2.2 Brief history of LCA

Concerns over the limitations in supply of raw materials and energy resources in the 1960s initiated an interest in predicting future resource supplies and consumption patterns. In 1969, researchers working for Coca-Cola Company started a study on beverage containers that became the base of the modern life cycle inventory analysis [7]. The study was made to compare different beverage

containers to identify the one with the lowest releases to the environment and least demand for natural resources. The study quantified the consumption of raw materials and fuels used in production of containers and the environmental loadings due to the manufacturing processes of the containers. Several companies followed the same procedure both in the United States and Europe in the early 1970s. These studies faced the problem of lacking the proper information as specific industrial data were not available [7].

The oil shortages in the early 1970s and the formation of public interest groups pushed the industry to ensure the accuracy of information in the public domain. The availability of such information helped the few studies that were performed at that time. At the same time a protocol for conducting these studies was developed and many modifications were made to the assumptions used in the early studies [7]. The interest in these studies faded in the second half of the 1970s in the U.S. due to availability of oil supplies after ending the oil crisis, while studies of life cycle inventory analysis continued on a lower pace in Europe. The public interest shifted to monitoring hazardous waste management in the early 1980s, and the European LCA researchers developed standardized pollution regulations.

During the 1990s, great efforts were made to standardize the formats of LCA modeling and reporting procedures and to monitor environmental advertisement claims. These efforts lead to increased dependency on these studies due to conformity of LCA studies [7]. These efforts were crowned at the end of the decade with the advent of the ISO 14040 series of standards for LCA studies.

2.3 LCA standards

LCA became an internationally accepted environmental management tool with the introduction of the ISO14040 series of international standards as a development of the ISO 14000 Environmental Management Standards. The series of ISO 14040s are shown in Table 2.1.

Table 2.1: Life Cycle Assessment Standards

ISO standard #	Name of the standard	Year of issue
ISO 14040	Life Cycle Assessment – Principles and Framework	1997, 2006
ISO 14041	Life Cycle Assessment – Goal and Scope Definition and Inventory Analysis	1998
ISO 14042	Life Cycle Assessment – Life Cycle Impact Assessment	2000
ISO 14043	Life Cycle Assessment – Life Cycle interpretation	2000
ISO 14044	Life Cycle Assessment – Requirements and Guidelines	2006

2.4 Phases of Life Cycle Assessment

A full LCA study is aimed at assessing the environmental loading and potential impacts associated with a product or a system by:

- Establishing an inventory of (in and out) flow of energy, material and the environmental releases associated with the system.
- Estimating the environmental impacts associated with some identified emissions of the system.
- Interpreting the findings of the study to help decision-makers make a more informed decision.

The international standard ISO 14040 [10] defined the four phases that a full LCA study will pass through, as shown in Table 2.2, while the framework of the study is shown in Fig. 2.2.

Table 2.2: Phases of LCA [10]

LCA phase	Primary activities
Goal scope & definition	Life cycle definition Functional unit definition System boundary definition Data Quality determination
Inventory analysis	Data collection Quantification of inputs/outputs
Impact assessment	Classification Characterization weighting
Interpretation	Reporting Critical review

Fig. 2.2: Framework of LCA study [10]

There are different levels as to which degree a study will go in covering of LCA phases. In many cases, a study requirement is limited only to the first two phases, and in this case the study is called a Life Cycle Inventory analysis [11]. When the study includes the third phase, then it will be called a Life Cycle Impact Assessment (LCIA) as shown in Fig. 2.3. Life Cycle Inventory analyses can assist in comparing products or processes and considering environmental factors in material selection. In addition, Life Cycle Inventory analyses can be used in policy-making, by helping the government develop regulations regarding resource use and environmental emissions [11].

Fig. 2.3: Different levels of LCA Methods [11]

2.4.1 Goal and scope definition

The first phase of an LCA study is the Goal and Scope definition which include:

- Definition of the life cycle of the system
- Definition of the functional units of the system
- Definition of system boundaries
- Determination of data quality requirements for the system

These definitions have to be carefully laid out at the start of the study, and followed during the course of the study as the final results will be affected by those definitions. The interpretation of the results of the study may vary if these definitions are altered.

Definition of the life cycle of the system must include the entire life cycle of the system from the outset to the end of the expected functional service life of the system. The definition of the life cycle should include all the activities required to generate, use and disposal of the system subject to study. However, sometimes the setting of the boundary of the system may be altered later to exclude specific life stages for different practical reasons [7].

Definition of the functional unit of the system can be expressed by various methods depending on the nature of the system and its applications. The definition of the functional unit has to be clearly identified and measurable. The functional unit will facilitate comparison between different systems and serve as a basis for normalization of the results.

Definition of the system boundaries should follow the goal and the scope of the study, and will determine the extent to which a specific process or activity is included or excluded. The definition of the system boundaries will result in a clear picture of the components of the system under assessment; however there should be a balance between practical aspect of the study as to which part to be included and the validity of the expected results.

The definition of data quality requirements for the system will indicate the data that are required for the study and quality indicators of these data can be established. Data quality requirements may address aspects such as time, geographical and technology-related coverage of the included data.

2.4.2 Inventory analysis

The second phase of LCA study is the inventory analysis which includes two steps:

- Collection of data relevant to the study
- Calculating relevant inputs and outputs of the system.

The collection of data relevant to the study requires gathering of data as defined in the goal and scope phase and might result in the refining of system boundaries for practical reasons such as unavailability of data or the quality of available data. During this step of the inventory analysis, decisions might be required with respect to allocation of energy, materials and environmental releases flows for the different products if the system has multiple products. The type and quality of the data has to be examined against the set definitions of the study to ensure it is valid for the system under study. However, system boundaries might be refined in consideration of the defined scope of the study and the availability or quality of data.

The collection of data may reveal the need to refinement of data gathering process which should be restricted only to include inputs and outputs that are significant to the study. This refining process may involve exclusion of life cycle stages, subsystems or other flows in case of insignificance. It may also involve the inclusion of unusual unit processes in cases where they appear to generate significant impacts.

The inventory data should cover the (input and output) flows for every activity in every life cycle stage of the system in order to quantify (input and output) flows of the system and normalize the results with respect to the functional unit of the system. The data will then be aggregated in order to result in detailed input tables that cover flows of the studied system such as:

- energy consumption,
- materials consumption, and
- other activities (such as transportation) which are related to the system.

The output flows of the system are aggregated in tables that cover environmental releases such as:

- emissions to air,
- waste water discharges, and
- solid waste disposal.

Examining of the inventory tables against the set definitions may lead to some conclusions which can be drawn directly from these data to verify some of the points such as:

- Verify whether certain substances or emissions are significant to the study and therefore, should be considered and included in the tables.
- Evaluate the criteria set in the definition stage, to identify the key data that can be at the centre of interest of the study and subject it to further investigation.
- Conduct a primary estimation of the environmental impact categories by considering the key contributors to these categories and decide whether to stop at this stage or proceed to the next phase of impact assessment.

2.4.3 Impact assessment

The main purpose of impact assessment is to assess the potential effects of the consumption of energy and materials and the emissions associated with the system on the environment, and some times may be expanded to cover issues related to human health. The impact assessment phase of the study may include four steps:

- Category definition.
- Classification.
- Characterization.
- Weighting.

Category definition step will lay the rules for the selection and definition of the environmental impact categories to be addressed by the study. In general cases, the selection of the impact categories of the study is preferably expanded to cover the complete categories. It is not recommended to avoid or disguise impact categories which are included in the goal and scope of the study. Many impact categories does exist based on many models that have been developed worldwide to represent the different potentials of impact from emissions on the environment. One of these models is developed by the US Environmental

Protection Agency which is called TRACI [12] which can be used to provide the definition of these impact categories.

The classification step is carried out to assign the relevant input and output inventory data to the defined impact categories. This step requires knowledge of the relevant environmental processes, and if human health criteria are included, knowledge in this field is essential also. Classification is a mandatory step in impact assessment, and in some cases, no further steps in impact assessment phase are necessary prior to interpreting results [11].

The characterization step is performed to use the relative importance of the contributing substances in each impact category to determine the total loading of this impact category in terms of the reference substance of the category. The relative importance (or impact potential) can be expressed relative to a reference substance in that impact category by using “the characterization factor” for each substance to convert the impact of that substance to an equivalent amount of the category indicator which is usually the reference substance of that impact category. The characterization step can be performed if the ability to model the categories in terms of standardized indicators does exist. Characterization factors do not yet exist for all impact categories. “The result of the characterization step is the expression of contributions to impact categories in terms of equivalent amounts of emitted reference substance for each impact category [11]”.

The weighting step is implemented sometimes to provide an aggregated score by combining the impact categories to make it easier for decision makers to take a decision. This step is accomplished by giving relative “weight” for different impact categories, a process that gives to categories a relative importance and ranks the categories according to their relative importance to each other. This ranking is done by assigning a numerical value (weighting) to each impact category to represent its degree of significance. The process of weighting is based on ethical

or societal value judgments rather than scientific information [11]. The weighting factors may be based on:

- Proxy methods.
- Assigning a monetary value to the category.
- Environmental state indicators.
- Environmental political goals.

Many approaches are used for weighting impact categories, some of them are not based on science, which raises a difficulty in the precision of the process due to the molding of weighting numbers that will not allow any changing to these weights in the event of the existence of new information. Allocating a weighting factor beyond two significant figures is almost certainly unrealistic. This, in turn, indicates that there is little to be gained by determining the value of other data beyond two significant figures also [11].

The weighting process is helpful in reducing the LCA study to a single “score” which will make the comparison between alternative systems very easy. The weighting step is valuable to people who are not involved in the details of the LCA and have to take decisions based on LCA outcome. The simplification of the weighting process is a major cause for its weakness because the departing from the details will shadow a lot of important aspects of the system that can otherwise be dealt with to improve the environmental performance of the system. For example it is important to show the size of greenhouse gas emissions during the usage phase of the life cycle relative to other phases of a system, or the significance of transportation emissions in relation to the geographical location of the system. Obscuring such information may ultimately act against the main goal of conducting such a study.

2.4.4 Interpretation

The final phase of LCA study is the Interpretation phase of the study which includes:

- Reporting of the study results
- Critical review of the results

The first step of the final phase of an LCA in earlier studies was called “improvement assessment” and was required to compare the results of alternative systems by considering the inventory analysis and impact assessment to select the preferred product, process or service, taking into account the uncertainty and the assumptions used in the study. Current applications of LCA are aimed at a variety of goals, from hot spot analysis in product development to comparative studies of alternative products, therefore the term “improvement assessment” was deemed not appropriate. Consequently, the step naming has been replaced by “reporting of results” [11].

Reporting of results step will incorporate reviewing of the results of inventory analysis and impact assessment to point to basic subjects such as:

- Indication of significant environmental issues related with the consumption of materials, energy and emissions associated with the system under study.
- Evaluation of the bases of the study and the information that resulted from the study.
- Draw conclusions from the results of the study and give recommendations on the main questions that led to commencing of the study.
- Examining of the definitions established during goal and scope setting against the results of the study which might lead to reconsideration of these definitions.

The second step is to perform a critical review of all the phases of the study to evaluate it for completeness, sensitivity and consistency [11]. A critical review process can ensure the quality of the study. If reasonable, a reviewer or a review panel may be consulted in order to confirm that the study has the following points:

- Carried out according to ISO standards and/or any standards related to the study as defined in the goal and scope phase
- The results of the study are scientifically and technically valid
- The data that was used in the study is appropriate and reasonable according to the goal of the study
- The interpretations of the results has answered the questions raised at the goal and scope phase of the study and is within the limitations
- The reporting process is transparent and consistent.

2.5 LCA Software tools

The LCA method has evolved to become a widely accepted tool to establish the environmental performance of a technological system along its life cycle stages. However, LCA methodology contains a lot of calculations and a fundamental need for LCI data. This has necessitates the need for computer software that can deal with these calculations and can have access to LCI data.

Currently more than 30 LCA or LCA-type software tools [8] have been developed to access a LCI database and perform the calculations required to establish the (in and out) flows of LCA. These software tools differ in many aspects such as their applicability to different cases, scope of covering LCA phases and methodology. Many LCI databases exist with different nature and applications which are usually developed either by industry (or industry associations), consultants (or research institutes) and government. These LCI databases might be administrated by the same parties that developed it. LCA software tools usually have access to one or more of these LCI databases. However, there seem to be a tendency of these software tools to use the same databases [8].

Many documents contain a review of available software tools [13]. These software tools are designed for a variety of LCA applications by different types of users; however the majority of these software tools are designed to be used by LCA experts. Some of these software tools are available free of cost such as

BEES, which was developed as a tool to serve a certain policy of the U.S. government. These software tools usually follow the ISO 14040s series of standards.

The incorporation of LCA into the construction industry lack behind its application in other industries, but currently few LCA software tools have been introduced such as BEES [14] and ATHENA Estimator [15]. None of these software tools is capable of properly modeling a true building due to many hurdles such as the uncertainty in the construction method that is used to construct the building, material selection, method of utilization of the building and LCI data availability. The same hurdles render these software tools unable to cover all life cycle stages of the building and eventually these software tools can not establish all environmental impact associated with the building.

2.6 LCA limitations

The LCA methodology has been widely acclaimed as an environmental management tool to evaluate the performance of a system from ecological point of view. However performing a full LCA study requires a considerable amount of time and access to a variety of databases, in addition to financial resources. One of the main criticism to LCA stem from this point as there will be a conflict between the inclusiveness of the study and the practical aspects that are always behind the management system [16, 17].

A proper LCA study has to cover all life cycle stages of a system and cover all unit processes that are within the boundary of the system, but the results of such a study may not be interpreted easily to a useful decision. When enough resources are not available to perform a full LCA study, the goals and scope of the study is reduced but then significant underlying details may be obscured.

The availability of LCI data type and quality as defined in the scope of the study is a crucial requirement to perform such a study; however the path to collect such

a LCI data may not be an easy one. The availability of quality modern data that can be utilized for LCA purposes is not following the demand to widen the application of LCA studies to ever-increasing fields of study. The pursuit of quality and representative LCI data may be beyond the available resources for the study. The requirements of LCI data to be representative and transparent have led to refrain from participating in providing such a data by many stakeholders due to the need to protect proprietary information or industrial secrets. Sometimes the quality of data may be reduced by using industry average data instead of site specific data but then the true representative of the study may be under suspicion.

The LCIA phase of the study is an important phase as it will lead to interpretation of the results into indicators about the potential impact of the system on the environment and other areas of concern, however, some impact indicators are still to evolve to be defined on solid bases [18]. Some indicators have been introduced long enough to become well characterized, well established methodologically and easily measured such as global warming and energy consumption. Other indicators have a complex methodology that is contested frequently such as resource depletion. The list of impact indicators required to establish the goals of a study may sometimes include new concepts, such as land use, that are still evolving and very hard to be measured due to lack of LCI data and the proper modeling [12]. These practical issues in determining the impact indicators may limit the applicability of LCA to cover these impact indicators [9]. The weighting process that might be used sometimes as a part of the goals to provide an aggregated score for impact indicators which is based on value judgment rather than science as the case with the indicators themselves and this might lead to controversy in the wisdom of using such a process [7].

The application of LCA to evaluate the impact of engineering structures on the environment can be very useful as the construction industry is the largest single

pollutant; however the inclusion of all life cycle stages of buildings and other structures may be problematic due to the complexity of these systems.

Although performing of LCA on a system is by no means simple, however, LCA became generally recognized as the best accepted methodology that can be utilized to establish systematically the environmental impacts of a system or to compare alternative systems to select the environmentally sound one. LCA can not establish the performance or the cost of the system, and therefore it is only a tool in a more comprehensive management scheme.

2.7 LCA and construction industry

Application of LCA methodology to construction industry came at a later stage than being applied to other industrial systems and therefore less application of LCA methodology can be found today to assess environmental performance of the construction industry fields [9]. LCA systematic and transparent methodology has become an accepted protocol that can be used to ensure equitable treatment of materials, energy and other activities that constitute part of the construction process. LCA also ensure functional equivalence when assessing building products or partial building designs, and therefore LCA became the only logical approach to assess the environmental performance of engineering structures [18].

Structural systems, such as commercial buildings, are one of the significant contributors to energy consumption, and their environmental impacts, such as air emissions and solid waste generation are huge. For example, 38% of US primary energy consumption is related to building operations [3] and 65% of all 1997 municipal solid waste were related to buildings [4, 19]. Structural systems are a very complex industrial product in terms of production and use with considerably extended lifetime that may span several decades. The impact on human health from the envelope of buildings, such as “sick building” syndrome, draw a lot of attention in terms of measures taken to deal with the subject such as issuing

strict codes for the operation of buildings, however comprehensive approaches, especially at the design process, have been lacking behind these actions [20,16]. The greatest opportunities to affect the comprehensive environmental behavior of a building, or any construction system, are available at the design stage where changes can be made easily to enhance the system's overall environmental impact throughout the long life time of the system. This fundamental assessment of the need to a comprehensive approach have led to model buildings as a network of interrelated environmental systems and manage these system to produce a more environmentally friendly buildings [21].

Buildings, and other structures, have a long life expectancy and are very complex systems in terms of production and use, therefore the definition of the life cycle of such systems will incorporate assumptions or estimates of the:

- Projected functional service life of the system.
- Expected scenarios of use and maintenance schemes of the system.
- Plan of maintenance and repair including replacement of components.
- Expected scenarios of major refurbishment or renovation for the system.
- Expected scenarios of demolition and recycling procedures (if any).

The approaches of LCA have been applied to evaluate limited flow aspects (such as energy) of buildings by many researchers [22, 23, 24 and 25]. Many researchers tried to assess the environmental performance during all stages of life cycle of different buildings by applying of LCA approaches [26, 27 and 28].

The burdens of wastes from the construction industry have increased dramatically, for example 17% of the total UK wastes arise from the construction and demolition industry [29]. Requirements for sustainable construction industry called for the recycling of these wastes, however the recycling process has its own environmental impact due to energy requirements and the transportation activities associated with recycling. This situation has lead to adopt approaches

of LCA to assess the environmental gain from reuse and recycling (of construction wastes) into the construction industry by many researchers [29, 30].

The methodology of LCA has been applied to assess different environmental aspects of infrastructure projects such as roads. A comparison between asphalt and concrete roads on the bases of energy consumption and green house gases emissions was made by using LCA methodology [31], while a hybrid of LCA methodology and input – output schemes was used to produce a model to evaluate the emission of CO₂ for highway projects in Japan [32]. Other studies were performed to evaluate the operation impacts versus the construction impacts of roads using LCA methodology [33]. Partial LCA studies were performed to establish LCI inventory for road projects on regional level in Europe [34]. Comparison of alternative materials and designs of expansion joints of bridges to select an environmentally sound one was made by adopting LCA methodology [35].

3. Practical issues of conducting an LCA study

Conducting of a LCA study requires many decisions at various points during the four phases of the study. It is important to discuss the practical issues that may help in taking decisions during such a study. This chapter is part of the literature review and is aimed at touching these practical issues within each phase of a LCA study to facilitate the application of LCA method in assessing the environmental loading of a system.

3.1 Goal and scope definition phase

Goal and scope definition phase of the study will set the purpose of the study and the method followed to reach these goals by determining the type of information needed from the study, the expected accuracy of the required information and the method of reporting the required information. This phase of the study will help in estimating the time and resource needed to reach the set goals. Basic decisions have to be made at this phase to make optimum use of resources and time to conduct the study such as:

1. Defining the Goal(s) of the study.
2. Determining specificity of information.
3. Determining the functional unit.
4. Defining the scope of the study.

3.1.1 Defining the goal(s) of the study

The major goal of conducting LCA study is to quantify the overall environmental impacts from a system, and the aim is to choose the system with the least effect on human health and the environment. LCA study can help guide the development of a new system that requires less resources and has less emissions. There may be some secondary goals for performing a LCA study, which would vary depending on the type of system under study. The following might be goals for conducting LCA study [7]:

- To determine environmental loading of a new system or modifications to an existing system.

- To determine environmental loading of a process within the system to initiate improvements to the process as part of overall improvement of the system.
- To determine the environmental loading of different components of the system to identify the one that needs more attention for improvements.
- To identify the area of the system that lack the required data or the quality of the data is not up to the specification, which can initiate a research in this direction to provide the required data and improve its quality.
- To help broaden the range of environmental issues considered in developing regulations or setting public policies.
- To establish the environmental loading of the system and get the required certification for the system from the regulating authority.
- To provide information for the public and industry on the possible lines for improvement in the current systems.
- To guide the production of new systems towards better environmental performance.
- To support eco labeling claims of the product.

Conducting LCA study can provide an answer for a number of important questions for the task of environmental performance improvement of the system, which might represent the goal of the study. Some of the goals that can initiate such a LCA study are:

- To identify the alternative system (or a sub system) that has a better overall environmental performance or in a certain stage of its life cycle.
- To quantify the overall environmental impact of the recommended improvement on the system.
- To identify the technology or process recommended for the system that causes the least environmental impact.
- To improve the environmental impact of the system in a select impact category of concern such as global warming.

3.1.2 Determining specificity of information

At the start of a LCA study, the specificity of the required information has to be decided. The specificity can be decided from the nature of the study, whether it is for a specific product or it is a general study. This nature will determine the type of inventory data required for the study, whether it is product-specific or more general information. The definition of the level of specificity will identify the expected quality of required inventory data, approaches to different phases of the study and study results [7].

3.1.3 Determining the functional unit

The functional unit is usually related to the function of the system being studied. The proper selection of the functional unit will improve the accuracy of the study and the usefulness of the results especially when the study is performed to compare alternative systems. The selection of the functional unit should be based on the amount of service that the system will deliver to the user. For example, when comparing different walls of different materials then the unit area is not a proper selection because different materials of the alternative walls may have different thermal insulation values. The selection of the functional unit in this example should reflect equal thermal insulation of the wall rather than the unit area.

3.1.4 Defining the Scope of the Study

The scope of the system is easier to understand if the activities within the system are broken down into primary and secondary categories. The primary activities directly contribute to making, using, or disposing of the system. The secondary category includes auxiliary activities that contribute to making or doing something that in turn is in the primary activity category. Several tiers of auxiliary activities may extend further and further from the primary activities. Setting the system boundary will define a cutoff point beyond which further auxiliary activities are not going to be included in the study and the reason for this decision may be identified to maintain the transparency of the study [7].

A complete LCA boundary should cover all life cycle stages of the system starting with acquiring raw materials from earth and ending with materials in the environment or on earth but not in the system. In some cases, and due to study limitations, a reduction in the scope of the study may become feasible without affecting the goals of the study provided that this reduction does not exclude consequential activities [7]. For example in the case of a LCA study to compare different processes to produce the same product, it is possible to eliminate the acquiring of raw materials stage or the disposal stage from the study as the same amount of raw materials will be consumed by the different processes and the same disposal method will be used for the product regardless of the method of production. The exclusion of these two stages of the life cycle of the product from the study will not harm the goal of the study, which still can be achieved. The report of such a study should clearly identify the stages that have been excluded from the life cycle and point to the fact that environmental impacts determined by the study does not represent the full system impact, but rather a partial impact from the stages that were included in the scope of the study.

3.2 Life cycle inventory phase

The main purpose of life cycle inventory (LCI) phase of the LCA study is to quantify consumption of energy and raw material, emissions to air, effluents to water and solid wastes for the entire life cycle of a system associated with the functional unit of the system. The results can be segregated by life cycle stage, media (air, water, and land), specific processes, or any combination thereof. According to the ISO 14041 (1998) standard [36], data collection for each unit process (smallest portion of a system for which data are collected) and preparation of the inventory are the main activities in the LCI phase. The LCI phase is the most time and resource consuming phase of a LCA study, especially for the utterly important data collection step of LCI phase because the final results are directly based on the collected data. The preparation of such inventory is the basic step in conducting LCA study, and the level of accuracy, detail and quality of the data for LCI phase will be reflected throughout the

remainder of the LCA phases and might determine the validity and reliability of the LCA study.

3.2.1 Preparation of system flow diagram

The first step in conducting LCI is to prepare a system flow diagram [7] which will act as a tool to map the inputs and outputs to the system. The system boundary as defined in the goal and scope definition phase is used as the system boundary for the flow diagram. The system flow diagram will link the unit processes inside of the system boundary together to form a complete life cycle picture of the required inputs and outputs to the system as shown in Fig. 3.1.

Fig. 3.1: Example of unit process for LCI [36]

Preparing a more detailed flow diagram will lead to a more comprehensive result, however expanding beyond the boundaries of the system as defined in the goal and scope definition might overburden the resources available for the study. When the goal of conducting LCA is to compare alternative systems the same system boundary and level of details should be used when evaluating the alternative systems to maintain accuracy of the results.

The system under LCA study is viewed as being made up of a linked series of subsystems, and each subsystem requires inputs of materials, energy and transportation; and has outputs of product/s (and may be a co-products) and environmental emissions to the three media (air, water and land). For each subsystem, the (in and out) flows and the actual activities that occur within the subsystem should be described, while describing the method adopted to generate the data for LCI can be used in judging the quality of data. Some subsystems may need to be grouped into a larger subsystem due to lack of specific data for the individual subsystems [7]. When the subsystem has a co-product (or a by-product), it should be quantified to allocate part of the (in and out) flows of the subsystem to these co-products as long as there is a value or a use for these co-products (it will not be wasted). This allocation process will reduce the (in and out) flows burden from the major product of the unit process which is considered part of the system.

3.2.2 Setting criteria for collection of LCI data

Determining the required accuracy of the data for the LCI is part of the goal and scope definition phase of the study, and planning for data collection should lead to fulfillment of accuracy definition. Setting goals for data quality and collection plan should coincide with the study goals, keep a balance between the available resources and the expected quality of the data and will serve as a starting point to the data collection process. There is no unified definition for data quality and it depends largely on the type of the study. The quality of the data can be measured against a quality indicator to verify if the data has met the set quality. No specific indicators are available as a benchmark for all studies but it can be described by some general requirements such as precision, completeness, representativeness, consistency, and reproducibility [7].

The source of data that are required for every unit process in the system along its life cycle should be capable of meeting the defined accuracy of the study. The type of data may be:

- Based on a model.
- Process site specific (measured, sampled).
- Non-site specific (surrogate data).
- Data that was not foreseen to be used as LCI data.

Many categories for data sources may be available such as:

- Direct measurements at the location of the unit process or at laboratories.
- Private sources such as industry data reports/databases, consultants and trade unions.
- Government documents, reports, databases and other publicly available references.
- Data from previous related LCA/LCI studies.
- Specifications of equipments and processes.
- Best engineering judgment.

It is recommended to get well-characterized industry LCI data for unit processes that represent the current industry standard and reflect the goal of the study in location specificity, whether to be facility specific or representative of the industry in general for the unit process or aggregated unit processes under study. The use of proprietary data is a critical issue that is faced when preparing LCI, and in some cases will place a hurdle in the path to get credible LCI data that meet the defined quality. Current studies often contain insufficient source and documentation data for verification of LCI accuracy in order to comply with the need for protection of proprietary data and therefore there should be a balance between protection of confidential business information and the need for representative and transparency of LCI data. The LCI data in publicly available government documents and databases provide data on broad categories of processes, and therefore may be less specific and less accurate than industry specific data and might be several years old. However, depending on the purpose of the study and the specific data objectives, these limitations may not be critical [7].

3.2.3 Collection of LCI data

The collection of LCI data for the study can be performed by researching available sources, by making site – specific measurements and by making personal contact with experts. Several general purpose (non – site specific) databases are available which contain basic LCI data that can be utilized in LCA study; few of them are publicly available. The source of the data has to be clearly mentioned in the study report. Several commercial databases are available and the LCI data can be purchased from these databases, however the quality of the data has to be insured before deciding to buy it from these databases. These commercial databases usually contain proprietary LCI data and therefore there is no record of assumptions made to generate these data or the method used to make the computation. This might affect the transparency of the study that depends on these databases and therefore the definitions set for the accuracy of the study might need to be revisited [7].

3.2.4 Allocation of LCI data

The unit process (that is part of the system) usually has multiple input of materials and energy and releases multiple emissions, and might also has multiple output in the form of co-products beside the major product which is of prime interest to the study. This situation will require assigning a part of the energy and material input, and a part of released emissions to the major product from this unit process which is of interest to the study. This process is called “allocation”.

The guidance of ISO 14041 [36] in this regard strongly suggests avoiding allocation as long as it is possible and suggests few steps to do so. However ISO 14041 recognizes the fact that it is not possible to avoid allocations in many cases. When the allocation is unavoidable, ISO 14041 provides a step-wise approach to allocation which reflects the physical relationships between the inputs and the outputs. This allocation will require a good understanding of the physical relationships between co-products and the (in and out) flows of the unit

process. Allocation on other bases than the physical relationships of the co-products might be followed if this physical relationship can not be configured, and the ISO 14041 suggested the economic value of the co-products as an example for such alternative.

The allocation is usually made with reference to the weight or volume of co-products, but in some cases one of the products will far outweighs the other co-product/s which might suggest that the allocation process in this case is impractical [7]. Allocation that is based on market value usually reflects the expected economic gain based on gross sales, and in most cases reflects the use of energy. This will render the allocation process to cover only limited aspects of the environmental burdens of the system. Moreover, market value is highly time-dependent, and sometimes might change over a short period of time which affects the consistency of results. The use of other arbitrary criteria for allocation has to be carefully laid out and judged against the set quality of LCI data [7].

3.2.5 Setting boundaries of LCI data

The collection of LCI data provides numerical values that reflect the set type, quality and accuracy of LCI data to fill the worksheets. The collection of LCI data may not be a simple task because some LCI data may be difficult or impossible to obtain, or the available data can not be related to the functional unit, which lead to the common practice of refining the system boundaries or data quality goals of the study based on the availability of data or its quality. Therefore the collection of LCI data is an iterative process. Different criteria can be used in defining the boundary for the collection of unit processes included in the system under study, such as [7]:

1. Incorporate all unit processes, no matter how minor are they, assuming that the end of the study will reveal the processes that can be excluded, and not before that.

2. Incorporate unit processes that are more than a predetermined and clearly identified threshold within the defined scope of the study.
3. Use sensitivity analysis to determine the unit processes that have negligible effects and therefore can be excluded from the defined scope of the study.
4. Exclusion of certain classes or types of inputs, such as capital equipment, from the defined scope of the study.

The first criterion does not involve any assumptions to be used in defining the system boundary and there are no explanations regarding inclusion or exclusion of input to be made in the final report of the study. However, adopting such a criterion could be an endless exercise of including unit processes that are distantly related to the system. Furthermore, there will be difficulty in interpretation of the results due to complexity of the computation.

The second criterion will require less resource provided that there is a clear definition of the threshold. There are two options within this criterion which depend on the type of threshold [7]; the first one is to specify a percentage contribution of the subsystems of the unit process to the total emissions of the system below which the subsystem will be excluded. An example of such a percentage is the 1% which has been adopted extensively to define inert contributions; however adopting the 1% rule might exclude processes that contribute to environmentally damaging substances therefore a rationale must be provided for such a practice. The second option is to set the number of back steps to include subsystems from the main unit process to be included in the study, for example taking one step back from a unit process and include the inputs from this one step back. Again, the same drawbacks of the first option apply here.

The third criterion is based on a systematic approach to the problem rather than depending on an arbitrary threshold. The use of such analysis will require

availability of a large existing database to provide preliminary values to be used in the sensitivity analysis, and the methodology of the sensitivity analysis has to be clearly described in the final study report.

The application of the fourth criterion has been found to be applicable to many systems, especially the exclusion of contribution from the manufacturing process of capital equipment from the system boundary as these equipments will be used numerous times to produce the same system again and again rendering such a contribution a minimal [7]. Applying such a criterion will eliminate a complex subsystem from the study and therefore reduce required resources; however applying this criterion might exclude processes that contribute to environmentally damaging substances therefore a preliminary analysis should be performed to ensure that a significant contribution is not left out.

One subject of interest in defining the system boundary is the way to deal with capital equipments and personnel issues. These two categories of activities have been shown to have little effect on the results. The (in and out) flows that are associated to build capital equipment are allocated to a large number of systems produced during the lifetime of the equipment, leaving the share of the system of interest a minimal from these flows. In some cases, the contribution of the activity where this equipment has been used is itself a small part from the total flows of the life cycle of the system. As for the case of personnel issues, such as energy consumption in the site office or the transportation of personnel to and from site, the contribution of these issues can not be modeled properly for all the cases. In many situations, the personnel consequences are very small and would probably occur whether or not the product was manufactured. Therefore, exclusion from the inventory may be justified. The capital equipment and personnel issues are not usually included in the boundary of LCA study [7]. The study report should clearly state whether they are included or excluded from the scope of the study.

3.2.6 LCI of energy

Energy is used almost in all activities of a system to move these activities. The term “energy” generally reflects the utilization of energy embodied in electricity or fuels.

3.2.6.1 Documentation of energy

Energy LCI data include the combination of energy requirements of all unit processes that are part of the system, which include energy requirements for the process itself, energy requirements for the transportation within the process and inherent energy of material resources.

Process energy is the energy required to operate the subsystems within the process such as reactors, heat exchangers, motors, Transportation energy is the energy required to power various modes of transportation such as trucks to move the components of unit process between them. The energy required to operate a conveyor, for example, that will move materials between two points within the unit process boundary is included in the process energy, while the energy required for such a conveyor to move materials between two unit processes will be considered transportation energy. The inherent energy is the energy that is naturally available in a raw material such as crude oil.

There are two methods to report energy inputs in a unit process. The first method is to report the actual units of energy forms consumed in the unit process such as kilowatt-hours (kWh) of electricity or cubic meter of natural gas. The other method is to include quantities of primary fuels used to generate the consumed energy forms in the unit process. The first method is easier to be implemented as energy forms can be straight forward reported from monitoring the consumption at each process. The second method allows comparison between unit processes on the bases of primary fuels required to generate the energy forms that are consumed in these unit processes. Conversion factors are used to convert the

fuels and electricity consumed by the process into energy equivalent of megajoules (Mj)

3.2.6.2 Precombustion of fuels

The amount of energy transformed during fuel combustion is only part of the total energy associated with the use of fuel. The other part of the total energy is the amounts of energy spend to acquire the fuel which may be of significant percentage from the total energy. The energy consumed to acquire raw materials of fuel (such as drilling for oil), the energy consumed to transfer these raw materials into usable fuels and the energy consumed to transport these fuels to point of use can be aggregated and are called “precombustion energy”. The total energy consumption may include the precombustion energy as it is of significant value, and it is analogous to including acquiring of raw materials into the life cycle of the system. The report of the study should clearly state whether the precombustion energy was included or excluded.

3.2.6.3 LCI of electricity

Electricity is generated from a variety of primary fuels such as fossil fuels and nuclear fuel, and can be generated using renewable sources such as hydropower, wind, solar energy, combustible solid waste, the selection of fuel types in electricity generation is an interchangeable process that is based on the cost per energy unit. However, reasons other than cost, such as scarcity of fuel type or emissions to the environment can be a decisive factor in the selection of fuel type. This diversity in primary fuel types used for energy generation necessitates the LCI to include the primary fuels consumed in the energy requirements of the system. Thus, it would consider not only electricity, but also the primary fuels that produce the electricity.

One of the considerations associated with the consumption of electricity in the unit process is the type of primary fuels used to generate the electricity. The user of electricity from a utility is not simply purchasing power from the nearest plant.

The utility usually generate electricity from different generation plants using different fuels, and once electricity is generated and fed into transmission lines it becomes mixed and is indistinguishable from electricity from any other source. The utility is interconnected with neighboring utilities (also using various types of fuel), to form regional grids and national grid. One of the points of consideration here is to relate the consumption of electricity at a specific location to the type of primary fuel used to generate this electricity; therefore it is possible to assume the fuel mix in the regional grid as a base to perform life-cycle inventories of electricity in this case [7]. If the activities of the life cycle are more scattered, then the mix of national grid may be used.

The percentage of generation of electricity from nuclear fuel is increasing with time as a substitute for electricity plants that are operated by the more polluting fossil fuel. There is no direct conversion factor for combustion energy of nuclear fuel to energy units, therefore the energy equivalency of fossil fuel that produce the same amount of electricity as the nuclear fuel is used to determine the combustion energy of nuclear fuel. The precombustion energy required for mining and processing of the nuclear fuel is usually included in LCI of nuclear fuel.

The generation of electricity from hydropower is one of the cleanest sources for energy. The energy of one unit of electricity generated from hydropower is identical to the energy of electricity from other sources, but there is no precombustion energy as there is no inherent energy in water and the energy required to construct the hydropower plant is assumed to be negligible with respect to the amount of electricity produced from it. The impact of the hydropower plant on land use, natural habitat and other similar impact categories may be included if such impacts are of interest, provided the required data are available.

3.2.7 LCI of water

Water is used in many unit processes for many purposes such as mixing, cooling, Water might be recycled at the unit process and therefore the quantities of water that was used at the process is released back to the same source of water without affecting the quality and in this case the water can be excluded from the LCI. The water should be included in the study if it is consumed in the unit process, or the water is discharged in bad quality and can not be used. Sometimes the water is taken from groundwater and then is discharged to surface water which affects the groundwater level or quality, and in this case the water should be included in the LCI. In general, the goal of LCI is to measure, per unit of product, the volume of water which was consumed by the unit process and therefore became unavailable for other beneficial uses [7].

3.2.8 LCI of transportation

Energy requirements and emissions generated during transportation between unit processes and for disposal within the system boundary are included in the LCI. The usual unit for reporting of transportation process is tone – kilometer to cover the weight of shipment and the distance traveled. Different modes of transportation do exist such as trucks, railroad, ships, Calculations are made to calculate the combustion emissions and the amount of fuel consumed in the transportation process to further calculate precombustion energy and emissions. It is important to follow the flow diagram of the system to trace transportation activities and avoid double – counting of a transportation energy or emission.

3.2.9 LCI of environmental releases

The purpose of performing the LCI is to quantify three categories of environmental releases, namely emissions to air, effluents to water and solid waste. LCI data usually tend to be limited to regulated emission of the unit processes due to limitations of available data, however it is recommended to collect and report all the available data beyond the regulated emissions and

include this information in the final report especially if the study is not performed for comparative reasons.

When performing comparative LCA study, some of the LCI data available in one of the alternatives may not be available for the other alternative, and in this case there are two options to report the study [7]:

- The first option is to report only the LCI data that are available for all alternatives and thus a comparison can be made on equal bases, but this option may shadow potentially consequential information that is available for some of the alternatives only.
- The second option is to report all LCI data, even those not available for some of the alternatives. In this case the results of the study must be evaluated with caution when dealing with information that is not comparably available.

3.2.9.1 Emissions to air

Emissions to air include pollutants that can be calculated usually in units of weight per the functional unit of the system. The study report usually includes regulated pollutants beside other pollutants whenever possible. These pollutants are generated by the unit processes and from combustion of fuels in transportation and energy generation that are included in the life cycle of the system.

Many categories of pollutants do exist such as particulates, nitrogen oxides, volatile organic compounds (VOCs), sulfur oxides, aldehydes, Some categories include many substances; some of them may be emitted in a certain unit process while other substances of the same category will be emitted in other unit processes. The normal practice is to calculate and report all substances that can be calculated and detailed in the most specificity form possible [7].

3.2.9.2 Effluents to water

Effluents to water include pollutants that can be calculated usually in units of weight per the functional unit of the system. The study report usually includes regulated pollutants beside other pollutants whenever possible. The effluent values include those pollutants that are present in the waste stream after wastewater treatment, and are actually discharged into receiving waters. Other pollutants that are not treated before discharging should be included also. These pollutants are generated by the unit processes and from combustion of fuels in transportation and energy generation that are included in the life cycle of the system.

Many categories of pollutants do exist such as biological oxygen demand (BOD), chemical oxygen demand (COD), suspended solids, dissolved solids, oil and grease, sulfides. Some waterborne categories of pollutants such as BOD and COD consist of multiple substances and the composition of this category may vary according to the unit process that generated it. The normal practice is to calculate and report all substances that can be calculated and detailed in the most specificity form possible.

3.2.9.3 Solid wastes

Solid wastes include all solid materials that are disposed from all unit processes within the system boundary that can be calculated usually in units of weight per the functional unit of the system. The normal practice is to make distinction in study report between industrial solid wastes and post-consumer solid wastes, as they differ in the method of disposal [7]:

- Industrial solid waste refers to the solid waste generated during the unit processes of a production system. It is typically divided into two types: process solid waste and fuel-related solid waste. Process solid waste is the waste generated during the manufacturing process that is not recycled, while fuel-related waste is solid waste that are generated during the production and combustion of fuels used within the system boundary.

- Post-consumer solid waste refers to the disposal of the system once it has met its intended use and is discarded into the municipal solid waste stream.

In many cases there are regulations to the method of disposal of some types of solid wastes, and it is suggested that the study report follows the categories of the regulations for ease of interpretation of results.

3.2.10 Reporting of LCI results

Reporting of LCI results should include description of the methodology used to produce the results, the unit processes included in the system boundary and the assumptions made during the calculations. The LCI results usually contain large information that need to be carefully reported to avoid shadowing any of these information while summarizing the results. These results can cover many aspects such as the overall system, contribution of the life cycle stages, contribution of the unit processes, data categories it is recommended to develop a reporting format that increases comprehension of the findings without oversimplifying them [7]. Two main types of format for presenting results are tabular and graphical. The tabular format is the most comprehensive format and the choice of how the tables should be created varies, based on the purpose and scope of the study. Graphical presentation of information helps to clarify tabular data and can aid in interpretation. Both bar charts and pie charts are valuable in helping visualize and assimilate the information. However, dissimilar data should not be aggregated or summed when creating or simplifying a graph.

3.3 Life cycle Impact assessment phase

The Life Cycle Impact Assessment (LCIA) phase of the study is conducted to evaluate the potential impacts of the environmental releases of the system on the environment and human health. In addition to ecological and human health issues, Impact assessment should also address resource depletion. LCIA attempts to establish a linkage between the system and its potential

environmental impacts. "An important distinction exists between life cycle impact assessment (LCIA) and other types of impact analysis. LCIA does not necessarily attempt to quantify any specific actual impacts associated with a product, process, or activity. Instead, it seeks to establish a linkage between a system and potential impacts. The models used within LCIA are often derived and simplified versions of more sophisticated models within each of the various impact categories. These simplified models are suitable for relative comparisons of the potential to cause human or environmental damage, but are not indicators of absolute risk or actual damage to human health or the environment [7]". The key concept here is that of stressors. A stressor is a set of conditions that may lead to an impact. For example, if a system is emitting greenhouse gases, the increase of greenhouse gases in the atmosphere may contribute to global warming. LCIA provides a systematic procedure for classifying and characterizing these types of environmental stressors. LCI data will reveal many facts about the emissions of harmful substances to the environment and conducting LCIA will establish meaningful indicators about the potential impact of these substances using science-based characterization factors. Conducting LCIA will require the following steps [37]:

1. Selection of environmental impact categories according to the goals of the study.
2. Classification, by assigning specific results of the LCI to the impact categories that they belong to.
3. Characterization, by using science-based conversion factors to aggregate the relative impacts of individual components of each impact.
4. Normalization, by relating the potential impact of a category to a reference point which allow the comparison between impacts of different systems.
5. Grouping, by sorting or ranking the indicators according to a form in line with the goals of the study.
6. Weighting, by comparing different potential impacts based on certain criteria to emphasize the most important potential impacts.

7. Evaluating LCIA, by comparing LCIA results against the goals of the study to verify reliability of the results and applicability of goals.

According to ISO 14042 [37], the first three steps (selection, classification, and characterization) are mandatory steps for a LCIA, while the other steps (except step 7) are optional and depend largely on the scope and definition of the study. Table 3.1 shows some of the impact categories that may be included in a LCA study.

The first step, the selection of related impact categories, is performed to select the impact categories that will serve the goals as defined in the first phase of the study. In general, there are three main categories of potential impacts: human health, ecology, and resource depletion. The domain of the effects of each of these general categories may have any of the three spatial scales: global, regional and local effects.

The second step, classification, is performed by going through the results of the LCI, identify the relevant substances that contribute to a certain potential impact category and assign it to that potential impact category. This step is repeated until all the substances that contribute to the potential impact categories identified by the goal and scope phase of the study are covered. There are some substances that contribute to more than one potential impact category, and in this case the ISO 14042 suggests two ways to deal with this case [37]:

- Partition a representative portion of the substance weight to the potential impact categories to which it contributes. This way is applicable in cases when the effect of one category is dependent on effect of the other category.
- Assign the full weight of the substance to all impact categories to which it contributes. This way is applicable in cases when the effects of the potential impact categories are independent of each other.

Table 3.1: Commonly used life cycle impact categories [7]

Impact Category	scale	Examples of LCI Data (i.e. classification)	Common Possible Characterization Factor	Description of Characterization Factor
Global Warming	Global	Carbon Dioxide (CO ₂) Nitrogen Dioxide (NO ₂) Methane (CH ₄) Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Methyl Bromide (CH ₃ Br)	Global Warming Potential	Converts LCI data to Carbon Dioxide (CO ₂) equivalents Note: global warming potentials can be 50, 100 or 500 years potential
Stratospheric Ozone Depletion	Global	Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Halons Methyl Bromide (CH ₃ Br)	Ozone Depleting Potential	Converts LCI data to trichlorofluoromethane (CFC-11) equivalents.
Acidification	Regional Local	Sulfur Oxides (SO _x) Nitrogen Oxides (NO _x) Hydrochloric Acid (HCL) Hydroflouric Acid (HF) Ammonia (NH ₄)	Acidification Potential	Converts LCI data to hydrogen (H ⁺) ion equivalents.
Eutrophication	Local	Phosphate (PO ₄) Nitrogen Oxide (NO) Nitrogen Dioxide (NO ₂) Nitrates Ammonia (NH ₄)	Eutrophication Potential	Converts LCI data to phosphate (PO ₄) equivalents
Photochemical Smog	Local	Non-methane hydrocarbon (NMHC)	Photochemical Oxident Creation Potential	Converts LCI data to ethane (C ₂ H ₆) equivalents.
Terrestrial Toxicity	Local	Toxic chemicals with a reported lethal concentration to rodents	LC50	Converts LC50 data to equivalents; uses multi-media modeling, exposure pathways.
Aquatic Toxicity	Local	Toxic chemicals with a reported lethal concentration to fish	LC50	Converts LC50 data to equivalents; uses multi-media modeling, exposure pathways.
Human Health	Global Regional Local	Total releases to air, water, and soil.	LC50	Converts LC50 data to equivalents; uses multi-media modeling, exposure pathways.
Resource Depletion	Global Regional Local	Quantity of minerals used Quantity of fossil fuels used	Resource Depletion Potential	Converts LCI data to a ratio of quantity of resource used versus quantity of resource left in reserve.
Land Use	Global Regional Local	Quantity disposed of in a landfill or other land modifications	Land Availability	Converts mass of solid waste into volume using an estimated density.
Water Use	Regional Local	Water used or consumed	Water Shortage Potential	Converts LCI data to a ratio of quantity of water used versus quantity of resource left in reserve.

The third step, characterization, is performed to convert the effects of related substances into an equivalent of a reference substance effect by using science-based conversion factors, and combine the converted effects to establish the impact indicator of all contributing substances in an impact category relative to its characterized substance. These conversion factors are called “characterization factors” and sometimes are referred to as “equivalency factors”. Impact indicators are typically calculated using the following equation:

$$\sum (\text{substance weight (from LCI inventory data)} \times \text{characterization factor}) = \text{impact indicator} \quad (3.1)$$

This step can put these different quantities of substances on an equal scale to determine the amount of impact each one has, which allows a direct comparison between different substances of a category to identify the relative impact of these substances. There are many models that define characterization factors for different potential impact categories, and these models converge on some categories such as global warming while a consensus is still being developed on other categories [7]. Some categories have not been modeled yet and definite characterization factors for it are to be developed. The LCA report should identify the model used for the characterization of LCI results.

The fourth step, normalization, is performed to relate the impact indicator of a category to a reference point that can be defined in the goal and scope phase of the study. Normalization is done by dividing the impact indicator value by the selected reference value. The selection of the reference value depend on the goals of the study and may refer to various aspects such as the area of concern, the number of inhabitants of an area, relative value of a standard impact indicator, The normalization allows comparing different systems to determine their relative potential impact in a selected category of choice [7].

The fifth step, grouping, assigns certain impact categories into a general category that include many indicators to enhance the interpretation of results. The selection of these general categories depends on the goals of the study. ISO 14042 suggested two methods for grouping [37]:

- Sort indicators by characteristics such as emission media (air or water) or location (local, regional, or global).
- Sort indicators by a ranking system such as priority level (high, medium or low).

The sixth step, weighting, is performed by assigning weights (or relative values) to the indicators of different impact categories based on their perceived importance or relevance. The weights reflect the perceived importance of the impact categories as defined in the goals of the study and varies from a study to another. Weighting is performed to facilitate the interpretation of results for stakeholders who are not familiar with LCA. It is vital to explain in detail the weighting methodology in the final report of the study as the methodology of weighting is an arbitrary one and may vary with location and time. Weighting is prone to be challenged for integrity of results due to its arbitrary base [7].

The seventh step, evaluation, is performed to verify the accuracy of results in view of study goals. The results will be verified to determine whether:

- the goals have been met
- the methodology is described
- the system boundaries are defined
- assumptions and simplifications are mentioned
- limitations are identified

Based on verification of results, a decision has to be made whether to interact with any of the phases of the study in view of these results or to proceed with preparation of final study report.

3.4 Life cycle interpretation phase

Life cycle interpretation phase is the last phase of the LCA study, the purpose of which is to communicate effectively the results of the LCI and the LCIA phases. According to ISO 14043 [38], this phase of LCA study contains two major objectives:

1. Verify the results of the study with the goals, scope and within the limitation. Develop conclusions and recommendations based on the goals and findings of the study.
2. Prepare a clear, complete, consistent and transparent report of the results of the LCA study.

Conducting LCA study requires making assumptions, engineering estimates and decisions based on values, and reporting of this study must clearly reflect these aspects. In comparative studies, it may not be possible sometimes to state the recommended alternative due to the uncertainty in the final results. While this may not be considered as accomplishment of the goal of the study, it still reveals pros and cons of the alternatives from the perspective of the impact indicators of the alternative systems and a more informative decision may be within reach. The ISO 14043 [38] stated three steps to perform the interpretation phase:

1. Identification of the significant issues based on the results of LCI and LCIA.
2. Evaluation of results considering its completeness, sensitivity and consistency checks.
3. Conclusions, recommendations and reporting.

Figure 3.2 shows the interaction between the interpretation phase and the other phases of the LCA study.

Fig. 3.2: Relation between interpretation phase and other phases [38]

The first step, identification of significant issues, is performed through reviewing results of LCI and LCIA to identify the data elements that contribute most to the results. Identifying important contributing data is important due the big size of data and limited resources available to assess these data. This step requires comprehensive review of study goals, rules, impact category weights, results, limitations, this step can be performed only if the goals of the study have been met by the results. The significance of any of the following issues may be reviewed [7]:

- Inventory parameters like energy use, emissions, waste,
- Impact category indicators like resource use, acidification,
- Essential contributions to the results from life cycle stages, unit processes,

Some approaches are recommended to identify environmental issues and determine its significance such as [7]:

- Contribution analysis - the contribution of individual issues is compared to the total result to identify significant contributions that need to be examined for relevance.
- Dominance analysis - statistical tools or other techniques, such as quantitative or qualitative ranking are used to identify significant contributions that need to be examined for relevance.
- Anomaly assessment - based on previous experience, unusual or surprising deviations from expected or normal results are observed to identify significant contributions that need to be examined for relevance.

The second step, evaluation of results, determines the reliability and confidence of results by performing the following tasks [7]:

1. Completeness check - The completeness check ensures that all relevant information and data needed for the interpretation are available and complete. A checklist can be developed to verify the inclusion and representativeness of specified significant data categories in the results and therefore the results are in line with the goals and scope of the study and within its boundary. Data can be categorized by life cycle stage, unit processes or type of data represented (raw materials, energy, transportation, environmental emissions). If deficiencies are noted, then a fair comparison cannot be performed and additional efforts are required to provide the missing data. In some cases, data may not be available and the incompleteness of the data should be reported with the final results. An estimate of the incompleteness quantitative or qualitative impact on the comparison can be established.
2. Sensitivity check - The objective of the sensitivity check is to evaluate the reliability of the results by examining the uncertainty in the significant issues identified above to determine whether it will affect the ability to draw comparative conclusions. If deficiencies are noted, then the accuracy of the results may not be sufficient and additional efforts are required to improve the accuracy of the data collected, otherwise the deficiencies for

each relevant significant issue should be reported and quantitative or qualitative impact of this deficiency on the comparison can be estimated. Additional guidance on how to conduct a sensitivity check can be found in the EPA document entitled "Guidelines for Assessing the Quality of Life Cycle Inventory Analysis," April 1995, EPA 530-R-95-010.

3. Consistency Check - The consistency check determines whether the assumptions, methods, and data used throughout the LCA phases are consistent with the goal and scope of the study. This check will increase confidence in the final results. Some inconsistency may be acceptable depending on the goal and scope of the study and should be mentioned in the final report.

The third step, drawing conclusions and recommendations, is performed to interpret the results of the LCIA and present recommendations on area of concern defined in the goals of the study. If the study is performed for comparative reasons with normalizing and weighting of LCIA results within the scope of the study, the reporting phase will recommend the lowest score alternative and clearly identify the underlying assumptions used in the study. If possible, a recommendation to improve the environmental performance may be added. If the LCIA phase stops at establishing of impact indicators, then the form of reporting will depend largely on the specified goals of the study to prepare the recommendations. In general, the conclusions and recommendations of the final report of the study should be based on facts with full recognition of the uncertainties and limitations of the study. When the results are not clear enough to produce a definite recommendation, the report of the study can refer to the pros and cons of the environmental behavior of the system. ISO 14040 suggested a format for the final report of the study that contains administrative information and all the relevant information about the phases of the study. Critical review may be performed by a reviewing panel to verify the quality of the study.

4. LCA model for concrete bridge decks

The model that was developed during the course of this study can estimate the emissions, global warming potential impact, acidification potential impact in addition to energy and raw materials consumption of a concrete bridge deck during its life cycle. This model can be used as a tool in performing a LCA study of a concrete bridge deck. The model does not cover all phases of a LCA study, and therefore should not be used as a substitute for such a study. The model was developed as a first step in a continuous effort to build a comprehensive model that can be used to conduct full LCA study of concrete bridge decks. This chapter is dedicated to the explanation of the model.

4.1 Brief description of the model

The model was developed to calculate

1. emissions to air
2. effluents to water
3. generation of solid wastes
4. impact indicators of Global Warming Potential and Acidification Potential
5. consumption of energy and raw materials

during construction and operation of a concrete bridge deck along its life cycle. The life cycle of a concrete bridge deck can be divided into three stages as follows:

- The construction stage.
- The operation stage.
- The end of life stage.

These stages cover all construction activities and other processes that consume energy and raw materials, and produce emissions to air, water and generate solid wastes. Fig. 4.1 shows the three stages of the life cycle of a concrete bridge deck.

Fig. 4.1: Life cycle stages of a concrete bridge deck

The consumption of energy and raw materials, the emissions and solid waste generation are attributed to processes that produce them. These processes are:

- Material acquiring, production and processing.
- Construction equipment at site.
- Transportation of materials and equipments.

The model calculates total energy and raw materials consumption and the emissions of the bridge deck during its life cycle. For ease of comparison, the

model classifies the energy and raw materials consumption and the emissions and solid wastes, or (in and out) flow using two methods

- Flows (in and out) classified according to stages of the life cycle.
- Flows (in and out) classified according to processes that produced them.

The model can accommodate two methods of construction for concrete bridge decks:

- Cast in situ construction.
- Precast construction.

A combination of both methods is also possible.

The model covers two activities that are being performed during the operation stage. These are:

- Maintenance & repair works.
- Resurfacing of the bridge deck.

Any scenario of utilizing these activities can be modeled.

The model runs on three sheets of Microsoft Excel and includes several macros written in Visual Basic to facilitate the calculations.

4.2 System boundaries of the model

The model was developed to determine emissions in addition to energy and raw materials consumption for construction activities of a concrete bridge deck in North America. The construction activities of the life cycle of a bridge deck starts with the construction process of the bridge deck which is termed as the construction stage. During the operation of the bridge deck, the construction activities are the periodical maintenance & repair activities and the resurfacing activity, these activities are termed the operation stage. The last stage in the life of the bridge is at the decommissioning of the bridge deck which is termed end of life stage. The construction activity in this stage is the demolishing activity. The “in flow” to the system is the energy and raw materials that are being consumed

by the life cycle stages. The “out flow” of the system is the emissions to air, effluents to water and solid wastes. These (in and out) flows are attributed to contributors (unit processes) that are being utilized through the life cycle stages.

These contributors are:

- Construction materials.
- Electricity.
- Construction equipments.
- Transportation.

The model traces each contributor during every life cycle stage to establish the (in and out) flows.

4.2.1 Construction materials

The construction materials (as a unit process of the system) start with acquisition of raw materials from their natural resources using equipments and an energy source (fuels or electricity). These raw materials are transported to a manufacturing facility where it is processed and the final construction material is produced. The LCI data that was used in the model covers (in and out) flows of the above activities. The activities of this unit process consumed fuels and electricity. The upstream flows of fuels and electricity (energy, raw materials and emissions) were added to flows of the construction materials as reported in the source of LCI data. Fig. 4.2 shows the system boundary of construction materials.

Fig. 4.2: System boundary of construction materials

4.2.2 Electricity

The electricity consumed in the life cycle stages of a bridge deck is assumed to be supplied by the national grid. The electricity is generated from different facilities that use different fuels. The electricity (as a unit process of the system) starts with acquisition of raw materials that are transported to different facilities where it is processed to produce the fuels that are treated in the generation plants to transform its inherent energy into electricity with different efficiencies. The LCI data that was used in the model covers (in and out) flows of the above activities. Fig. 4.3 shows the system boundary of electricity.

Fig. 4.3: System boundary of electricity

4.2.3 Construction equipments

The construction equipments used during the life cycle stages are assumed to be powered by engines that run on diesel fuel. Diesel fuel starts with acquisition of raw materials which are transported to refineries to produce the diesel fuel. The LCI data that was used in the model covers (in and out) flows of the above activities. The model also calculates the emissions to air generated by the combustion of diesel fuel in the engines of construction equipment itself. Fig. 4.4 shows the system boundary of construction equipments.

Fig. 4.4: System boundary of construction equipments

4.2.4 Transportation

The transportation activities performed during the life cycle stages of the bridge deck are assumed to be done by using two types of trucks, both of them are powered by engines that run on diesel fuel. Diesel fuel starts with acquisition of raw materials which are transported to refineries to produce the diesel fuel. The LCI data that was used in the model covers (in and out) flows of the above activities. The model also calculates the emissions to air generated by the combustion of diesel fuel in the engines of transportation trucks itself. Fig. 4.5 shows the system boundary of transportation.

Fig. 4.5: System boundary of transportation

4.2.5 Construction stage

The construction stage includes the construction activity which is being done one time only during this stage. The construction can be done using precast concrete, precast pre-stressed concrete, cast in situ normal concrete, cast in situ post tensioned concrete, precast post tensioned concrete or any combination of these options. The model can accommodate different concrete mix designs for different construction types. The construction activity starts with construction materials which are transported to facilities that process them and produce the final product. These facilities consume electricity to produce the final products. The final product is transported to the site of the bridge deck. Construction equipments are used at the construction site to utilize the final product and produce the bridge deck. These construction equipments have to be transported in and out of the construction site. The model accumulate the (in and out) flows of the contributors (construction materials, electricity, construction equipment and transportation) that reflect the utilization of these contributors during the construction stage. The flow diagram and system boundaries of the construction stage are shown in Fig.4.6.

Fig. 4.6: Flow diagram of the bridge deck showing system boundary (Construction stage)

4.2.6 Operation stage

The operation stage includes two types of construction activities, namely maintenance & repair and resurfacing of the bridge deck. These activities are repeated a number of times during the operation stage. The model can

accommodate different mix designs for the different construction activities. The construction activity starts with construction materials which are transported to facilities that process them and produce the final product. These facilities consume electricity to produce the final products. The final product is transported to the site of the bridge deck. Construction equipments are used at the construction site to utilize the final product and perform the maintenance & repair and/or the resurfacing of the bridge deck. These construction equipments have to be transported in and out of the construction site. The model accumulates the (in and out) flows of the contributors (construction materials, electricity, construction equipment and transportation) that reflect the utilization of these contributors during the construction stage. The flow diagram and system boundaries of the operation stage are shown in Fig. 4.7.

4.2.7 End of life stage

The end of life stage contains two construction activities. The first one is being done at the time of the first and second life stages by transporting the wastage of construction activities of the construction stage and the operation stage to the crusher/landfill site. The second construction activity is being done at the end of useful life of the bridge deck when the bridge deck is decommissioned. The construction activity in this stage is the demolishing of the bridge deck. Construction equipments are transported in and out of the site to demolish the bridge deck. The wastage is transported to the crusher/ landfill site. Electricity is consumed at the crusher site while construction equipments may be used to treat the wastage at the landfill site. The model accumulates the (in and out) flows of the contributors (electricity, construction equipment and transportation) that reflect the utilization of these contributors during the end of life stage. The flow diagram and system boundaries of the end of life stage are shown in Fig. 4.8.

Fig. 4.7: Flow diagram of the bridge deck showing system boundary (Operation stage)

Fig. 4.8: Flow diagram of the bridge deck showing system boundary (End of life stage)

4.2.8 Exclusions to the boundary of the system

The model deals with the above contributors to establish the (in and out) flows of the system only. Other contributors are excluded from the scope of the model such as the traffic and the capital equipments.

The (in and out) flows of traffic on the bridge deck are huge in comparison to construction activities [6]. The traffic was excluded from the scope of the model because the traffic on the bridge deck is related to the engineering design of the bridge irrespective of the construction activities that are being performed during the life cycle stages of the concrete bridge deck. The model was designed to be used in determining the effects of construction activities on the (in and out) flows of the concrete bridge deck, and since traffic may not be modeled easily and include many uncertainties which create many difficulties in predicting traffic patterns, therefore inclusion of traffic may shadow the main goal of the model to predict the effect of construction activities. If the (in and out) flows of the traffic are part of the LCA study then a model that can reflect the traffic has to be used to model the (in and out) flow of traffic.

Capital equipments and facilities that are being used to produce the contributors to the (in and out) flows of the system are excluded because they are used many times to produce a multiple of the contributor, one of them will be used briefly during its life within the system and therefore it is a common practice to exclude the capital equipment and facilities from the scope of the model [7].

4.3 Source of Data for Life Cycle Inventory

The collection of Life Cycle Inventory (LCI) data for any Life Cycle Assessment (LCA) study is a crucial part of the study. The availability of public access to LCI data for Life Cycle Assessment is not in line with the increasing interest in these studies. Further increase of access to Life Cycle Inventory data on processes, materials and products at the international level is one of the remaining challenges for the life Cycle Initiative of the United Nations Environmental Program (UNEP) and Society of Environmental Toxicology and Chemistry (SETAC) [5]. There are two types of databases, the extensive general databases which include data on various industrial sectors and smaller databases with data on specific fields [8].

In Canada, a study was started by The Canadian Raw Materials Database project [39]. The information for the study was provided by industry associations and their contractors. The data covered cradle-to-gate Life Cycle Inventory for some of the products such as steel, aluminum, some plastic products, glass, paper and softwood lumber. The data represented Canadian production environment, with modification on some products with data on US production (in some cases) to protect the privacy of industrial information. The results of this study are not available to the public.

In the United States, a moderate number of Life Cycle Inventory data is available from work done at various levels of government and private research entities. A collaborative project to develop a publicly available LCI modules database for the US received government funding in 2001 and the database is hosted by the National Renewable Energy Laboratory site (NREL) [40].

In other parts of the world, LCI data are becoming available mainly through restricted access databases especially in Europe and Japan. Some restricted access programs contain LCI data that are utilized by these programs.

In this study, LCI data that represent the North American industrial set was sought. The LCI data that are publicly available on U.S. Life Cycle Inventory Database project site [41] hosted by NREL were the main source for LCI data. The LCI data in this site are divided into “modules” that contain similar processes. In this model, the NREL site was used to supply LCI data for the following products or processes:

- Electricity generation
- Fuel and energy precombustion
- Portland cement production
- Steel production
- Transportation by diesel-powered trucks

The above LCI data are publicly available after registering to the site, logging in and accepting terms of “Data Use Disclaimer agreement”.

The other source of LCI data was from a thesis by Alissa Kendall [42] for the following products or processes:

- Fine aggregate
- Coarse aggregate
- Super plasticizer
- Plastic fibers

The LCI data for combustion of fuel in diesel engines that power construction equipments were edited based on a report to the US Environmental Protection Agency [43] which formed a base for the NONROAD2004 emission inventory model [44].

4.4 LCI data preparation for the model

Preparation of Life Cycle inventory data for this model passed through several stages before being applied to the model. These steps are shown in Fig. 4.9.

Fig. 4.9: Flow chart of LCI data preparation

The first step is to search for the appropriate data that can be incorporated into the model and cover the activities that are modeled. The second step is to

change the units of the LCI data to the system of units being used in this model; in this model the SI system is being used and the kilo gram was selected as a unit for weights. The next step is to unify the emissions types and naming format of the different LCI data with the emissions types and naming format that are being used in the model. The last step of the process is to incorporate upstream emissions to the emissions that are covered by the LCI data source so that the final result is a LCI data that cover the cradle – gate scope of the Life Cycle Assessment. The calculations of the model will expand the scope to cover the cradle – grave scope of the study.

The calculation of energy and raw materials consumption is part of the LCI preparation process. In this model, the embodied energy of the raw materials that are used to produce the fuels which are consumed in every activity are calculated based on the quantities of the fuels as reported by the source of LCI data. The model assumes an equal amount of raw material to the fuel being used for the purpose of calculating embodied energy of fuels. The embodied energy of fuels raw materials are derived from NREL site [45] and shown in table 4.1 below.

Table 4.1: Embodied energy in raw materials of fuels

Type of raw material of fuel	Unit	Amount of embodied energy
Coal	Mj/kg	26.4
Natural Gas	Mj/kg	46.8
Crude Oil	Mj/kg	42
Uranium ore	Mj/kg	2.291×10^6
Wood	Mj/kg	9.5

The average density of natural gas was taken as 0.8 kg/m^3 [46] and the average density of crude oil was taken as 870 kg/m^3 [47] for the purpose of transforming the units into volume units because the conventional units for reporting of crude

oil and natural gas are volume units. The value of energy equivalent to one kWh of electricity equals to 11.3 MJ/kWh [7].

The raw materials that are reported by the source of LCI data were used to prepare the amounts of raw materials consumption in this model. As for the raw materials of petroleum based fuels (i.e. crude oil), the amount of crude oil input to oil refineries versus the amount of output of petroleum products output was used as a base for estimating the amount of crude oil consumption. This input was derived from data reported by Petroleum Navigator of the Energy Information Administration web site [48]. The raw materials that are calculated by the model are:

- Coal
- Crude oil
- Natural gas
- Uranium ore
- Fine aggregate and sand
- Coarse aggregate
- Calcite ore
- Shale and clay
- Iron ore
- Anhydrate gypsum
- Water

4.4.1 LCI data for fuels precombustion

The LCI data for fuels and energy precombustion was obtained from NREL site using the following link [49]:

http://www.nrel.gov/lci/database/xl/SS_FuelsandEnergyPrecombustion.xls

“The module reflects energy and environmental emissions for the production and transportation of fuels. The module represents current technologies and markets for fuel and energy production in the United States. Precombustion energy and emissions are based on iterative calculations; fuels are used to make fuels [49]”.

The LCI data in this module represents cradle – to – gate emissions and covers the years 2000-2004. This data represents total chain of the supply and production process for these fuels. The units of the module were transformed to SI units.

The emissions are shown in kg per conventional unit of the fuel type used. For radioactive wastes, the unit of Curie per conventional unit of the fuel type is used. Although the data represents U.S. situation, the model was developed with the assumption that these LCI data can be expanded to represent North America. The LCI data in this module are very important as the precombustion fuel emissions were added to the emissions of the products or processes in other modules to complete the cradle to gate circle of these products or processes.

4.4.2 LCI data for electricity consumption

The LCI raw data for electricity consumption was obtained from NREL site using the following link [50]:

http://www.nrel.gov/lci/database/xl/SS_ElectricityGeneration.xls

“The data in this module are representative of year 2000 mix of fuels used for utility electricity generation. Data are weighted according to percent share of consumption. The data in this module includes generation and transmission of electricity for U.S. grid [50]”. The module does not show emissions of electricity generation and transmission process, but it includes the mix of fuels consumed per kWh of electricity. The units of consumed fuels were transformed to SI units. The upstream emissions of fuel precombustion for the consumed types of fuel (coal, residual fuel oil, natural gas and nuclear fuel) were added according to its consumption rate to create the electricity emissions and solid wastes per every kWh of electricity. The module shows use of renewable sources for electricity generation such as hydroelectric energy, biomass/wood, wind, solar, geothermal and other sources. As these sources are renewable, the model was developed with the assumption that there are no emissions from these sources. The emissions from the generation and transmission of electricity were collected from

the Energy Information Administration site [51] for the whole United State in year 2005 and then divided by the total kWh of electricity generated throughout the U.S. in year 2005 from the same site [52]. These emissions were added to the precombustion emissions of the fuels used in the generation of electricity.

The emissions are shown in kg per kWh of electricity. For radioactive wastes, the unit of Curie per kWh is used. Although the data represents U.S. situation, the model was developed with the assumption that these LCI data can be expanded to represent North America.

The energy of electricity was calculated by summing up the embodied energy of raw materials of fuels that are consumed in the generation of electricity in addition to the energy equivalent of electricity. The raw materials of the fuels consumed in electricity generation were also calculated.

4.4.3 LCI data for Portland cement production

The LCI raw data for cement production was obtained from NREL site using the following link [53]:

http://www.nrel.gov/lci/database/xl/SS_Portland_Cement_Production.xls

This LCI data was prepared to reflect the weighted average of Portland cement production according to the four main methods that are followed in cement plants in the United States. The four types of plants are

- Wet
- Long dry
- Dry with preheater
- Dry with preheater and precalciner

“The system boundary includes the four main steps in manufacturing Portland cement:

1. Quarry and crush: extracting raw material from the earth, crushing to 5-cm pieces, and conveying and stockpiling.

2. Raw meal preparation: recovering materials from stockpiles, proportioning to the correct chemical composition, and grinding and blending.
3. Pyroprocess: processing raw meal to remove water, calcining limestone and causing the mix components to react to form clinker, cooling and storing the clinker.
4. Finish grind: reclaiming the clinker from storage, adding gypsum and grinding to a fine powder, and conveying to storage.

The system boundary includes transporting all fuel and materials from their source to the cement plant. It also includes combustion of fuel in the cement kiln. Upstream profiles of producing fuel and electricity are not included [53]”.

The upstream emissions for electricity and fuel precombustion for the consumed types of fuel (coal, gasoline, LPG, distillate oil, natural gas and residual oil) consumed in cement production where added to the emissions of cement production according to its consumption as shown in the LCI data for the cement production. The production of cement consumes some wastes from other products such as waste oils, waste tires and waste solvents, which are used as fuels in the cement kiln. As the emissions of these waste products are allocated to its original use, no emissions where added to the production of cement from use of these wastes. The model takes a conservative stand as it does not assign any credit to use of wastes in production of Portland cement.

The units of emissions are in kg per kg of produced Portland cement. For radioactive emissions the unit is in Curie per kg of Portland cement. Although the data represents U.S. situation, the model was developed with the assumption that these data can be expanded to represent North America.

The energy of cement was calculated by summing up the embodied energy of raw materials of fuels that are consumed in the production of Portland cement in addition to the energy equivalent of electricity consumed during the production process. The raw materials of the fuels consumed in production of Portland

cement were calculated in addition to the raw materials consumed during the production process.

4.4.4 LCI data for steel production

The LCI raw data for steel rebar production was obtained from NREL site using the following link [45]:

http://www.nrel.gov/lci/database/xl/SS_Steel_Billet_Production.xls

“The module represents production and processing of steel billet. The boundaries of the module includes

- Extraction of limestone
- Lime production
- Exploration, mining and processing of iron ore and coal
- Transportation to mill by ship, rail and truck
- Primary processes (sinter plant, coke ovens, stoves, boilers, blast furnace and BOF)
- Casting line.

The data in this module represent U.S and Canadian average technologies, and therefore are applicable to North American market. The data in this module where drawn from reports, public and private U.S and Canadian statistical sources. Other data where based on industry publications [45]”.

The upstream precombustion emissions for the types of fuels consumed in the production of steel (coal and natural gas) are added to the emissions of steel production according to the amounts of fuel consumed. The module shows consumption of renewable energy sources but the model was developed with the assumption that there are no emissions from these sources. The production of steel consumes some quantity of scrap steel. The model was developed with the assumption that there are no emissions for scrap steel as its emissions where allocated for its original use.

The units of the module were transformed to SI units and the emissions are shown in units of kg per kg of steel produced. For radioactive emissions the unit is in Curie per kg of steel.

The energy of steel was calculated by summing up the embodied energy of raw materials of fuels that are consumed in the production of steel in addition to the energy equivalent of electricity consumed during the production process. The raw materials of the fuels consumed in production of steel were calculated in addition to the raw materials consumed during the production process.

4.4.5 LCI data for aggregate

The LCI data for fine aggregate and coarse aggregate was reported by A. Kendall in her thesis [42]. The source of the data was based on information on use of fuel and electricity from Portland Cement Association. Values of the emissions were used in this model without editing.

The energy of aggregate was calculated by summing up the embodied energy of raw materials of fuels that are consumed in the acquiring of aggregate in addition to the energy equivalent of electricity consumed during the acquiring process. The raw materials of the fuels consumed in acquiring of aggregate were calculated in addition to the raw materials consumed during the acquiring process.

4.4.6 LCI data for super plasticizer

The LCI data for super plasticizer was reported by A. Kendall [42]. The source of the data was based on information from Ecopilan for formaldehyde, which was used as super plasticizer. Values of the emissions were used without editing.

The energy of super plasticizer was calculated by summing up the embodied energy of raw materials of fuels that are consumed in the production of super plasticizer in addition to the energy equivalent of electricity consumed during the

production process. The raw materials of the fuels consumed in production of super plasticizer were calculated in addition to the raw materials consumed during the production process.

4.4.7 LCI data for plastic fibers

The LCI data for plastic fibers was reported by A. Kendall [42]. The source of the data was based on industry sources and polyethylene data from Association of Plastic Manufacturers in Europe. Values of the emissions were used in this model without editing.

The energy of plastic fibers was calculated by summing up the embodied energy of raw materials of fuels that are consumed in the production of plastic fibers in addition to the energy equivalent of electricity consumed during the production process. The raw materials of the fuels consumed in production of plastic fibers were calculated in addition to the raw materials consumed during the production process.

4.4.8 LCI data for combination truck transportation

LCI raw data for combination truck transportation was obtained from NREL site using the following link [54]:

[http://www.nrel.gov/lci/database/xl/SS Diesel Fueled Combination Truck Transportation.xls](http://www.nrel.gov/lci/database/xl/SS_Diesel_Fueled_Combination_Truck_Transportation.xls)

The LCI data in this module are given for the combustion of diesel fuel in a combination truck engine in two methods. The first method is for the emissions per 1000 gallons of diesel. The other method is the emissions per 1 ton - mile. The LCI data in the module represents current technologies for combination truck transportation in North America [54].

In this model the emissions per ton – km was used, the precombustion emissions of diesel fuel were added to emissions of diesel engine combustion emissions. The precombustion emissions of diesel fuel are not included in the fuel

precombustion module [49], therefore the precombustion emissions of kerosene was used from the same module as a substitute for diesel fuel.

The units were transformed to SI units and the emissions are shown in kg per ton – km of transportation. For radioactive emissions the unit is in Curie per ton – km.

The energy of transportation by combination truck was assumed to be equal to the embodied energy of raw material of diesel fuel. The raw material of the diesel fuel consumed during transportation was calculated also.

4.4.9 LCI data for single unit truck transportation

LCI raw data for single unit truck transportation was obtained from NREL site using the following link [55]:

http://www.nrel.gov/lci/database/xl/SS_Diesel_Fueled_Single_Unit_Truck_Transportation.xls

The LCI data in this module are given for the combustion of diesel fuel in a single unit truck engine in two methods. The first method is for the emissions per 1000 gallons of diesel. The other method is the emissions per 1 ton - mile. The LCI data in the module represents current technologies for single unit truck transportation in North America [55].

In this model the emissions per ton – km was used, the precombustion emissions of diesel fuel were added to emissions of diesel engine combustion emissions. The precombustion emissions of diesel fuel are not included in the fuel precombustion module [49], therefore the precombustion emissions of kerosene was used from the same module as a substitute for diesel fuel.

The units were transformed to SI units and the emissions are shown in kg per ton – km of transportation. For radioactive emissions the unit is in Curie per ton – km.

The energy of transportation by single unit truck was assumed equal to the embodied energy of raw material of diesel fuel. The raw material of the diesel fuel consumed during transportation was calculated also.

4.4.10 LCI data for diesel fueled construction equipment

LCI data for combustion of diesel fuel in equipment engines are derived from “Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling--Compression-Ignition [43]”. The term compression ignition refers to diesel fueled engines. The report gives the combustion emissions of hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x), non-methane hydrocarbons (NMHC), particulate matters (PM) and diesel consumption (BSFC). The carbon dioxide emission (CO₂) can be calculated by the following equation:

$$\text{CO}_2 = (\text{BSFC} * 453.6 - \text{HC}) * 0.87 * (44/12) \quad (4.1)$$

The emissions in the report are given in units of gm per hp – hr (horse power – hour) depending on the horse power rating category. The emissions are given in 10 categories of horse power rating of the engine as follows:

- < 11 hp
- ≥11 to <25
- ≥25 to <50
- ≥50 to <75
- ≥75 to <100
- ≥100 to <175
- ≥175 to <300
- ≥300 to <600
- ≥600 to <750
- ≥750 (except power generation sets)

In each power category, several values for the emissions are given according to the model year of the engine. In order to facilitate using these data in the model, average values were selected for the model year.

The precombustion emissions of diesel fuel were added to combustion emissions of the engines according to the rate of diesel consumption per hp – hr. The precombustion emissions of diesel fuel are not included in the fuel precombustion module [49], therefore the precombustion emissions of kerosene was used from the same module as a substitute for diesel fuel.

The unit of emissions was transformed into kg per hp – hr according to horse power rating category. For radioactive emissions the unit is Curie per hp – hr according to horse power rating category. Although the data represents U.S. situation, the model was developed with the assumption that these data can be expanded to represent North America.

The energy of construction equipment was assumed equal to the embodied energy of raw material of diesel fuel consumed. The raw material of the diesel fuel consumed during operation of construction equipment was calculated also.

4.5 Model framework

The model runs on three sheets of Microsoft Excel. The first sheet contains the input tables and a copy of the emissions table (output of the model), so that the user does not need to access the other sheets. The first sheet contains also a copy of the impact indicators table and a copy of the energy & raw materials consumption table. The second sheet contains the calculations of the model starting from establishing the number of repetitions of activities and ending with calculating emissions, impact indicators and energy & raw materials consumption. The third sheet contains “the emissions per unit of material or process table” and “the energy & raw materials consumption per unit table” that are built into the model and used by different parts of the model. The model was designed to trace the contributors to energy and raw materials consumption and emissions to establish an inventory for each contributor to calculate its emissions, in addition to its energy and raw materials consumption. Fig. 4.10 shows a general flowchart of the main steps in the model.

4.6 Input tables

The input tables require from the user all the data that is needed to define the bridge deck which is being assessed to determine its environmental impact. A snapshot of input tables from the Excel sheet is provided in Appendix (C).

4.6.1 Life cycle definition table

The first table is the life cycle definition table. In this table the repetition of each activity cycle (in years) is required from the user. The activities are:

- Construction, the input here defines the total expected life of the bridge deck from first construction to final demolishing.
- Resurfacing, the input here defines the period between cycles of resurfacing along the life span of the bridge deck.
- Maintenance & repair, the input here defines the period between cycles of maintenance & repair that are performed between cycles of resurfacing.

4.6.2 Construction materials tables

The second group of tables is the construction materials tables, which are designed to enable the user to define for every activity the following:

- Volume of concrete for each activity (in m^3).
- Density of the concrete for each activity (in kg/m^3).
- The constituents of the concrete mix for each activity (in kg/m^3 for every component of the concrete mix).

The model was designed to accommodate different mix designs for the two types of construction (the cast in situ construction and the precast construction). Different mixes can be specified for the resurfacing activity and the maintenance & repair.

The materials that constitute a part in concrete mix and have an impact on the environment, and therefore are included in the model are:

- Fine Aggregate
- Coarse Aggregate

- Cement
- Fly Ash
- Silica Fume
- Slag
- Super Plasticizer
- Air Entraining Agent
- Steel Rebar
- Prestressing Steel
- Steel Fibers
- Plastic Fibers

If any of the materials is not used in the activity, the user has to input zero in its respective cell.

4.6.3 Equipment tables

The third group of tables is Equipment tables, which are designed to enable the user to define the following for every type of equipment used:

- The number of pieces used at site of the equipment type.
- The horse power rating of the type of equipment (in hp)
- The number of hours of usage per piece of equipment (in hr)
- The weight of the piece of equipment (in kg)

The model can accommodate 21 different types of equipment per activity. There are tables for every activity in every stage of the life cycle of the bridge deck.

4.6.4 Transportation distances table

The fourth table is designed to enable the user to define the transportation distances (in km) for the following:

- Transportation of fine aggregate from supplier to batch plant
- Transportation of coarse aggregate from supplier to batch plant
- Transportation of Portland cement from factory to batch plant
- Transportation of fly ash from grinding plant to batch plant

- Transportation of silica fume from supplier to batch plant
- Transportation of additives (super plasticizer and air entraining agent) from the supplier to batch plant
- Transportation of steel from supplier to fabrication plant
- Transportation of fabricated steel from fabrication plant to construction site
- Transportation of prestressing steel from supplier to construction site
- Transportation of fresh concrete from batch plant to construction site
- Transportation of pre cast concrete from fabrication plant to construction site
- Transportation of construction equipment from yard to construction site
- Transportation of demolished concrete from construction site to landfill site
- Transportation of demolished concrete from construction site to crusher site
- Transportation of scrap steel from construction site to scrap yard
- Transportation of steel fibers from supplier to batch plant
- Transportation of PVC fibers from supplier to batch plant

If any of the distances above is not applicable the user has to input zero in its respective cell.

4.6.5 Wastage percentage

The fifth input that is required from the user is the expected wastage percentage from construction activities (in decimal format).

4.6.6 Electricity consumption table

The sixth and last table is designed to enable the user to define electricity consumption per unit of:

- Production of precast concrete units (in kwh/m³) at the fabrication plant
- Production of fresh concrete (in kwh/m³) at the batch plant
- Fabrication of steel (in kWh/kg) at the fabrication plant

- Crushing of demolished concrete (in kWh/kg) at the crusher site
- Grinding of fly ash (in kWh/kg) at the grinding plant

If any of the above activities does not apply to the case being modeled, the user has to input zero in its respective cell.

4.7 Managing inventories of the concrete bridge deck

The environmental impact of the concrete bridge deck is attributed to the source of emissions, and the model is designed to establish an inventory of materials and processes that are consumed along the life cycle of the bridge deck and contribute to environmental emissions. These are:

- Emissions that are related to production of materials that constitute a part in the concrete mix for different activities. The emissions that are related to consumption of energy during the preparation and processing of a material are added in a later part of the model to the emissions of the production of the material itself.
- Emissions that are generated during transportation process for hauling materials and equipments during the life cycle of the concrete bridge deck.
- Emissions that are generated by equipments that are used at site during the life cycle of the concrete bridge deck.

The calculation of emissions in the model follows the above understanding, and furthermore tabulates the emissions according to the three stages of the life cycle.

4.7.1 Cycles of activities

The first step in the calculations of the model is to calculate the number of repetitions of each cyclic activity. The number of construction activities is set to 1 time at the start of the life cycle, and similarly 1 time for demolishing at the end of life cycle. The model then uses information from the input tables to calculate the number of repetition for the resurfacing of the bridge deck and the maintenance & repair; both activities are being done during the usage stage of the bridge deck

and according to the case as defined by the user. These calculations are the starting point in the model and the results of these calculations will be utilized in other calculations of other parts of the model.

4.7.2 Materials inventory

The second step in the model is to establish inventories of the attributers to environmental emissions as explained above. The model starts with materials inventory part and enters into a series of calculations to establish an inventory of material weights to determine its emissions later. The first step in these calculations is to establish for every activity the total volume of concrete consumed in this activity along the life cycle of the bridge deck by utilizing the physical volume of concrete, the wastage percentage (both as defined by the user in the input tables) and the number of repetition of the activity as calculated by the model.

The total volume of concrete consumed in every activity calculated above is used to calculate the total weight of concrete mix component that is consumed during the life cycle of the bridge deck for every activity. This is accomplished through utilization of the total volume calculated by the model and the mix design proportion as defined by the user in the input tables. The model then accumulates the total weight of every component of concrete mix tabulated according to the first two stages of the life cycle as there is no material consumption in the end of life stage. This inventory will be used later to calculate the emissions and will be utilized by other parts of the model also.

The materials inventory part of the model will also calculate the total weight of concrete in every activity by utilizing the total volume calculated by the model and the density of concrete as defined by the user in the input tables. The materials inventory will be utilized by other parts of the model. This will conclude the establishing of materials inventory.

4.7.3 Construction equipment inventory

After establishing materials inventory above, the model will enter into the equipment inventory part and start a new set of calculations to establish an inventory of horse power by hour product (hp-hr) to determine equipment emissions later. The first set of calculations will go through every type of equipment as defined by the user in the input tables and is aimed at assigning the horse power rating of the engine of that type of equipment into one of the ten horse power categories as defined by the NONROAD model [43]. This is done by using a special logical function that is defined through a macro written in visual basic language. The model will then calculate the total product of horse power rating of the engine by the hours of usage for the type of equipment for the activity. This is done by utilizing the number of pieces per type of equipment, the horse power rating of the equipment engine, the hours of use per piece of equipment (as defined by the user in the input tables for these three values) and the number of repetition of the activity as calculated by the model. The same calculations will be repeated until all the types of equipments for every activity is included.

The next step in this set of calculations is to establish the inventory of total horse power by hour product of construction equipments as calculated above according to its category and tabulated according to the three stages of the life cycle. These calculations are done by using 30 special logical functions that are defined through macros written in visual basic language. This inventory will be used later to calculate construction equipment emissions.

The construction equipment part of the model will also establish another inventory of the total weight of construction equipments tabulated according to the stages of the life cycle. This is done by utilizing the number of pieces of the type of equipment, the weight of the type of equipment for every type of equipment (both as defined by the user in the input tables) and the number of repetition of the activity as calculated by the model. These calculations will be

repeated for every type of equipment for every activity. This inventory will be utilized by other parts of the model. This will conclude the establishing of construction equipment inventory.

4.7.4 Disposal inventory

After establishing construction equipment inventory, the model enters into another part that is aimed at calculating the weight of the disposal materials which are generated due to the following:

- Demolishing of the concrete bridge deck at the end of life of the bridge deck.
- Removal of the surface layer of the bridge deck before every resurfacing layer activity.
- Clearing the wastage of the concrete in every activity of construction, resurfacing and maintenance & repair according to the wastage percentage defined by the user in the input tables.

The total weight of disposal due to demolishing of the bridge deck at the end of life and clearing the waste at the construction stage is taken from the materials inventory. The total weight of disposal due to removal of the surface layer before the resurfacing activity and clearing the waste after the resurfacing activity is taken from the materials inventory also.

As maintenance & repairs are done to fill gaps, cracks and holes that develop during the usage stage of the bridge deck, the calculations of the weight of disposal due to clearing waste of maintenance & repair activity is different from above calculations. The calculation of weight of disposal of maintenance & repair is done in this part of the model by utilizing the volume of maintenance & repair, the density of concrete used for the maintenance & repair activity, the wastage percentage (as defined by the user for these 3 values in the input tables) and the number of repetition of the maintenance and repair activity as calculated by the model.

The model then calculates the total weight of disposal that goes to the landfill, or to the crusher according to the case as defined by the user in the input tables. The model will also calculate the total weight of scrap steel by utilizing the total weight of steel rebar and prestressing steel as calculated in the materials inventory. The values of weights of disposal will be utilized by other parts of the model. This will conclude establishing of the disposal inventory.

4.7.5 Electricity inventory

This part of the model is designed to establish an inventory of electricity consumption tabulated according to the life cycles of the bridge deck. Electricity is consumed in the construction phase and the usage phase to process the materials that are consumed in these stages. At the end of life stage, electricity is consumed in the crusher that processes the disposal.

The model uses the total volume of concrete calculated by the model and the user defined electricity consumption from the input tables to calculate the total electricity consumed at the batch plant and the precast fabrication plant. The model uses the total weight of concrete mix components calculated by the model and the user defined electricity consumption from the input tables to calculate the total electricity consumed at steel fabrication plant and the grinding plant of fly ash. These are electricity consumptions that are related to materials preparation, and the model will tabulate these values according to the construction stage and the usage stage.

The model will utilize the total weight of disposal as calculated by the model and the electricity consumption rate per kg of disposal at the crusher as defined by the user in the input tables to calculate the electricity consumption at the end of life stage. This will conclude establishing of electricity consumption inventory.

4.7.6 Transportation inventory

The last inventory to be prepared by the model before calculating emissions is the transportation inventory. This part of the model create inventory of transportation process that is used to transfer the materials and equipments from its origin to its destination. The LCI data that was prepared for this model cover the cradle – gate cycle of materials and processes. The transportation of materials to site and disposals to its destination will enlarge the scope to cover the cradle – grave scope.

The transportation process in this model is assumed to be done by two types of diesel fueled trucks:

- Single unit truck for transportation of fresh concrete, disposals and short items.
- Combination truck for transportation of aggregate, steel rebar, precast units and construction equipments.

This part of the model will create an inventory of the product of weight of hauled items by the distance of transportation (ton. km). The inventory of the product of ton.km (TKM) of both single unit trucks and combination trucks will be tabulated according to the three stages of the life cycle.

The model starts with transportation using single unit trucks, and calculates the TKM of transporting disposals to the land fill and the crusher by utilizing the weights of disposal as calculated by the model and the distances as defined by the user in the input table. The same is being done to calculate the TKM of scrap steel to scrap yard. These calculations cover the end of life stage of the life cycle. The TKM of hauling fresh concrete, air entraining agent, super plasticizer, prestressing steel, steel fibers and plastic fibers are calculated by utilizing its weights as calculated by the model and the distances as defined by the user in the input tables. The accumulated results are tabulated according to the first two stages of the life cycle.

The next step in this part of the model is to establish the inventory of the TKM of the combination truck by utilizing the weights of the precast concrete, the aggregate, the binder substances, the steel rebar and the construction equipments as calculated by other parts of the model and the distances as defined by the user in the input tables. The accumulated results are tabulated according to the stages of the life cycle. This will conclude establishing of transportation inventory.

4.8 Calculation of emissions

The calculation of emissions part of the model is designed to establish emissions of the concrete bridge deck during its life cycle by utilizing the inventories that were prepared by the model and the emissions per unit table that was prepared from the LCI data (see Appendix A). The emissions per unit table is the core of the model and contains emissions of the contributors (materials or processes) per its conventional units as explained by table 4.2.

In the preparation of the emissions per unit table for the model, some assumptions were made. These assumptions are:

1. The emissions of air entraining agent are identical to emissions of super plasticizer.
2. The emissions of production of prestressing steel and steel fibers are identical to the emissions of production of steel rebar.

The reason for these assumptions is the uncertainty of exact type of material to be used due to availability of many types of these materials, as well as lack of LCI data.

Table 4.2: Contributors to emissions and their units

Classification of contributor	Contributor	unit
Construction materials	Fine aggregate	1 kg
	Coarse aggregate	1 kg
	Cement	1 kg
	Super plasticizer/ air entraining agent	1 kg
	Steel (rebar, prestressing, fibers)	1 kg
	PVC fibers	1 kg
Electricity	Electricity	1 kWh
Transportation	Single unit truck	1 ton.km
	Combination truck	1 ton.km
Construction equipments (according to its engine horse power category)	<11 hp	1 hp.hr
	≥11 - <25 hp	1 hp.hr
	≥25 - <50 hp	1 hp.hr
	≥50 - <75 hp	1 hp.hr
	≥75 - <100 hp	1 hp.hr
	≥100 - <175 hp	1 hp.hr
	≥175 - <300 hp	1 hp.hr
	≥300 - <600 hp	1 hp.hr
	≥600 - ≤750 hp	1 hp.hr
	>750 hp	1 hp.hr

The emissions in each type of contributor are divided to:

- Emissions to air (with 140 types of emissions)
- Effluents to water (with 94 types of emissions)
- Solid wastes (with 15 types of emissions)

In the emissions to air category, there are at least 13 substances which are listed on the First Priority Substances List out of 44 in the list. There are 7 substances listed on the Second Priority Substances List out of 25 in the list. These lists are part of the Priority Substances Assessment Program (PSAP) developed between Environment Canada and Health Canada according to The Canadian Environmental Protection Act [56].

4.8.1 Calculation of construction materials emissions

The model starts with calculating materials emissions and utilizes the emissions per unit table and the inventories of fine aggregate, coarse aggregate, cement, super plasticizer, air entraining agent, steel rebar, prestressing steel, steel fibers and plastic fibers as established by the model. The results are summed and tabulated according to the first two life cycle stages.

4.8.2 Calculation of electricity emissions

The next step in the calculations of this part is to utilize the emissions per unit table and the inventory of electricity to calculate electricity emissions and the results are tabulated according to the three stages of the life cycle.

4.8.3 Calculation of transportation emissions

The third step in the calculations of this part is to utilize the emissions per unit table and the inventories of transportation process as established by the model to calculate emissions of single unit and combination trucks. The results are tabulated according to the two types of trucks and the stages of the life cycle.

4.8.4 Calculation of construction equipment emissions

The fourth step in this part of the model is to calculate emissions of construction equipments. The model first utilizes the emissions per unit table and the inventories of construction equipments as established by the model for the 10 categories and 3 stages of the life cycle. The next step is to sum the emissions of the 10 categories in each stage to tabulate construction equipment emissions according to the life cycles.

4.8.5 Accumulating emissions

The last step in this part of the model is to accumulate the results and show emissions according to the contributor as:

- Construction materials, including the electricity consumed in its processing
- Transportation, and

- Construction equipments.

The second method adopted in showing results is to tabulate the sums of emissions according to the life cycle stages. The model adds to emissions according to the life cycle stage the solid wastes that are generated through the three life cycle stages from construction activities. The total emissions of the concrete bridge deck are shown also.

The zero value for any emission type means either the material or process under consideration does not contribute to this emission or there is no information available for this emission. This concludes this part of the model.

4.9 Calculation of impact categories

The calculation of impact categories part of the model is designed to establish indicators for impact categories of the concrete bridge deck during its life cycle by utilizing the emissions that were calculated by the model.

The model calculates indicators of Global Warming Potential (GWP) as total weight in kg of CO₂ equivalents of the following emissions to air shown in table 4.3 by utilizing the weight of the emission as calculated by the model and ratio of its effect to global warming by the effect of Carbon Dioxide (characterization factors) as shown in table 4.3. These characterization factors are provided by a model developed by Centre of Environmental Science, Leiden University, Netherlands [57].

Table 4.3: GWP emission equivalents [57]

substance	formula	100 years GWP (kg CO ₂ equivalent)
Carbon Dioxide	CO ₂	1
Methane	CH ₄	24.5
Nitrous Oxide	N ₂ O	320
Halon – 1301	CF ₃ Br	5600

The model calculates indicators of Acidification Potential (AP) as total weight in kg of SO₂ equivalents of the following emissions to air shown in table 4.4 by utilizing the weight of the emission as calculated by the model and ratio of its effect to acidification by the effect of Sulphur Dioxide (characterization factors) as shown in table 4.4. These characterization factors are provided by a model developed by Centre of Environmental Science, Leiden University, Netherlands [57].

Table 4.4: AP emission equivalents [57]

substance	formula	100 years AP (kg SO ₂ equivalent)
Sulphur Dioxide	SO ₂	1
Nitrogen Oxides	NO _x	0.7
Hydrogen Chloride	HCl	0.88
Hydrogen Fluoride	HF	1.6
Ammonia	NH ₃	1.88

The model shows the GWP and AP results tabulated according to contributor (materials, electricity, transportation and construction equipment) and according to the life cycle stages in addition to total indicator value for the bridge deck as a whole.

4.10 Calculation of energy & raw materials consumption

The calculation of energy & raw materials consumption part of the model is designed to establish the consumption of energy and raw materials for the materials and processes that consist parts in the life cycle of the bridge deck. The energy calculation (measured in Mj) reflects the electricity used to acquire and process the raw materials of the unit processes in addition to the embodied energy in raw materials of the fuels used in the unit process. The values of the energy and raw materials consumption per unit of materials, electricity,

transportation and construction equipment are summed up and tabulated in a table built in the model (see Appendix B).

4.10.1 Calculation of construction materials energy and raw materials

The first set of calculations in this part of the model is done by utilizing the inventory of construction materials established by the model and “the energy & raw materials consumption per unit” table built in the model to establish the energy and raw materials consumed by the construction materials used along the first two phases of the life cycle of the bridge deck. The model tabulates the results of these calculations according to the material and the life cycle.

4.10.2 Calculation of electricity energy and raw materials

The second set of calculations in this part of the model is done by utilizing the inventory of electricity consumption established by the model and “the energy & raw materials consumption per unit” table built in the model to establish the energy and raw materials consumed by usage of electricity along the life cycles of the bridge deck. The model tabulates the results of these calculations according to the life cycle stages of the bridge deck.

4.10.3 Calculation of transportation energy and raw materials

The third set of calculations in this part of the model is done by utilizing the inventory of transportation activities established by the model and “the energy & raw materials consumption per unit” table built in the model to establish the energy and raw materials consumed by the transportation activities along the life cycle of the bridge deck. The model tabulates the results of these calculations according to the two types of trucks used in the transportation activities and the life cycle stages of the bridge deck.

4.10.4 Calculation of construction equipment energy and raw materials

The fourth set of calculations in this part of the model is done by utilizing the inventory of construction equipment as established by the model and “the energy

& raw materials consumption per unit” table built in the model to establish the energy and raw materials consumed during the operation of construction equipments along the life cycle of the bridge deck calculated for the ten categories of horse power rating of the diesel engines of the equipment. The model accumulates the results according to the life cycle stages of the bridge deck.

4.10.5 Accumulating energy and raw materials

The model accumulates the results and shows it in two different manners:

- According to the contributor. The contributors along the life cycle of the bridge deck include construction materials (including electricity used to process these materials), transportation activities and construction equipment.
- According to the three life cycle stages of the bridge deck.

The model also calculates the total consumption of energy and raw materials along the life cycle of the bridge deck. This will conclude the calculations of this part of the model.

5. Performance evaluation of the model

The environmental loading of a construction project is an important issue to be considered in the series of decisions to be taken during the preparation for the construction of such a project. Many design options are available and will be studied in order to reach the optimum design, and the environmental loading of the project will be one of the factors to be considered in the optimum design. The case studies that are being presented in this chapter are designed to demonstrate the possibility of utilizing the model developed during the course of this study to estimate the environmental loading of multiple options for an imaginary concrete bridge deck to be constructed in North America.

5.1 Base option

It is assumed that a concrete bridge deck in a certain location in North America is to be constructed after the previous one has served its useful service life and decommissioned. The bridge is designed for a certain traffic conditions and the dimensions of the bridge deck are as shown in Table 5.1.

Table 5.1: Dimensions of the bridge deck

Dimension	Value (m)
Length	1500
Width	32.5
Thickness	0.225

The expected life time of the new concrete bridge deck is 75 years, starting with the construction of the new concrete bridge deck and ending with the demolishing activity. The resurfacing activity is expected to be repeated every 15 years within the expected life time of the concrete bridge deck. The maintenance and repair activity is expected to be repeated every 5 years within the cycle of resurfacing activity.

The assumed construction method is a conventional cast in situ method by supplying fresh concrete from a batch plant to the site of construction. The steel reinforcement for the concrete bridge deck is to be fabricated in a plant and then delivered ready to be fixed in location. The transportation method to be adopted is by using trucks. The distances of transportation for the different materials are assumed to be as shown in table 5.2.

Table 5.2: Distances of transportation

Transportation of	Starting point	Ending point	Distance (km)
Fine aggregate	Quarry	Batch plant	70
Coarse aggregate	Quarry	Batch plant	70
Cement	Supplier	Batch plant	350
Chemical additives	Supplier	Batch plant	100
Steel rebar	Supplier	Fabricating facility	70
Fabricated steel	Fabricating facility	Site	120
Fresh concrete	Batch plant	Site	68
Construction equipment	Yard	Site	150
Construction wastage	Site	Landfill	80
Scrap steel	Site	Scrap yard	200

The compressive strength of concrete for the bridge deck is assumed to be 35 MPa. The mix design for the concrete bridge deck was assumed to be identical to the mix reported by Prusinski et. al. [58]. Values for chemical additives and steel rebar consumption are assumed. The values of the mix content are shown in table 5.3.

Table 5.3: Concrete mix proportions

Component	Amount (kg/m ³)
Fine aggregate	712
Coarse aggregate	1187
Cement	335
Water	141
Super plasticizer	4
Air entraining agent	14
Steel rebar	130
Density of the mix	2580

The same concrete mix is assumed to be used for the resurfacing activity and maintenance & repair activity. The thickness of the resurfacing layer is 0.07 m.

The construction equipments to be used at site for construction stage were assumed as shown in table 5.4.

Table 5.4: construction equipments used at construction stage

Activity	Equipment type	No. of pieces	Horse power rating (hp)	Usage time/piece (hr)	Equipment weight (kg)
Cast in situ construction	Concrete pump	2	300	150	7000
Cast in situ construction	Vibrator	4	5	176	27
Cast in situ construction	Trawler	2	12	42	63

The construction equipments to be used at site for operation stage were assumed as shown in table 5.5.

Table 5.5: construction equipments used at operation stage

Activity	Equipment type	No. of pieces	Horse power rating (hp)	Usage time/piece (hr)	Equipment weight (kg)
Resurfacing	Cutter	1	300	144	27000
Resurfacing	Conveyor	1	127	144	12000
Resurfacing	Spreader	1	250	144	2300
Resurfacing	Lighting	3	20	144	1500
Resurfacing	Warning light	2	20	1432	1500
Maintenance & repair	Saw	1	15	17	780
Maintenance & repair	jack hammer	1	80	8	1670
Maintenance & repair	Vibrator	1	5	3	27
Maintenance & repair	lighting	1	20	16	1500
Maintenance & repair	Warning light	2	20	72	1500

The construction equipments to be used at site for end of life stage were assumed as shown in table 5.6.

Table 5.6: construction equipments used at end of life stage

Activity	Equipment type	No. of pieces	Horse power rating (hp)	Usage time/piece (hr)	Equipment weight (kg)
Demolishing	Saw	1	15	90	780
Demolishing	Crane	1	300	100	25000
Demolishing	Breaker	1	300	240	35000
Demolishing	Loader	1	400	240	35000
Demolishing	Warning light	2	20	720	1500
Demolishing	Generator	1	100	240	3500
Demolishing	Loader at landfill	1	400	90	35000

The wastage percentage of construction activity was assumed to be 0.6%. The electricity consumption at the batch plant was assumed to be 22kWh/m³ of fresh concrete, while the electricity consumption at the steel fabrication plant was assumed to be 18kWh/kg of fabricated steel.

These parameters of the base option will be used for other design options in the case studies unless otherwise noted.

5.2 Case study 1

The first alternative to reduce the environmental loading of the base option is to use supplementary cementitious materials to reduce the amount of Portland cement in the mix, and hence reducing the emissions, energy and consumption of raw materials related to Portland cement.

Case study one is designed to investigate the effect of using slag cement at two different replacement percentages to determine the effect of using slag cement.

The first replacement percentage is 35% of the amount of Portland cement. The changes in the mix design from the base option are shown in table 5.7 [58].

Table 5.7: Case study 1, changes in mix proportions of 35% slag replacement

Component	Amount (kg/m ³)
Cement	218
Slag	117
Density of the mix	2521

The second replacement percentage is 50% of the amount of Portland cement. The changes in the mix design from the base option are shown in table 5.8 [58].

Table 5.8: Case study 1, changes in mix proportions of 50% slag replacement

Component	Amount (kg/m ³)
Cement	167
Slag	167
Density of the mix	2495

The distance for transportation of slag cement from the supplier to the batch plant was assumed to be 600 km. All other parameters remained unchanged from the base option.

The effect of using slag cement in two different replacement percentages on the environmental loading of the concrete bridge deck was investigated through the following parameters:

- Reduction in consumption of some of the raw materials.
- Reduction in consumption of energy.
- Reduction in impact indicators of global warming potential and acidification potential.

The reduction in consumption of raw materials varied according to the material in question, as can be seen in table 5.9.

Table 5.9: Case study 1, reduction in consumption of raw materials

Raw material type	Base option amount	35% slag replacement amount	Reduction %	50% slag replacement amount	Reduction %
Coal (kg)	9184965	8756278	4.7	8569414	6.7
Crude oil (liter)	15980208	15939107	0.3	15918116	0.4
Natural gas (m ³)	1505283	1486898	1.2	1478884	1.8
Calcite ore (kg)	13505208	8884198	34.2	6869912	49.1
Shale & clay (kg)	1058127	688572.4	34.9	527484.4	50.1
Anhydrite gypsum (kg)	459456.1	298989.4	34.9	229042.3	50.1
Iron ore (kg)	1889697	1845036	2.4	1825569	3.4
Water (kg)	7947486	5171798	34.9	3961882	50.1

The consumption of materials that are directly related to the production of Portland cement (such as calcite ore, shale & clay, anhydrite gypsum and water) followed closely the percentage of replacement of slag. The consumption of raw materials for fuels did not follow the same scenario as fuels raw materials are less related to Portland cement as a unit process. The results of the model revealed that the largest contributor to coal consumption is electricity consumption which accounted for 75–81%, the cement production accounted for 7-13% while the steel rebar accounted for 11%. Figure 5.1 shows the distribution of contributors to coal consumption.

Fig. 5.1: Case study 1, contributors to coal consumption

The largest contributor to crude oil consumption was the transportation which accounted for 39%, electricity accounted for 29% while equipment accounted for 16%. Figure 5.2 shows the distribution of contributors to crude oil consumption.

Fig. 5.2: Case study 1, contributors to crude oil consumption

The largest contributor to natural gas consumption was electricity which accounted for 90-92%, steel rebar accounted for 5.9% while cement accounted for 1.8-3.5%. Figure 5.3 shows the distribution of contributors to natural gas consumption.

Fig. 5.3: Case study 1, contributors to natural gas consumption

The reduction in consumption of energy was 1.9% for the 35% slag replacement and 2.8% for the 50% slag replacement, as can be seen in table 5.10.

Table 5.10: Case study1, reduction in energy consumption

Energy of (Mj)	Base option amount	35% slag replacement amount	Reduction %	50% slag replacement amount	Reduction %
Cement	53901532	35076220.6	34.9	26870316	50.1
Steel	35712155	35712155	0.0	35712155	0.0
Electricity	760736369	760736369	0.0	760736369	0.0
Transportation	41680104	41734835.2	-0.1	41738184	-0.1
Equipment	17675979	17675979.5	0.0	17675979	0.0
Others	71055070	71055069.6	0.0	71055070	0.0
Total	980761208	961990629	1.9	953788072	2.8

There were no changes in energy from steel, electricity consumption and equipment because these parameters remained unchanged. There was a small increment in transportation energy as a new material, the slag, has to be transported to the batch plant. The reduction in cement energy followed closely the reduction in its content as expected. The cement accounted for only 2-5% of

the total energy, which explains the minor reduction in total energy. Figure 5.4 shows the distribution of the contributors to energy.

Fig. 5.4: Case study 1, contributors to energy

The total reduction in global warming potentials was 8.4% for the 35% slag replacement and 12.1% for the 50% slag replacement, as can be seen in table 5.11.

Table 5.11: Case study 1, reduction in GWP

GWP of (kg CO ₂)	Base option amount	35% slag replacement amount	Reduction %	50% slag replacement amount	Reduction %
Cement	9152844.9	5956179.64	34.9	4562761.5	50.1
Steel	4538566.6	4538566.59	0.0	4538566.6	0.0
Electricity	18531038	18531038.4	0.0	18531038	0.0
Transportation	3342840.1	3360545.17	-0.5	3366401.6	-0.7
Equipment	723912.57	723912.565	0.0	723912.57	0.0
Others	1447098.88	1447098.88	0.0	1447098.88	0.0
Total	37736301	34557341.3	8.4	33169780	12.1

The reduction in global warming potential of cement followed closely the reduction in cement consumption; however the cement contributed only 13-24%

of the total global warming potential. There was a slight increase in transportation to haul the slag to batch plant. The distribution of contributors to global warming potential is shown in figure 5.5.

Fig. 5.5: Case study 1, contributors to global warming potential

The total reduction in acidification potentials was 5.9% for the 35% slag replacement and 8.5% for the 50% slag replacement, as can be seen in table 5.12.

Table 5.12: Case study 1, reduction in AP

AP of (kg SO ₂)	Base option amount	35% slag replacement amount	Reduction %	50% slag replacement amount	Reduction %
Cement	36748.954	23914.2446	34.9	18319.628	50.1
Steel	35123.504	35123.5043	0.0	35123.504	0.0
Electricity	120132.91	120132.911	0.0	120132.91	0.0
Transportation	15378.698	15501.3606	-0.8	15545.597	-1.1
Equipment	2991.6941	2991.69409	0.0	2991.6941	0.0
Others	3573.67	3573.67	0.0	3573.67	0.0
Total	213949.44	201237.388	5.9	195687.01	8.5

The reduction in acidification potential of cement followed closely the reduction in cement consumption; however the cement contributed only 9-17% of the total acidification potential. There was a slight increase in transportation to haul the slag to batch plant. The reduction in global warming potential was more than the reduction in acidification potential because cement contributed less to acidification potential. The distribution of contributors to acidification potential is shown in figure 5.6.

Fig. 5.6: Case study 1, contributors to acidification potential

5.3 Case study 2

The second alternative to reduce the environmental loading of the base option is to reduce the thickness of the concrete bridge deck, leading to reduction in the volume of concrete and hence reducing the emissions, energy and raw materials consumption related to concrete. This alternative was assumed to be possible through the use of prestressing steel and increasing the compressive strength of the concrete.

Case study two is designed to investigate the effect of using higher compressive strength for the concrete (50MPa) and the post-tensioning effect using two different construction methods:

- Post-tensioning coupled with cast in situ construction of the bridge deck.
- Post-tensioning coupled with precast construction of the bridge deck.

The extra strength of concrete was assumed to result in reducing the thickness of concrete to 0.18 m and the elimination of the resurfacing activity from the life cycle of the bridge deck. The same mix was assumed to be used for the two methods of construction. The changes in the mix design from the base option are shown in table 5.13.

Table 5.13: Case study 2, changes in mix proportions of 50 MPa mix

Component	Amount (kg/m ³)
Fine aggregate	555
Coarse aggregate	1055
Cement	338
Silica fume	15
Slag	151
Water	178
Super plasticizer	5
Air entraining agent	17
Prestressing steel	10
Density of the mix	2509

The distances for the transportation from the supplier to the batch plant was assumed to be 600 km for both of slag and silica fume. The electricity consumption at the precast plant was assumed to be 35 kWh/m³ of concrete. The assumed elimination of resurfacing activity resulted in the elimination of construction equipments related to this activity. Other changes in the construction equipment from the base option are shown in table 5.14.

Table 5.14: Case study 2, changes in construction equipment

Activity	Equipment type	No. of pieces	Horse power rating (hp)	Usage time/piece (hr)	Equipment weight (kg)
Cast in situ construction	Tensioning machine	1	50	66	150
Precast construction	Crane	2	300	176	25000
Precast construction	Tensioning machine	1	50	66	150

All other parameters remained unchanged from the base option.

The effect of using 50 MPa post-tensioned concrete using two different construction methods on the environmental loading of the concrete bridge deck was investigated through the following parameters:

- Reduction in consumption of some of the raw materials.
- Reduction in consumption of energy.
- Reduction in impact indicators of global warming potential and acidification potential.

The reduction in consumption of raw materials varied according to the material in question. The consumption of materials that are directly related to the production of Portland cement (such as calcite ore, shale & clay, anhydrite gypsum and water) was in the range of 67-68%, which suggests that adopting this option resulted in the reduction in cement consumption in the same range also. The results of the raw material consumption can be seen in table 5.15.

Table 5.15: Case study 2, reduction in consumption of raw materials

Raw material type	Base option amount	Cast in situ construction amount	Reduction %	Precast construction amount	Reduction %
Coal (kg)	9184965	6753566.4	26.5	6784193.5	26.1
Crude oil (liter)	15980208	7604525	52.4	6934824.5	56.6
Natural gas (m ³)	1505283	1170635.4	22.2	1176570.7	21.8
Calcite ore (kg)	13505208	4423118	67.2	4428376.4	67.2
Shale & clay (kg)	1058127	334794.41	68.4	335214.94	68.3
Anhydrite gypsum (kg)	459456.1	145373.19	68.4	145555.79	68.3
Iron ore (kg)	1889697	1562229.8	17.3	1562280.6	17.3
Water (kg)	7947486	2514606	68.4	2517764.5	68.3

The raw materials for fuels showed different results. The major contributor to coal consumption is the electricity at 81% of the total consumption; however the results for both construction methods are almost identical which suggest that the increase in electricity consumption at the precast plant (during the construction stage) is not large in comparison with cast in situ option. The distribution of the contributors to coal consumption is shown in figure 5.7.

Fig. 5.7: Case study 2, contributors to coal consumption

The major contributor to crude oil consumption is the electricity, and the increase in consumption of electricity at the precast plant is more evident in crude oil than in coal. The distribution of the transportation reveals a considerable reduction in transportation activity in the precast construction method, which is reflected in the large drop in crude oil consumption. The distribution of the contributors to crude oil consumption is shown in figure 5.8.

Fig. 5.8: case study 2, contributors to crude oil consumption

The major contributor to natural gas consumption is the electricity at 92% of the total consumption; however the results for both construction methods are almost identical which suggest that the increase in electricity consumption at the precast

plant is not large in comparison to cast in situ construction. The distribution of the contributors to coal consumption is shown in figure 5.9.

Fig. 5.9: Case study 2, contributors to crude oil consumption

The total reduction in consumption of energy was at 29% for both methods of construction as can be seen in table 5.16.

Table 5.16: Case study 2, reduction in energy consumption

Energy of (Mj)	Base option amount	Cast in situ construction amount	Reduction %	Precast construction amount	Reduction %
Cement	53901532	17054593	68.4	17076015	68.3
Steel	35712155	30846286	13.6	30846286	13.6
Electricity	760736369	601424256	20.9	604725915	20.5
Transportation	41680104	14021731	66.4	9268221.1	77.8
Equipment	17675979	6197457.3	64.9	6340530.4	64.1
Others	71055070	25795571	63.7	25795213	63.7
Total	980761208	695339894	29.1	694052180	29.2

The energy reduction in all the categories was consistent for both methods of construction and can be used as an indicator to the reduction of use of the respective material or activity, however the reduction in energy of transportation

was not in line with the trend of other categories which indicates a reduction in transportation activity in the precast construction method. The largest contributor to energy was the electricity. Figure 5.10 shows the distribution of the contributors to energy.

Fig. 5.10: Case study 2, contributors to energy

The total reduction in global warming potentials was 38% for both methods of construction, as can be seen in table 5.17.

Table 5.17: Case study 2, reduction in GWP

GWP of (kg CO ₂)	Base option amount	Cast in situ construction amount	Reduction %	Precast construction amount	Reduction %
Cement	9152844.9	2895985.3	68.4	2899622.8	68.3
Steel	4538566.6	3920175.7	13.6	3920175.7	13.6
Electricity	18531038	14650300	20.9	14730726	20.5
Transportation	3342840.1	1136016.3	66.0	796070.51	76.2
Equipment	723912.57	253720.78	65.0	259567.33	64.1
Others	1447098.88	483346.24	66.6	483694.99	66.6
Total	37736301	23339544	38.2	23089858	38.8

The reduction in global warming potential of cement followed closely the suggested reduction in cement consumption; however the cement contributed only 12% of the total global warming potential. The distribution of contributors to global warming potential is shown in figure 5.11.

Fig. 5.11: Case study 2, contributors to global warming potential

The total reduction in acidification potentials was 32% for both methods of construction, as can be seen in table 5.18.

Table 5.18: Case study 2, reduction in AP

AP of (kg SO ₂)	Base option amount	Cast in situ construction amount	Reduction %	Precast construction amount	Reduction %
Cement	36748.954	11627.47	68.4	11642.075	68.3
Steel	35123.504	30337.84	13.6	30337.84	13.6
Electricity	120132.91	94974.882	20.9	95496.269	20.5
Transportation	15378.698	5261.6397	65.8	3825.5334	75.1
Equipment	2991.6941	1172.1748	60.8	1211.7203	59.5
Others	3573.67	1105.83	69.1	1107.43	69.0
Total	213949.44	144479.83	32.5	143620.87	32.9

The reduction in acidification potential of cement followed closely the suggested reduction in cement consumption; however the cement contributed only 8% of the total acidification potential. The distribution of contributors to acidification potential is shown in figure 5.12.

Fig. 5.12: Case study 2, contributors to acidification potential

5.4 Case study 3

The third alternative to reduce the environmental loading of the base option is to change the location of the batch plant and move it to the construction site, leading to reduction in the transportation of fresh concrete and hence reducing the emissions, energy and raw materials consumption related to transportation process.

Case study three is designed to investigate the effect of shifting the batch plant closer to site of the bridge deck on the environmental loading. The shifting of the batch plant led to the assumed changes to the transportation distances as shown in table 5.19.

Table 5.19: Case study 3, the changes in transportation distances

Transportation of	Starting point	Ending point	Distance (km)
Fine aggregate	Quarry	Batch plant	140
Coarse aggregate	Quarry	Batch plant	140
Cement	Supplier	Batch plant	420
Chemical additives	Supplier	Batch plant	170
Fresh concrete	Batch plant	Site	1

All other parameters remained unchanged from the base option.

The effect of shifting the batch plant closer to construction site on the environmental loading of the concrete bridge deck was investigated through the following parameters:

- Reduction in consumption of some of the raw materials.
- Reduction in consumption of energy.
- Reduction in impact indicators of global warming potential and acidification potential.

The reduction in consumption of raw materials clearly indicates the fact that the only material that is affected by this option is the crude oil, being the raw material for diesel fuel used in the transportation activity. The consumption of other materials that are not directly related to the transportation remained unchanged. The reduction in consumption of the raw material can be seen in table 5.20.

Table 5.20: Case study 3, reduction in consumption of raw materials

Raw material type	Base option amount	Shifting batch plant amount	Reduction %
Coal (kg)	9184965	9184964.9	0.0
Crude oil (liter)	15980208	13531448	15.3
Natural gas (m ³)	1505283	1505282.7	0.0
Calcite ore (kg)	13505208	13505208	0.0
Shale & clay (kg)	1058127	1058127.4	0.0
Anhydrite gypsum (kg)	459456.1	459456.15	0.0
Iron ore (kg)	1889697	1889696.7	0.0
Water (kg)	7947486	7947486	0.0

The coal and natural gas are not an input in the transportation activity, and hence the distribution of the contributors to both of these materials remained unchanged from the base option as shown in the previous case studies. The reduction in transportation activity resulted in shifting the major contributor to crude oil from transportation in the base option to electricity in this case study. The distribution of contributors to crude oil consumption is shown in figure 5.13.

Fig. 5.13: Case study 3, contributors to crude oil consumption

The total reduction in consumption of energy was 1.7% for this case study from the base option as can be seen in table 5.21.

Table 5.21: Case study 3, reduction in energy consumption

Energy of (Mj)	Base option amount	Shifting batch plant amount	Reduction %
Cement	53901532	53901532	0.0
Steel	35712155	35712155	0.0
Electricity	760736369	760736369	0.0
Transportation	41680104	25347682	39.2
Equipment	17675979	17675979	0.0
Others	71055070	71055070	0.0
Total	980761208	964428787	1.7

The small amount in reduction of total energy is due to the high contribution from electricity which remained unchanged. The reduction in transportation energy of 39% suggests a reduction in transportation activity at the same percentage. Figure 5.14 shows the distribution of the contributors to energy.

Fig. 5.14: Case study 3, contributors to energy

The total reduction in global warming potentials was 3.2%, as can be seen in table 5.22.

Table 5.22: Case study 3, reduction in GWP

GWP of (kg CO ₂)	Base option amount	Shifting batch plant amount	Reduction %
Cement	9152844.9	9152844.9	0.0
Steel	4538566.6	4538566.6	0.0
Electricity	18531038	18531038	0.0
Transportation	3342840.1	2152857.3	35.6
Equipment	723912.57	723912.57	0.0
Others	1447098.88	1447098.88	0.0
Total	37736301	36546319	3.2

Although the reduction in transportation was relatively high at 35%, transportation only contributed 6% to the total global warming potential; which explained the minimal reduction in total global warming potential. The distribution of the contributors to global warming potential is shown in figure 5.15.

Fig. 5.15: Case study 3, contributors to global warming potential

The total reduction in acidification potentials was 2.4%, as can be seen in table 5.23.

Table 5.23: Case study 3, reduction in AP

AP of (kg SO ₂)	Base option amount	Shifting batch plant amount	Reduction %
Cement	36748.954	36748.954	0.0
Steel	35123.504	35123.504	0.0
Electricity	120132.91	120132.91	0.0
Transportation	15378.698	10275.324	33.2
Equipment	2991.6941	2991.6941	0.0
Others	3573.67	3573.67	0.0
Total	213949.44	208846.06	2.4

Although the reduction in transportation was relatively high at 33%, transportation only contributed 5% to the total acidification potential; which explained the minimal reduction in total acidification potential. The acidification potential was smaller than the global warming potential which indicates that the effect of transportation activity on acidification potential is less than global warming potential. The distribution of the contributors to acidification potential is shown in figure 5.16.

Fig. 5.16: Case study 3, contributors to acidification potential

5.5 Case study 4

The fourth alternative to reduce the environmental loading of the base option is to continue using the older bridge deck (no demolishing of older bridge deck and no new construction stage) and hence reducing the emissions, energy and raw materials consumption related to construction of new bridge deck. This alternative was assumed to be possible through reduction in repetition time between the activities of the operation stage to elongate the useful life time of the old bridge deck to 75 years (equal to the base option time).

Case study four is designed to investigate the effect of elimination of new construction stage on the environmental loading. The elimination of new construction stage was coupled with the assumption that the repetition time for periodical activities to be reduced from the base option. The resurfacing activity is assumed to be repeated every 10 years within the extended life time of the concrete bridge deck. The maintenance and repair activity is expected to be repeated every 3 years within the cycle of resurfacing activity. The materials, electricity, transportation and construction equipment of the construction stage were all eliminated. All other parameters remained unchanged from the base option.

The effect of eliminating the construction stage on the environmental loading of the concrete bridge deck was investigated through the following parameters:

- Reduction in consumption of some of the raw materials.
- Reduction in consumption of energy.
- Reduction in impact indicators of global warming potential and acidification potential.

The reduction in consumption of raw materials was considerable in all categories. The reduction in consumption of the raw material can be seen in table 5.24.

Table 5.24: Case study 4, reduction in consumption of raw materials

Raw material type	Base option amount	No new construction amount	Reduction %
Coal (kg)	9184965	1185559.5	87.1
Crude oil (liter)	15980208	10413734	34.8
Natural gas (m ³)	1505283	73994.987	95.1
Calcite ore (kg)	13505208	11281010	16.5
Shale & clay (kg)	1058127	902173.47	14.7
Anhydrite gypsum (kg)	459456.1	391738.42	14.7
Iron ore (kg)	1889697	109026.83	94.2
Water (kg)	7947486	6776132.7	14.7

The reduction in consumption of raw materials directly related to cement was in the range of 14-16%. Although calcite ore is an input in cement production, it is an input in steel production also while the water and shale & clay are an input to cement production only, hence it might be suggested that the reduction in cement consumption in this case study is equal to the reduction in consumption of these two categories of raw materials (i.e.14.7%). The reduction in consumption of raw materials of fuels was very high. The major contributor to coal consumption is electricity in the base option, but it shifted to cement production in this case study. The distribution of the contributors of consumption of coal is shown in figure 5.17.

Fig. 5.17: Case study 4, contributors to coal consumption

The crude oil is mainly consumed in the transportation activity. The elimination of the construction stage has eliminated consumption of electricity at the construction stage and hence there was a remarkable drop in electricity contribution to crude oil consumption. The distribution of contributors to crude oil consumption is shown in figure 5.18.

Fig. 5.18: Case study 4, contributors to crude oil consumption

The elimination of using steel in the construction stage due to elimination of the stage itself resulted in higher contribution from cement in the consumption of natural gas. The distribution of the contributors to natural gas consumption is shown in figure 5.19.

Fig. 5.19: Case study 4, contributors to natural gas consumption

The total reduction in consumption of energy was remarkable at 82% for this case study from the base option as can be seen in table 5.25.

Table 5.25: Case study 4, reduction in energy consumption

Energy of (Mj)	Base option amount	No new construction amount	Reduction %
Cement	53901532	45957162	14.7
Steel	35712155	0	100.0
Electricity	760736369	15230265	98.0
Transportation	41680104	34838359	16.4
Equipment	17675979	21371987	-20.9
Others	71055070	60582496	14.7
Total	980761208	177980270	81.9

The reduction in cement energy and others (mainly aggregates) at 14.7% is in line with the earlier findings in this case study. The remarkable drop of 98% in electricity energy is a clear indicator to the percentage of drop in electricity consumption in this case study, which reveals the huge amount of electricity consumed at the construction stage. There was an increase of 20.9% construction equipment energy which suggests an increase in construction

equipment usage at the same amount. The reduction in transportation energy was at 16.4% which suggests a reduction in transportation activity at the same percentage. Figure 5.20 shows the distribution of the contributors to energy.

Fig. 5.20: Case study 4, contributors to energy

The total reduction in global warming potentials was remarkable at 65.3%, as can be seen in table 5.26.

Table 5.26: Case study 4, reduction in GWP

GWP of (kg CO ₂)	Base option amount	No new construction amount	Reduction %
Cement	9152844.9	7803837.1	14.7
Steel	4538566.6	0	100.0
Electricity	18531038	370999.26	98.0
Transportation	3342840.1	2793344.9	16.4
Equipment	723912.57	875387.37	-20.9
Others	1447098.88	1233815.73	14.7
Total	37736301	13077384	65.3

Although the reduction percentages of global warming potentials are almost identical to those of energy, the total reduction in global warming potential is less.

The largest contributor to global warming potential was cement. The distribution of the contributors to global warming potential is shown in figure 5.21.

Fig. 5.21: Case study 4, contributors to global warming potential

The total reduction in acidification potentials was remarkable at 75.2%, as can be seen in table 5.27.

Table 5.27: Case study 4, reduction in AP

AP of (kg SO ₂)	Base option amount	No new construction amount	Reduction %
Cement	36748.954	31332.646	14.7
Steel	35123.504	0	100.0
Electricity	120132.91	2405.1119	98.0
Transportation	15378.698	12848.364	16.5
Equipment	2991.6941	3498.4607	-16.9
Others	3573.67	3046.96	14.7
Total	213949.44	53131.544	75.2

Although the reduction percentages of the contributors to acidification potential are almost identical to those of global warming potential, the increase in acidification potential of transportation activity was different from that of global

warming potential. The largest contributor to acidification potential was cement. The distribution of the contributors to global warming potential is shown in figure 5.22.

Fig. 5.22: Case study 4, contributors to acidification potential

5.6 Discussion of results

The case studies were performed to decide the option to be selected that will result in least environmental loading. The criterion for least environmental loading was based on the reduction in total global warming potential and total acidification potential.

The largest reduction in environmental loading was achieved by the fourth option due to elimination of the construction stage and all the activities associated with this stage, which are larger than activities associated with other stages. The results of case study 4 shows the benefits to the environment that can be achieved when adopting a better maintenance program. The second option that achieved the second least environmental loading was the option to use higher strength concrete with precast construction method, which indicates the benefits of using concrete with higher strength and durability on the environmental performance of concrete.

The case studies have shown some of the points that worth mentioning:

- The largest contributor to electricity consumption is the construction stage, and electricity is the largest contributor to impact indicators.
- The largest contributor to crude oil consumption is transportation activity.
- The largest contributor to coal and natural gas consumption is electricity consumption.
- The contribution to energy can reveal the relative percentage of participation from materials or activities to the total system.

These points were observed from these case studies and can not be generalized for other cases as every case is unique and have to be analyzed by its own to establish its environmental loading, however, the case studies that were considered here revealed the flexibility of the model to tackle different scenarios and reach the required goals.

6 Conclusions and recommendations

6.1 Conclusions

Sustainable development is typically defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. Man kind needs infrastructure to facilitate its development and this will lead to more construction. The need for sustainable development will result in the need for sustainable construction. The construction industry is the largest contributor to environmental loading, and therefore has the largest obligation to improve its environmental performance. The construction industry has also a larger chance to improve its environmental performance due to its sheer size.

The need for sustainable construction requires tools to quantify its environmental loading, and to this end, the efforts of this study were dedicated to prepare a model that can be utilized to estimate the environmental loading of a concrete bridge deck. Concrete bridge decks are an important part of the infrastructure in North America, and due to the weather conditions, are prone to severe deterioration. This situation will place concrete bridge decks under periodical construction activities, which makes concrete bridge deck contribution to environmental loading a considerable one.

The main goal of Life Cycle Assessment technique is to optimize usage of resources and reduce emissions to the environment. This is achieved by considering all activities in all life cycle stages of a technological system (a bridge deck in this case). Adopting the methodology of Life Cycle Assessment will avoid shifting a problem from one life cycle stage to another or from one environmental media to the other. Applying Life Cycle Assessment methodology to estimate the environmental loading of a concrete bridge deck will ensure overall environmental benefits and contribute to sustainable development. The model that was developed during the course of this study adopted Life Cycle

Assessment technique to provide an estimation of the overall environmental loading of a concrete bridge deck.

The inclusion of all activities in every life cycle stage of a concrete bridge deck will cover cradle to grave emissions to all media. Many construction activities will take place during the three life cycle stages:

- The construction stage, where the concrete bridge deck starts to exist through the convergence of building materials via processing plants and construction equipments. Transportation will be required to move the materials and equipments.
- The operation stage, where the concrete bridge deck undergoes periodical construction activities that are required to repair or replace its deteriorated parts. The repaired and new parts of the concrete bridge deck will start its existence in a way similar to the one explained above, after removal of the deteriorated parts. Construction equipments and transportation of both materials and equipments are required to prepare the concrete bridge deck for these repairs.
- The end of life stage, where the concrete bridge deck is decommissioned by demolishing it. Construction equipments are required to perform demolishing while transportation is required to haul equipments in and out of the site, in addition to remove the wastage to the landfill site (or crusher).

In each of these life cycle stages, the unit processes that are to be included in an activity of a life cycle stage have to be covered from cradle to gate, that is from extraction of raw materials till the situation where it is ready to be used in the life cycle of the concrete bridge deck.

The cradle to gate life cycle inventory that was prepared for the model followed the methodology of Life Cycle Assessment by the inclusion of precombustion emissions of fuels. There are emissions associated with production of raw

materials of fuels and refining these raw materials to produce the fuels. These precombustion emissions were added to the emissions of these fuels while generating electricity. Precombustion emissions of diesel fuel were added to combustion emissions of diesel fuel in transportation trucks and construction equipments, both of which are powered by diesel engines. The collected life cycle inventory data for other materials covered the cradle to gate emissions of these materials. The model followed the real world scenario to include the anticipated types of construction activities and covered the majority of unit processes of every activity in order to estimate the cradle to grave environmental loading of a concrete bridge deck.

The model used the information provided by the life cycle inventory data on raw materials that were consumed to produce a unit processes to prepare an estimate of the consumption of categorized raw materials during the life cycle of the concrete bridge deck. The energy of consumed electricity, in addition to the embodied energy in raw materials of fuels consumed during the life cycle were summed up to estimate the total energy of the concrete bridge deck.

The model was used to estimate the environmental loading of an assumed concrete bridge deck to be constructed in a conventional method in lieu of the old bridge deck which is about to be decommissioned. The model was then used to estimate the environmental loading of four alternatives to the base option of the design to select the alternative with the least environmental loading per the functional unit which is the bridge deck itself.

The first alternative was based on using slag cement as a partial replacement of Portland cement to investigate the effect of reducing cement consumption on the environmental loading of the concrete bridge deck. Two percentages of replacement of slag instead of Portland cement were used. The first replacement percentage was 35% of the original Portland cement content in the base option.

The second replacement percentage was 50% of the original Portland cement content in the base option.

The first replacement percentage resulted in reduction of selected indicators as follows:

- 1.9% reduction in energy.
- 8.4% reduction in global warming potential.
- 5.9% reduction in acidification potential.
- 35% reduction in consumption of cement raw materials.

The reduction in consumption of fuels raw materials varied according to the type of material involved.

The second replacement percentage resulted in reduction of selected indicators as follows:

- 2.8% reduction in energy.
- 12.1% reduction in global warming potential.
- 8.5% reduction in acidification potential.
- 50% reduction in consumption of cement raw materials.

The reduction in consumption of fuels raw materials varied according to the type of material involved.

The second alternative was based on reducing the thickness of the concrete bridge deck to investigate the effect of reducing concrete volume on the environmental loading of the concrete bridge deck. The reduction in concrete thickness was assumed to be achieved through using higher strength concrete that contains slag and silica fume as a partial binder replacement and changing the mix proportions of concrete, coupled with using post-tensioning technique. Two methods of construction were investigated. The first construction method was assumed to be performed in the conventional way by using cast in situ concrete with post-tensioning. The second construction method was assumed to

be done by adopting the precast technique, and then applying the post-tensioning.

Both of the construction methods resulted in almost identical reduction in the selected indicators as follows:

- The reduction in energy was about 29%.
- The reduction in global warming potential was about 38%.
- The reduction in acidification potential was about 32%.
- The reduction in consumption of cement raw materials was about 68%.

The reduction in consumption of fuels raw materials varied according to the type of material involved.

The third alternative was based on changing the location of the batch plant and moving it closer to the construction site to investigate the effect of reducing the transportation process on the environmental loading of the concrete bridge deck.

The reduction in transportation process resulted in reduction of selected indicators as follows:

- 1.7% reduction in energy.
- 3.2% reduction in global warming potential.
- 2.4% reduction in acidification potential.
- 15.3% reduction in consumption of diesel fuel raw materials.

There was no reduction in consumption of other raw materials since there were no changes to other parameters than transportation.

The fourth alternative was based on eliminating the construction of new bridge deck by continue to use the old bridge deck, coupled with shorter periods between cycles of construction activities during the operation stage to elongate the useful life time of the old bridge deck. The model was used to investigate the effect of eliminating the construction stage on the environmental loading of the concrete bridge deck.

The elimination of construction stage resulted in reduction of selected indicators as follows:

- 81.9% reduction in energy.
- 65.3% reduction in global warming potential.
- 75.2% reduction in acidification potential.
- 14.7% reduction in consumption of cement raw materials.
- 94.2% reduction in consumption of iron ore.

The reduction in consumption of fuels raw materials varied according to the type of material involved.

These results pointed out that the option with the least global warming potential and acidification potential is the option to continue to use the old bridge deck with shorter periods of construction activities during the operation stage. This result is based on the environmental loading, which plays only one part between other factors to be considered in the final decision.

The application of the model on these alternatives exposed the high flexibility built into the model to deal with different construction activities scenarios. The case studies also exposed the ability of the model to provide an indication to the changes in the amounts of activities or its unit processes by analyzing some of the indicators provided by the model, such as energy.

6.2 Recommendations for future work

The single most important requirement to facilitate conducting of Life Cycle Assessment is the access to true and representative life cycle inventory data. In this study, a great deal was given to collect and accumulate data that are relevant to the construction activities of concrete bridge decks in North America.

The majority of life cycle inventory data that were prepared for this study were originated from U.S. official sites that provide general data which are representative for the average industry standards and practices in the U.S.A. The

unavailability of public data about the Canadian industry standards and practices led to a main assumption in this study, which was the assumption that although the majority of life cycle inventory data were representative for the U.S., it can be generated to represent North America. This assumption was based on the similarities and inter-dependability of the industrial set between the two countries, in addition to other factors. However, it is strongly recommended to conduct further search for Canadian data to verify this assumption, especially in the electricity generation field.

The life cycle inventory data prepared for the study covered many unit processes which are used in the construction activities; however there is a need to include more unit processes in the model such as the epoxy coated and galvanized steel rebar. The use of supplementary cementitious materials such as silica fume, fly ash and slag cement is increasing; however the model assumed that there are no emissions associated with the preparation of such materials, which are usually generated as residual from other industrial processes. These assumptions resulted from lack of LCI data on preparation of these residual to be used in construction activities, and therefore some work has to be done in this regard to determine the emissions, energy and raw materials consumption associated with these unit processes.

The model will require a candid observation while being applied to diversified situations in order to improve it so that it will be capable of dealing with any anticipated complex scenario, however this might lead to turning the model into a more complex tool.

The model can be developed to include aids to the user on the expected life time of a bridge deck based on the mix that is input to the model. The model can indicate the expected weights of equipments used on site based on the type of equipment in the input. These features will be very helpful for the user who is not familiar with these fields.

Reference

[1] **“Green Building Design”** a presentation by McCallum Sather architects Inc.

[2] Norris, G. A. **“Direct and Upstream Emissions of Carbon Dioxide from Fossil Fuel Combustion”**, a research report submitted to the National Renewable Energy Laboratory, 1999.

[3] **“Annual Energy Review 2000”**, Energy Information Administration, U.S. Department of Energy, 2001.

[4] **“Characterization of Municipal Solid Waste: 1998 Update 1999”**, report no. EPA530-R-01-014, U.S. U.S. Environmental Protection Agency, July 1999

[5] **“A marketing brochure of the Life Cycle Initiative”**, United Nations Environment Programme and Society of Environmental Toxicology and Chemistry.

[6] **“The Role of Eco-Efficiency: Global Challenges and Opportunities in The 21st Century, Part 1: Overview and Analysis”**, a report prepared for The Eco-efficiency Working Group Sustainability Project Policy Research Initiative, May 2000.

[7] **“Life Cycle Assessment: Principles and Practice”**, report no. EPA/600/R-06/060, U.S. Environmental Protection Agency, May 2006.

[8] Koskela, S. and Hiltunen, M. **“A Guide to The Utilization of LCI/LCA Databases for Estonian enterprises”**, Finnish Environment institute, the site was accessed on June 7th, 2007 on the following link:

<http://www.environment.fi/default.asp?contentid=107009&lan=en>

- [9] Scheuer, C. W. and Keoleian, G. A., **“Evaluation of LEED™ Using Life Cycle Assessment Methods”** report no. GCR 02-836, National Institute of Standards and Technology, U.S. Department of Commerce.
- [10] ISO 14040, **“Life Cycle Assessment – Principles and Framework”**, International Organization of Standards, 1997.
- [11] **“LCA Methods for Buildings, Annex 31 of Energy-Related Environmental Impact of Buildings”**, International Energy Agency, November 2001.
- [12] Bare, J. C., Norris, G. A., Pennington, D. W. and McKone, T., **“TRACI, The Tool for The Reduction and Assessment of Chemical and Other Environmental Impacts”**, Journal of Industrial Ecology, 6/3-4, p.49-78, 2002.
- [13] Jönbrink, A. K., Wolf-Wats, C., Erixon, M., Olsson, P., Wallén, E., **“LCA Software Survey”**, IVL Swedish Environmental Research Institute Ltd., Stockholm, September 2000.
- [14] **“Building for Environmental and Economic Sustainability (BEES)”**, U.S. Commerce Dept., National Institute of Standards and Technology, 2001.
- [15] Trusty, W. B., Meil, J. K. and Norris, G. A., **“ATHENA™: A LCA Decision Support Tool for The Building Community”**, Athena Sustainable Materials Institute, Canada.
- [16] Jonsson, A., **“Tools and methods for environmental assessment of building products—methodological analysis of six selected approaches”** Building and Environment, 35/3, p. 223-238, 2000.

- [17] Crawley, D. and Aho, I., **“Building Environmental Assessment Methods: Applications and Development Trends”**, Building Research and Information, 27/4-5, p. 300-308, 1999.
- [18] Cole, R., **“Emerging trends in building environmental assessment methods”**, Building Research and Information, 26/1, p.3-16, 1998.
- [19] **“Building Savings: Strategies for Waste Reduction of Construction and Demolition Debris from Buildings”**, report no. EPA-530-F-00-001, U.S. Environmental Protection Agency, June 2000.
- [20] Citherlet, S., Clarke, J. A. and Hand, J., **“Integration in Building Physics Simulation”**, Energy and Buildings, 33/5, p. 451-461, 2001.
- [21] Chevalier, J. L. and Le Teno, J. F., **“Requirements for an LCA-based Model for The Evaluation of The Environmental Quality of Building Products”**, Building and Environment, 31/5, p. 487-491, 1996.
- [22] Cole, R.J. and P.C. Kernan, **“Life-Cycle Energy Use in Office Buildings”**, Building and Environment, 31/4, p. 307-317, 1996.
- [23] Buchanan, A. and Honey, B., **“Energy and Carbon Dioxide Implications of Building Construction”**, Energy and Buildings, 20/3, p. 205-217, 1994.
- [24] Adalberth, K., **“Energy Use During The Life Cycle of Buildings: A Method”**, Building and Environment, 32/4, p. 317-320, 1997.
- [25] Suzuki, M. and Oka, T., **“Estimation of Life Cycle Energy Consumption and CO₂ Emission of Office Buildings in Japan”**, Energy and Buildings, 28/1, p. 33-41, 1998.

[26] Blanchard, S., Reppe, P., **“Life cycle analysis of a residential home in Michigan”**, report No. CSS98-05, Center for Sustainable systems, University of Michigan, U.S.A., September, 1998.

[27] Keoleian, G., Blanchard, S., and Reppe, P., **“Life-Cycle Energy, Costs, and Strategies for Improving a Single-Family House”**. Journal of Industrial Ecology, 4/2, p. 135-156, 2001.

[28] Adalberth, K., Almgren, A. and Petersen, E. H., **“Life Cycle Assessment of Four Multi-Family Buildings”**, International Journal of Low Energy and Sustainable Buildings, Vol. 2, 2001.

[29] Craighill, A. and Powell, J. C., **“A Life Cycle Assessment and Evaluation of Construction and Demolition Waste”**, working paper WM 99-03, The Centre for Social and Economic Research on the Global Environment, 1999.

[30] Powell, J. and Craighill, A., **“Information: The Key To Sustainability in The Building Sector”**, working paper PA 01-02 presented at the OECD workshop on the Design of Sustainable Building Policies, 28-29 June 2001, Paris.

[31] Pontarollo, G. and Smith, T. **“A Life-Cycle Analysis of The Environmental Impacts of Asphalt and Concrete Roads”**, Paris 2001 IRF World Road Congress.

[32] Inamura, H., Piantanakulchai, M. and Takeyama, Y., **“A Life Cycle Inventory Analysis of Carbon Dioxide for a Highway Construction Project Using Input-Output Scheme: A Case Study of the Tohoku Expressway Construction Works”**, Infrastructure Planning Review, vol.16, p.411-418, 1999, Japan.

[33] Stripple, H., **“Life Cycle Assessment of Road: A Pilot Study for Inventory Analysis, Second Revised Edition”**, a study submitted to the Swedish National Road Administration by Swedish Environmental Research Institute, March 2001.

[34] Stripple, H., **“Life Cycle Inventory of Asphalt Pavements”**, a report prepared for the European Asphalt Pavement Association (EAPA) and Eurobitume by Swedish Environmental Research Institute, October 2000.

[35] Keoleian, G. A. et al., **“Life Cycle Modeling of Concrete Bridge Design: Comparison of Engineered Cementitious Composite Link Slabs and Conventional Steel Expansion Joints”**, Journal of Infrastructure Systems, ASCE, March 2005.

[36] ISO 14041, **“Life Cycle Assessment – Goal and Scope Definition and Inventory Analysis”**, International Organization of Standards, 1998.

[37] ISO 14042, **“Life Cycle Assessment – Life Cycle Impact Assessment”**, International Organization of Standards, 2000.

[38] ISO 14043, **“Life Cycle Assessment – Life Cycle interpretation”**, International Organization of Standards, 2000.

[39] Curran, M. A. and Philippa, N., **“Summary of Global Life Cycle Inventory Data Resources”**, a report prepared for Task Force 1: Database Registry SETAC/UNEP Life Cycle Initiative, May 2006.

[40] National Renewable Energy Laboratory. **“U.S. Life Cycle Inventory Database”**, the site was accessed on June 15th 2007 on the following link: <http://www.nrel.gov/lci>

[41] National Renewable Energy Laboratory, **“U.S. Life Cycle Inventory Database”**, the site was accessed on June 15th 2007 on the following link:
<http://www.nrel.gov/lci/database/default.asp>

[42] Kendall, A., **“A Dynamic Life Cycle Assessment Tool for Comparing Bridge Deck Designs”**, a thesis submitted in partial fulfillment of the requirements for the degree of Master of Science (Natural Resource and Environment) in the University of Michigan, August 2004.

[43] **“Exhaust and Crankcase Emission Factors for NONROAD Engine Modeling-Compression-Ignition”**, report no. NR-009c, U.S. Environmental protection Agency, revised April 2004.

[44] **“NONROAD Model”**, U.S. Environmental Protection agency, the site was accessed on June 20th, 2007 on the following link:
<http://www.epa.gov/otaq/nonrdmdl.htm>

[45] National Renewable Energy Laboratory, **“U.S. Life Cycle Inventory Database, LCI Data for Steel Billet production”**, the site was accessed on June 15th 2007 on the following link:
[http://www.nrel.gov/lci/database/xl/SS Steel Billet Production.xls](http://www.nrel.gov/lci/database/xl/SS%20Steel%20Billet%20Production.xls)

[46] **“The Engineering Tool Box web site”**, the site was accessed on August 13th, 2007 at the following link:
http://www.engineeringtoolbox.com/gas-density-d_158.html

[47] **“Simetric.co.uk web site”**, the site was accessed on August 13th, 2007 at the following link:
http://www.simetric.co.uk/si_liquids.htm

[48] **“Energy Information Administration site (official energy statistics from the U.S. government), Petroleum Navigator”**, the site was accessed on July 27th, 2007 on the following link:

http://tonto.eia.doe.gov/dnav/pet/pet_pnp_wiup_dcu_nus_w.htm

[49] National Renewable Energy Laboratory, **“U.S. Life Cycle Inventory Database, LCI Data for Fuels and Energy Precombustion”**, the site was accessed on June 15th, 2007 on the following link:

http://www.nrel.gov/lci/database/xl/SS_FuelsandEnergyPrecombustion.xls

[50] National Renewable Energy Laboratory, **“U.S. Life Cycle Inventory Database, LCI Data for Electricity Generation”**, the site was accessed on June 15th, 2007 on the following link:

http://www.nrel.gov/lci/database/xl/SS_ElectricityGeneration.xls

[51] **“Energy Information Administration site (official energy statistics from the U.S. government)”**, the site was accessed on July 27, 2007 on the following link:

<http://www.eia.doe.gov/cneaf/electricity/epa/epat5p1.html>

[52] **“Energy Information Administration site (official energy statistics from the U.S. government)”**, the site was accessed on July 27, 2007 on the following link:

<http://www.eia.doe.gov/cneaf/electricity/epa/epates.html>

[53] National Renewable Energy Laboratory, **“U.S. Life Cycle Inventory Database, LCI Data for Portland cement production”**, the site was accessed on June 15th, 2007 on the following link:

http://www.nrel.gov/lci/database/xl/SS_Portland_Cement_Production.xls

[54] National Renewable Energy Laboratory, **“U.S. Life Cycle Inventory Database, LCI Data for Diesel Fueled Combination Truck transportation”**, the site was accessed on June 15th 2007 on the following link:

[http://www.nrel.gov/lci/database/xl/SS Diesel Fueled Combination Truck Transportation.xls](http://www.nrel.gov/lci/database/xl/SS%20Diesel%20Fueled%20Combination%20Truck%20Transportation.xls)

[55] National Renewable Energy Laboratory, **“U.S. Life Cycle Inventory Database, LCI Data for Diesel Fueled Single Unit Truck Transportation”**, the site was accessed on June 15th 2007 on the following link:

[http://www.nrel.gov/lci/database/xl/SS Diesel Fueled Single Unit Truck Transportation.xls](http://www.nrel.gov/lci/database/xl/SS%20Diesel%20Fueled%20Single%20Unit%20Truck%20Transportation.xls)

[56] **“Priority Substances Assessment Program, Environment Canada”**, the site was accessed on August 1st, 2007 on the following link:

<http://www.ec.gc.ca/substances/ese/eng/psap/psap.cfm>

[57] Schaltegger, S., Bennett, M. and Burritt, R., **“Sustainability Accounting and Reporting: Development, Linkages and Reflection. An Introduction”**, Springer Netherlands, 2006, pp 1-33.

[58] Prusinski, J. R., Marceau, M. L. and VanGeem, M.G., **“Life Cycle Inventory of Slag Cement Concrete”**, a paper presented at Eighth CANMET/ACI International Conference on Recent Advances in Concrete Technology, Montreal, Canada, May 2006.

Appendix (A)

Emissions per unit table

emissions /unit table	location	unit	fine agg. (1 kg)	coarse agg. (1 kg)	cement (1 kg)	sp. aea (1 kg)
output to nature	air	kg				
1,3Butadiene	air	kg			9.31218E-11	
Acenaphthene (C12H10)	air	kg	1.089E-10	1.089E-10	6.41973E-13	
Acenaphthylene (C12H8)	air	kg	1.228E-09	1.228E-09	3.14693E-13	
Acetaldehyde (CH3CHO)	air	kg	4.394E-08	4.394E-08	2.52564E-09	2.55E-09
Acetophenone (C8H8O)	air	kg	2.248E-11	2.248E-11	5.62791E-13	5.27E-11
Acid (organic)	air	kg				
Acrolein (CH2CHCHO)	air	kg	5.671E-09	5.671E-09	3.26918E-09	2.08E-11
Aldhydes (unspecified)	air	kg	2.502E-07	2.502E-07	2.25915E-07	4.2026E-06
Aluminium (Al)	air	kg	4.336E-11	4.336E-11		7.23E-11
Ammonia (NH3)	air	kg	2.456E-08	2.456E-08	4.87363E-06	1.83566E-05
Ammonia Chloride (NH3Cl)	air	kg			1.49971E-08	
Anthanthrene	air	kg				
Anthracene (C14H10)	air	kg	2.301E-10	2.301E-10	2.64342E-13	2.79E-11
Antimony(Sb)	air	kg	6.45E-11	6.45E-11	2.79271E-11	5.08E-08
Aromatic Hydrocarbons (unspecified)	air	kg	9.497E-14	9.497E-14		
Arsenic (As)	air	kg	2.648E-09	2.648E-09	6.991E-10	2.91E-08
Barium (Ba)	air	kg	2.528E-11	2.528E-11		3.34E-08
Benzene (C6H6)	air	kg	9.465E-08	9.465E-08	1.05899E-06	0.000177624
Benzo(a)anthracene	air	kg	6.094E-11	6.094E-11	1.00702E-13	
Benzo(a)pyrene (C20H12)	air	kg	5.637E-11	5.637E-11	4.78333E-14	
Benzo(b)fluoranthene	air	kg	9.912E-11	9.912E-11		
Benzo(e)pyrene	air	kg			4.12025E-14	
Benzo(g,h,i)perylene	air	kg	6.762E-11	6.762E-11	2.38735E-14	
Benzo(j)fluoranthene	air	kg	1.648E-13	1.648E-13	9.72622E-14	
Benzo(k)fluoranthene	air	kg	9.912E-11	9.912E-11		
Benzyl Chloride (C7H7Cl)	air	kg	1.049E-09	1.049E-09	2.62636E-11	2.73E-11
Beryllium (Be)	air	kg	3.026E-10	3.026E-10	1.02888E-10	1.85E-14

Biphenyl	air	kg	5.845E-11	5.845E-11	2.13991E-12	8.57E-17
Bromoform (CHBr3)	air	kg	1.681E-09	1.681E-09	1.46326E-12	
Butane (C4H10)	air	kg	1.732E-10	1.732E-10	1.89856E-10	4.86E-09
Cadmium (Cd)	air	kg	3.757E-11	3.757E-11		
Calcium (Ca)	air	kg	0.010520928	0.010520928	0.946391932	1.46185
Carbon Dioxide (CO2)	air	kg	1.948E-10	1.948E-10	4.87752E-12	3.49E-08
Carbon Disulfide (CS2)	air	kg	1.49188E-05	1.49188E-05	0.001211892	0.0110802
Carbon Monoxide (CO)	air	kg			3.0077E-11	
Carbon Tetrachloride	air	kg			6.16215E-13	
CFC12	air	kg	2.48E-09	2.48E-09		
Chlorides (Cl-)	air	kg	2.852E-14	2.852E-14	5.26925E-10	3.32E-09
Chlorine (Cl2)	air	kg	1.049E-11	1.049E-11	2.62636E-13	
Chloroacetophenone (2-C8H7ClO)	air	kg	3.297E-11	3.297E-11	8.25427E-13	6.4E-10
Chlorobenzene (C6H5Cl)	air	kg	8.842E-11	8.842E-11	2.21365E-12	8.07E-10
Chloroform (CHCl3, HC-20)	air	kg	4.414E-09	4.414E-09	5.90284E-10	7.79E-08
Chromium (Cr III, CrVI)	air	kg	7.224E-11	7.224E-11	1.25877E-13	
Chrysene (C18H12)	air	kg	1.963E-10	1.963E-10	4.42782E-10	5.94E-08
Cobalt (Co)	air	kg	2.128E-11	2.128E-11	1.48399E-10	1.79E-08
Copper (Cu)	air	kg				
Coronene	air	kg	7.943E-12	7.943E-12	1.98853E-13	1.04E-09
Cumene (C9H12)	air	kg	3.747E-09	3.747E-09	9.37985E-11	3.8E-10
Cyanide (CN-)	air	kg				
Di(2-ethylhexyl)phthalate (DEHP, C24H38O4)	air	kg	1.094E-10	1.094E-10	2.73892E-12	2.21E-11
Dibenzo(a,h)anthracene	air	kg	2.254E-12	2.254E-12		
Dichlorobenzene (1,4-C6H4Cl2)	air	kg	9.604E-13	9.604E-13		1.45E-11
Dimethyl Benzanthracene (7,12-C20H16)	air	kg	1.223E-14	1.223E-14		
Dimethyl Sulfate (C2H6O4S)	air	kg	7.193E-11	7.193E-11	1.80093E-12	1.1E-11
Dinitrotoluene (2,4-C7H6N2O4)	air	kg	4.196E-13	4.196E-13	1.05054E-14	1.4E-11
Dioxins (unspecified) (Teq)	air	kg	2.426E-14	2.426E-14	7.6118E-11	
Diphenyl ((C6H5)2)	air	kg	2.548E-12	2.548E-12		
Ethane (C2H6)	air	kg	3.844E-09	3.844E-09		
Ethyl Benzene(C6H5C2H5)	air	kg	2.998E-09	2.998E-09	1.25226E-07	1.4E-09
Ethyl Chloride (C2H5Cl)	air	kg	6.294E-11	6.294E-11	1.57582E-12	
Ethylene Dibromide (C2H4Br2)	air	kg	1.798E-12	1.798E-12	4.50233E-14	
Ethylene Dichloride (C2H4Cl2)	air	kg	5.994E-11	5.994E-11	1.50078E-12	2.27E-11

Fluoranthene	air	kg	6.791E-10	8.93727E-13	7.41E-12
Fluorene (C13H10)	air	kg	4.834E-10	1.14548E-12	7.41E-12
Fluorides (F-)	air	kg	3.067E-10	2.90926E-09	1.31E-09
Formaldehyde (CH2O)	air	kg	1.232E-07	1.25574E-08	0.00074036
Furan (C4H4O)	air	kg	1.128E-13		
Furans (unspecified)	air	kg		7.50056E-11	
Halogenated Hydrocarbons (unspecified)	air	kg	5.276E-19		0.00216
Halon 1301 (CF3Br)	air	kg	9.18E-16		
Hexane (C6H14)	air	kg	9.397E-09	2.5138E-12	
Hydrocarbons (NMHC)	air	kg	2.1636E-06		
Hydrocarbons (unspecified)	air	kg		1.11928E-05	
Hydrogen (H2)	air	kg			
Hydrogen Chloride (HCl)	air	kg	1.7983E-06	6.6522E-05	1.16063E-05
Hydrogen Fluoride (HF)	air	kg	2.248E-07	0.000000248	1.4507E-06
Hydrogen Sulfide (H2S)	air	kg	6.81E-09		0.000000748
Indeno (1,2,3-cd)pyrene	air	kg	2.712E-11	7.6785E-14	
Iron (Fe)	air	kg	8.382E-11		
Isophorone (C9H14O)	air	kg	8.692E-10	2.17613E-11	
Kerosene	air	kg		2.6939E-08	
Lead (Pb)	air	kg	2.62E-09	1.07408E-09	4.71E-08
Magnesium (Mg)	air	kg	1.648E-08	1.38465E-08	1.061E-07
Manganese (Mn)	air	kg	4.931E-09	1.99142E-09	6.92E-08
Mercaptan	air	kg		8.0077E-09	
Mercury (Hg)	air	kg	1.679E-10	6.26E-08	2.26E-09
Metals (unspecified)	air	kg	5.852E-13	2.85273E-08	
Methane (CH4)	air	kg	1.68091E-05	0.000881333	0.00771785
Methyl Bromide (CH3Br)	air	kg	2.398E-10	6.00311E-12	
Methyl Chloride (CH3Cl)	air	kg	7.943E-10	1.98853E-11	
Methyl Cholanthrene (3-C21H16)	air	kg	1.441E-15		
Methyl Chrysene (5-C19H15)	air	kg	3.297E-14	2.76929E-14	
Methyl Ethyl Ketone (MEK, C4H8O)	air	kg	5.845E-10	1.46326E-11	5.79E-09
Methyl Hydrazine (CH6N2)	air	kg	2.548E-10	6.3783E-12	
Methyl Methacrylate (CH2C(CH3)COOCH3)	air	kg			
Methyl Naphthalene (2-C11H10)	air	kg	2.997E-11	7.50388E-13	7.44E-10
	air	kg	1.921E-14		

Methyl Tert Butyl Ether (MTBE, C5H12O)	air	kg	5.245E-11	5.245E-11	1.31318E-12	4.45E-10
Methylene Chloride (CH2Cl2, HC130)	air	kg	4.346E-10	4.346E-10	1.616E-09	
Molybdenum (Mo)	air	kg	1.539E-11	1.539E-11		9.61E-09
Naphthalene (C10H8)	air	kg	4.659E-09	4.659E-09	1.42945E-10	8.12E-10
Naphthalene	air	kg			1.6364E-11	
Nickel (Ni)	air	kg	4.314E-09	4.314E-09	4.86105E-09	8.844E-07
Nitrogen Oxides (NOx)	air	kg	5.66773E-05	5.66773E-05	0.002643558	0.00369992
Nitrous Oxide (N2O)	air	kg	1.0713E-06	1.0713E-06	3.75813E-07	2.53916E-05
Organic Matter (unspecified)	air	kg	3.847E-07	3.847E-07	7.64487E-09	0.000888311
Particulates (PM10)	air	kg	1.2649E-06	1.2649E-06	0.000300137	0.00000188
Particulates (PM2.5)	air	kg			9.11107E-08	
Particulates (unspecified)	air	kg	2.081E-09	2.081E-09	0.002624346	
Penanthrene (C14H10)	air	kg	0.000000493	0.000000493		0.000694763
Pentane (C5H12)	air	kg	1.342E-09	1.342E-09		2.45E-11
Perchloroethylene	air	kg			7.14496E-11	
Perylene	air	kg				
Phenanthrene	air	kg			3.39868E-12	
Phenol (C6H5OH)	air	kg	2.398E-11	2.398E-11		1.64E-09
Phenols	air	kg			8.42561E-10	
Phosphorus (P)	air	kg	9.306E-11	9.306E-11		9.95E-13
Polyaromatic hydrocarbons (total)	air	kg			4.27627E-10	
Polycyclic Aromatic Hydrocarbons (PAH, unspecified)	air	kg	1.055E-16	1.055E-16		5.91E-11
Propane (C3H8)	air	kg	3.654E-10	3.654E-10		
Propionaldehyde (CH3CH2CHO)	air	kg	2.727E-08	2.727E-08	1.42574E-11	2.3E-10
Propylene	air	kg			6.14707E-09	
Propylene Oxide	air	kg				
Pyrene (C16H10)	air	kg	8.723E-10	8.723E-10	4.15394E-13	
Radionuclides (unspecified)	air	curie	1.65E-09	1.65E-09	3.32246E-06	
Selenium (Se)	air	kg	1.954E-09	1.954E-09	2.04508E-09	6.25E-14
Silicon (Si)	air	kg	3.757E-11	3.757E-11		
Sodium (Na)	air	kg	2.226E-10	2.226E-10		
Styrene (C6H5CHCH2)	air	kg	3.037E-09	3.037E-09	9.37985E-13	6.89E-09
Sulfur Dioxide	air	kg			0.001968479	
Sulfur Oxides (SOx as SO2)	air	kg	3.72285E-05	3.72285E-05		0.0049722
Tetrachloroethylene (C2Cl4)	air	kg	6.44E-11	6.44E-11		3.69E-10

TNMOC (unspecified)	air	kg				1.45142E-07	
Toluene (C6H5CH3)	air	kg	5.028E-09	5.028E-09		1.61964E-06	7.47E-08
Trichloroethane (1, 1, 1-CH3CCl3)	air	kg	2.997E-11	2.997E-11		1.26967E-12	
Trichloroethylene	air	kg					
Vanadium (V)	air	kg	8.069E-10	8.069E-10			3.163E-07
Vinyl Acetate (C4H6O2)	air	kg	1.139E-11	1.139E-11		2.85148E-13	3.03E-09
VOC (unspecified)	air	kg				6.73826E-05	1.1893E-06
Xylene (C6H4(CH3)2)	air	kg	6.917E-09	6.917E-09			8.02E-09
Xylenes	air	kg				9.45383E-07	
Zinc (Zn)	air	kg	2.311E-10	2.311E-10		9.89324E-11	0.000000281
1-Methylfluorene	water	kg				7.69902E-12	
2,4 Dimethylphenol	water	kg				1.89488E-09	
2-Hexanone	water	kg				4.41712E-10	
2-Methyl Naphthalene	water	kg				1.07163E-09	
4-Methyl 2-Pentanone	water	kg				2.84301E-10	
Acetone	water	kg				6.76481E-10	
Acid (benzoic)	water	kg				6.86255E-08	
Acid (H+) (unspecified)	water	kg	5.031E-13	5.031E-13		5.87773E-08	
Acid (hexanoic)	water	kg				1.42116E-08	
Alkylated Benzenes	water	kg				1.43776E-09	
Alkylated Fluorenes	water	kg				8.33237E-11	
Alkylated Naphthalenes	water	kg				2.35605E-11	
Alkylated Phenanthrenes	water	kg				9.76898E-12	
Aluminum (Al3+)	water	kg	2.561E-10	2.561E-10		3.62377E-06	2.868E-13
Antimony	water	kg				1.64052E-09	
AOX (Adsorbable Organic Halogenes)	water	kg	6.753E-16	6.753E-16			
Aromatic Hydrocarbons (unspecified)	water	kg	1.583E-13	1.583E-13			
Arsenic	water	kg				1.63812E-08	
Barium (Ba++)	water	kg	5.065E-13	5.065E-13		3.77875E-05	6.56E-12
Benzene	water	kg				1.13486E-07	
Beryllium	water	kg				7.85766E-10	
BOD	water	kg	3.391E-07	3.391E-07		9.83565E-06	6.25466E-05
Boron	water	kg				2.1232E-07	
Bromide	water	kg				1.44965E-05	
Cadmium (Cd++)	water	kg	5.276E-16	5.276E-16		2.53178E-09	2.28E-13
Calcium	water	kg				0.000217396	
Chlorides (Cl-) (unspecified)	water	kg	1.19725E-05	1.19725E-05		0.003171177	0.00147933

Chlorides (methyl chloride)	water	kg				2.72283E-12		
Chromium (Cr III, Cr VI)	water	kg	1.544E-13			1.544E-13	7.43438E-08	1.36E-12
Cobalt	water	kg					1.49875E-09	
COD	water	kg	2.8694E-06			2.8694E-06	1.50529E-05	0.000327786
Copper (Cu+, Cu++)	water	kg	1.055E-14			1.055E-14	1.54493E-08	5.25E-12
Cresols	water	kg					3.95174E-09	
Cyanide (CN-)	water	kg	7.386E-16			7.386E-16	4.88231E-12	8.56E-12
Cymene	water	kg					6.76012E-12	
Dibenzofuran	water	kg					1.2863E-11	
Dibenzothiophene	water	kg					1.04219E-11	
Dissolved Solids (unspecified)	water	kg	8.665E-08			8.665E-08	0.003014393	0.000018731
Ethylbenzene	water	kg					6.38378E-09	
Fluorines/Fluorides (F-)	water	kg	7.629E-09			7.629E-09	1.94842E-07	5.056E-08
Halogenated Matters (organic)	water	kg	2.11E-16			2.11E-116		
Hardness	water	kg					0.00066961	
Hydrocarbons (unspecified)	water	kg	7.708E-10			7.708E-10	1.35936E-08	9.31E-08
Inorganic Dissolved Matters (unspecified)	water	kg						
Iron (Fe++, Fe3+)	water	kg	1.527E-11			1.527E-11	8.26244E-06	1.01E-10
Lead (Pb++, Pb4+)	water	kg	2.11E-15			2.11E-15	2.72219E-08	5.66E-13
Lithium	water	kg					5.15462E-05	
Magnesium	water	kg					4.25004E-05	
Manganese	water	kg					1.08095E-06	
Mercury (Hg+, Hg++)	water	kg	2.427E-18			2.427E-18	3.28586E-11	1.31E-13
Metals (unspecified)	water	kg	2.045E-08			2.045E-08	0.00074503	2.4682E-06
Methyl Ethyl Ketone (MEK)	water	kg					5.44565E-12	
Molybdenum	water	kg					1.55511E-09	
Naphthalene	water	kg					1.22975E-09	
Nickel (Ni++, Ni3+)	water	kg	1.055E-15			1.055E-15	1.38024E-08	6.81E-12
Nitrates (NO3-)	water	kg	1.899E-09			1.899E-09	2.99386E-08	1.137E-08
Nitrogen (ammonia)	water	kg					1.04757E-08	
Nitrogenous Matter (unspecified, as N)	water	kg	2.849E-14			2.849E-14	5.89737E-06	
Oils (unspecified)	water	kg	1.933E-07			1.933E-07	8.89583E-06	2.20024E-05
Organic Carbons (unspecified)	water	kg					2.42681E-07	
Organic Dissolved Matters (unspecified)	water	kg						
Pentamethyl Benzene	water	kg	1.324E-12			1.324E-12	1.37789E-05	0
	water	kg					5.07009E-12	

Phenanthrene	water	kg				1.17555E-11		7.255E-07
Phenol (C6H5CH)	water	kg		6.521E-09				
Phenolic Compounds	water	kg				5.34843E-08		
Phosphates (PO4 3-, HPO4-, H2PO4, H3PO4, as P)	water	kg		1.054E-12	1.054E-12	5.51156E-09		2.281E-08
Polycyclic Aromatic Hydrocarbons (PAH, unspecified)	water	kg		2.532E-15	2.532E-15			3.76E-13
Radionuclides (unspecified)	water	curie		1.53E-11	1.53E-11	4.67995E-11		
Salts (unspecified)	water	kg		2.917E-09	2.917E-09			
Selenium	water	kg				4.52996E-09		
Silver	water	kg				1.41855E-07		
Sodium (Na+)	water	kg		1.54163E-05	1.54163E-05	0.000689178		0.00190489
Strontium	water	kg				3.68793E-06		
Sulfate (SO4-)	water	kg		1.761E-09	1.761E-09	0.000640112		1.323E-08
Sulfide (S-)	water	kg		2.827E-13	2.827E-13	6.71347E-08		
Sulfur	water	kg				1.79231E-07		
Sulfuric Acid	water	kg						
Surfactants	water	kg				6.42036E-08		
Suspended Solids (unspecified)	water	kg		1.5405E-06	1.5405E-06	0.000336322		0.000211864
TDS	water	kg						
Thallium	water	kg				3.46051E-10		
Tin	water	kg				9.70285E-09		
Titanium	water	kg				2.52051E-08		
TOC (Total Organic Carbon)	water	kg		1.583E-12	1.583E-12			
Toluene (C6H5CH3)	water	kg		2.321E-14	2.321E-14	1.07219E-07		2.3E-11
Total Alkalinity	water	kg				5.41303E-06		
Total Biphenyls	water	kg				9.30926E-11		
Total Dibenzo-thiophenes	water	kg				2.87323E-13		
Vanadium	water	kg				1.83698E-09		
Water, chemically polluted	water	kg		1.9011E-06	1.9011E-06			0.000185509
Xylenes	water	kg				5.69755E-08		
Yttrium	water	kg				4.55891E-10		
Zinc (Zn++)	water	kg		4.233E-14	4.233E-14	1.03214E-07		7.15E-11
Non-Allocated by products	solid waste	kg						
Recovered Matter:Aluminum Scrab	solid waste	kg		3.271E-13	3.271E-13			

Recovered Matter:Ash	solid waste	kg	1.515E-07	1.515E-07	1.515E-07		
Recovered Matters (total)	solid waste	kg	1.515E-07	1.515E-07	1.515E-07		
Waste (hazardous)	solid waste	kg	1.105E-09	1.105E-09	1.105E-09	0.000000205	
Waste (municipal and industrial)	solid waste	kg	1.799E-09	1.799E-09	1.799E-09		
Waste (unspecified)	solid waste	kg	7.466E-07	7.466E-07	7.466E-07	0.000057184	
waste (unspecified, to incineration)	solid waste	kg	2.914E-11	2.914E-11	2.914E-11		
Waste:Bauxite Residues (red mud)	solid waste	kg	2.182E-11	2.182E-11	2.182E-11		
Waste:FGD sludge	solid waste	kg	4.756E-08	4.756E-08	4.756E-08		
Waste:Mineral (inert)	solid waste	kg	4.683E-12	4.683E-12	4.683E-12		
Waste:Mining+Tailing	solid waste	kg					
Waste:Non Toxic Chemicals (unspecified)	solid waste	kg	1.097E-12	1.097E-12	1.097E-12		
Waste:Slags and Ash (unspecified)	solid waste	kg	1.47402E-05	1.47402E-05	1.47402E-05		
Wastes (total)	solid waste	kg	0.000015804	0.000015804	0.000015804	0.07755923	0.000057389

Emissions per unit table (cont'd)

emissions /unit table		location	unit	steel (1kg)	plastic fibers (1 kg)	electricity (1 kWh)	single unit truck (1 TKM)
output to nature		air	kg	1.28287E-09		1.69833E-10	1.62217E-05
1,3Butadiene		air	kg	1.89186E-11		1.3266E-12	6.46943E-06
Acenaphthene (C12H10)		air	kg				

Acenaphthylene (C12H8)	air	kg	9.27382E-12		6.50292E-13	1.38412E-07
Acetaldehyde (CH3CHO)	air	kg	5.18587E-08		5.01052E-09	0.02124598
Acetophenone (C8H8O)	air	kg	2.64178E-12		9.63977E-13	9.11403E-05
Acid (organic)	air	kg				0.000140053
Acrolein (CH2CHCHO)	air	kg	1.06458E-07		6.85507E-09	0.000689031
Aldhydes (unspecified)	air	kg	4.98882E-05	0.000005	5.59008E-07	1.13004E-09
Aluminum (Al)	air	kg				
Ammonia (NH3)	air	kg	2.39221E-05		3.06464E-07	2.54153E-13
Ammonia Chloride (NH3Cl)	air	kg	8.93358E-08		9.97672E-08	2.1045E-06
Anthanthrene	air	kg				7.63027E-09
Anthracene (C14H10)	air	kg	7.79001E-12		5.46245E-13	1.05195E-06
Antimony(Sb)	air	kg	2.62965E-09		5.79344E-11	1.03732E-09
Aromatic Hydrocarbons (unspecified)	air	kg				
Arsenic (As)	air	kg	3.42532E-08		1.43467E-09	0.00022784
Barium (Ba)	air	kg				
Benzene (C6H6)	air	kg	7.14965E-05		4.08084E-06	1.86331E-09
Benzo(a)anthracene	air	kg	2.96762E-12		2.08093E-13	6.0352E-10
Benzo(a)pyrene (C20H12)	air	kg	1.40962E-12		9.88443E-14	1.64906E-06
Benzo(b)fluoranthene	air	kg				
Benzo(e)pyrene	air	kg				3.26741E-08
Benzo(g,h,i)perylene	air	kg	1.00157E-12		7.02315E-14	1.35977E-10
Benzo(j)fluoranthene	air	kg	4.08048E-12		2.86128E-13	1.87625E-07
Benzo(k)fluoranthene	air	kg				
Benzyl Chloride (C7H7Cl)	air	kg	1.23283E-10		4.49856E-11	2.85536E-11
Beryllium (Be)	air	kg	2.80148E-09		1.73852E-10	7.83105E-10
Biphenyl	air	kg	6.3062E-11		4.42198E-12	3.72399E-11
Bromoform (CHBr3)	air	kg	6.86862E-12		2.50634E-12	9.88309E-11
Butane (C4H10)	air	kg				
Cadmium (Cd)	air	kg	9.59296E-09		3.89936E-10	1.21885E-09
Calcium (Ca)	air	kg				
Carbon Dioxide (CO2)	air	kg	2.706789536	3.4	0.66013574	0.162914275
Carbon Disulfide (CS2)	air	kg	2.28954E-11		8.35447E-12	9.10297E-12
Carbon Monoxide (CO)	air	kg	0.039304776	0.0008	0.000241894	0.000233908

Carbon Tetrachloride	air	kg	1.0019E-09			6.34581E-11	1.37613E-08
CFC12	air	kg	1.24704E-10			1.52366E-12	2.403E-09
Chlorides (Cl-)	air	kg					
Chlorine (Cl2)	air	kg	3.01125E-08			1.11134E-09	1.77544E-09
Chloroacetophenone (2-C8H7ClO)	air	kg	1.23283E-12			4.49856E-13	0.00016335
Chlorobenzene (C6H5Cl)	air	kg	3.87461E-12			1.41383E-12	1.44609E-10
Chloroform (CHCl3, HC-20)	air	kg	1.0391E-11			3.79164E-12	1.57066E-08
Chromium (Cr III, CrVI)	air	kg	3.90139E-08			1.23889E-09	6.07867E-12
Chrysene (C18H12)	air	kg	3.70953E-12			2.60117E-13	3.4797E-09
Cobalt (Co)	air	kg	2.88069E-08			1.08358E-09	3.93254E-07
Copper (Cu)	air	kg	9.29063E-10			2.26808E-10	2.20664E-07
Coronene	air	kg					4.68177E-13
Cumene (C9H12)	air	kg	9.33428E-13			3.40605E-13	4.88241E-14
Cyanide (CN-)	air	kg	4.40296E-10			1.60663E-10	2.3804E-11
Di(2-ethylhexyl)phalate (DEHP, C24H38O4)	air	kg	1.28567E-11			4.69136E-12	1.95553E-10
Dibenzo(a,h)anthracene	air	kg					
Dichlorobenzene (1,4-C6H4Cl2)	air	kg					
Dimethyl Benzanthracene (7,12-C20H16)	air	kg					
Dimethyl Sulfate (C2H6O4S)	air	kg	8.45369E-12			3.08473E-12	4.68177E-15
Dinitrotoluene (2,4-C7H6N2O4)	air	kg	4.93132E-14			1.79942E-14	4.18792E-06
Dioxins (unspecified) (Teg)	air	kg	3.68351E-11			2.35687E-12	1.47141E-14
Diphenyl ((C6H5)2)	air	kg					
Ethane (C2H6)	air	kg					
Ethyl Benzene(C6H5C2H5)	air	kg	8.51324E-06			4.84926E-07	2.80906E-14
Ethyl Chloride (C2H5Cl)	air	kg	7.39698E-12			2.69914E-12	1.87271E-16
Ethylene Dibromide (C2H4Br2)	air	kg	2.11342E-13			7.71182E-14	2.5682E-08
Ethylene Dichloride (C2H4Cl2)	air	kg	7.04474E-12			2.57061E-12	8.02588E-16
Fluoranthene	air	kg	2.63376E-11			1.84683E-12	2.67529E-14
Fluorene (C13H10)	air	kg	3.37567E-11			2.36706E-12	4.48112E-14
Fluorides (F-)	air	kg	1.53256E-08			1.10898E-08	3.87918E-13
Formaldehyde (CH2O)	air	kg	2.52528E-06			3.28817E-08	0.00014897
Furan (C4H4O)	air	kg					

Furans (unspecified)	air	kg	1.68253E-13			1.15693E-14	3.54477E-13
Halogenated Hydrocarbons (unspecified)	air	kg					
Halon 1301 (CF3Br)	air	kg					
Hexane (C6H14)	air	kg	1.17999E-11			4.30577E-12	1.137E-13
Hydrocarbons (NMHC)	air	kg	7.056E-10	0.021			
Hydrocarbons (unspecified)	air	kg	0.002201343			2.90327E-05	2.34088E-14
Hydrogen (H2)	air	kg		0.000001			
Hydrogen Chloride (HCl)	air	kg	6.53596E-05	0.00006		3.3973E-06	2.60841E-13
Hydrogen Fluoride (HF)	air	kg	7.89367E-06	0.000001		3.8745E-07	1.33765E-14
Hydrogen Sulfide (H2S)	air	kg					
Indeno (1,2,3-cd)pyrene	air	kg	2.26281E-12			1.58671E-13	3.07921E-10
Iron (Fe)	air	kg					
Isophorone (C9H14O)	air	kg	1.02149E-10			3.72738E-11	5.6468E-10
Kerosene	air	kg	2.45585E-07			1.7921E-07	1.57127E-09
Lead (Pb)	air	kg	3.79808E-08			2.48886E-09	
Magnesium (Mg)	air	kg	4.08048E-07			2.86128E-08	1.67206E-14
Manganese (Mn)	air	kg	1.05246E-07			4.17477E-09	3.32191E-07
Mercaptan	air	kg	3.79468E-08			1.30586E-08	4.87738E-12
Mercury (Hg)	air	kg	1.12882E-08			4.47574E-10	5.08306E-15
Metals (unspecified)	air	kg	1.00002E-06	0.000001		6.0167E-08	1.93925E-07
Methane (CH4)	air	kg	0.018460233			0.001650561	0.00000357
Methyl Bromide (CH3Br)	air	kg	2.8179E-11			1.02824E-11	2.60841E-14
Methyl Chloride (CH3Cl)	air	kg	9.33428E-11			3.40605E-11	3.94606E-14
Methyl Cholanthrene (3-C21H16)	air	kg					
Methyl Chrysene (5-C19H15)	air	kg	8.16096E-13			5.72257E-14	0.000101822
Methyl Ethyl Ketone (MEK, C4H8O)	air	kg	6.86862E-11			2.50634E-11	8.69471E-14
Methyl Hydrazine (CH6N2)	air	kg	2.99401E-11			1.09251E-11	3.21035E-14
Methyl Methacrylate (CH2C(CH3)COOCH3)	air	kg					
Methyl Naphthalene (2-C11H10)	air	kg	3.52237E-12			1.2853E-12	3.54477E-15
Methyl Tert Butyl Ether (MTBE, C5H12O)	air	kg					
Methylene Chloride (CH2Cl2, HC130)	air	kg	6.16415E-12			2.24928E-12	1.67206E-12
Molybdenum (Mo)	air	kg	4.23258E-08			3.05177E-09	6.73704E-11

Naphthalene (C10H8)	air	kg	8.5085E-09			3.53306E-10	1.51351E-09
Naphthalene	air	kg	4.82238E-10			3.38152E-11	1.62633E-11
Nickel (Ni)	air	kg	4.19576E-07			1.23916E-08	3.49614E-11
Nitrogen Oxides (NOx)	air	kg	0.006486213	0.057		0.001223788	0.001054918
Nitrous Oxide (N2O)	air	kg	1.50515E-05			7.81795E-07	5.36012E-06
Organic Matter (unspecified)	air	kg	4.03811E-06	0.000005		1.68267E-08	2.12674E-12
Particulates (PM10)	air	kg	0.000173989			6.87916E-06	2.04E-05
Particulates (PM2.5)	air	kg					
Particulates (unspecified)	air	kg	0.001836784	0.002		0.000416	3.12756E-13
Penanthrene (C14H10)	air	kg					
Pentane (C5H12)	air	kg					
Perchloroethylene	air	kg	1.97227E-09			1.42266E-10	
Perylene	air	kg					2.62715E-13
Phenanthrene	air	kg	1.00157E-10			7.02315E-12	1.00082E-13
Phenol (C6H5OH)	air	kg	9.76815E-09				
Phenols	air	kg	2.04426E-08			1.51955E-09	4.75389E-14
Phosphorus (P)	air	kg					
Polyaromatic hydrocarbons (total)	air	kg	6.3753E-09			7.89013E-10	
Polycyclic Aromatic Hydrocarbons (PAH, unspecified)	air	kg					
Propane (C3H8)	air	kg					
Propionaldehyde (CH3CH2CHO)	air	kg	6.6925E-11			2.44208E-11	1.45308E-08
Propylene	air	kg	8.48156E-08			1.12158E-08	1.37613E-13
Propylene Oxide	air	kg					3.37776E-14
Pyrene (C16H10)	air	kg	1.22414E-11			8.58385E-13	1.25102E-13
Radionuclides (unspecified)	air	curie	2.01156E-05			2.2094E-05	2.31596E-07
Selenium (Se)	air	kg	7.75006E-08			4.04595E-09	8.88227E-13
Silicon (Si)	air	kg					
Sodium (Na)	air	kg					
Styrene (C6H5CHCH2)	air	kg	4.40296E-12			1.60663E-12	1.13843E-12
Sulfur Dioxide	air	kg	0.01982949			0.003682464	7.63125E-14
Sulfur Oxides (SOx as SO2)	air	kg	0.006213893	0.014		4.76571E-05	3.26E-05
Tetrachloroethylene (C2Cl4)	air	kg	3.1752E-09				
TNMO (unspecified)	air	kg	4.12867E-06			2.97106E-07	

Toluene (C6H5CH3)	air	kg	0.000110058		6.27004E-06	3.37776E-12
Trichloroethane (1, 1, 1-CH3CCl3)	air	kg	3.26176E-09		2.56929E-12	4.12838E-13
Trichloroethylene	air	kg				2.75225E-14
Vanadium (V)	air	kg				
Vinyl Acetate (C4H6O2)	air	kg	1.3385E-12		4.88415E-13	1.27952E-12
VOC (unspecified)	air	kg	0.001748381		4.62997E-05	7.29E-05
Xylene (C6H4(CH3)2)	air	kg				
Xylenes	air	kg	6.42133E-05		3.65877E-06	5.77195E-12
Zinc (Zn)	air	kg	6.19375E-10		1.51205E-10	1.0505E-07
1-Methylfluorene	water	kg	8.23967E-10		2.66837E-11	2.20686E-11
2,4 Dimethylphenol	water	kg	2.02795E-07		6.56739E-09	5.43153E-09
2-Hexanone	water	kg	4.72731E-08		1.53091E-09	1.26613E-09
2-Methyl Naphthalene	water	kg	1.14661E-07		3.71438E-09	3.06989E-09
4-Methyl 2-Pentanone	water	kg	3.04265E-08		9.85345E-10	8.14925E-10
Acetone	water	kg	7.23986E-08		2.34459E-09	1.93908E-09
Acid (benzoic)	water	kg	7.34446E-06		2.37846E-07	1.96709E-07
Acid (H+) (unspecified)	water	kg	3.99606E-06	0.00007	2.27615E-07	1.20531E-08
Acid (hexanoic)	water	kg	1.52096E-06		4.92554E-08	4.07365E-08
Alkylated Benzenes	water	kg	2.27551E-07		4.21558E-09	9.14428E-09
Alkylated Fluorenes	water	kg	1.31874E-08		2.44308E-10	5.29944E-10
Alkylated Naphthalenes	water	kg	3.72886E-09		6.90802E-11	1.49846E-10
Alkylated Phenanthrenes	water	kg	1.54611E-09		2.8643E-11	6.21314E-11
Aluminum (Al3+)	water	kg	0.000417379		8.56465E-06	1.66935E-05
Ammonia (NH3)	water	kg	0.000122322	0.000005	3.67713E-06	3.53603E-06
Ammonium (NH4+)	water	kg			8.00034E-08	8.31825E-10
Antimony	water	kg	2.59498E-07		4.81155E-09	1.04241E-08
AOX (Adsorbable Organic Halogenes)	water	kg				
Aromatic Hydrocarbons (unspecified)	water	kg				
Arsenic	water	kg	1.8235E-06		5.67556E-08	5.31202E-08
Barium (Ba++)	water	kg	0.005810937		0.000112561	0.000228769
Benzene	water	kg	-3.9672E-05		3.93326E-07	3.25298E-07
Beryllium	water	kg	9.44012E-08		2.61599E-09	2.955E-09
BOD	water	kg	0.000650857	0.008	3.55477E-05	4.89855E-06

Boron	water	kg	3.18297E-05		7.35872E-07	6.08599E-07
Bromide	water	kg	0.001551323		5.02441E-05	4.15445E-05
Cadmium (Cd++)	water	kg	3.8671E-07		9.19351E-09	7.84567E-09
Calcium	water	kg	0.023260247		0.000753542	0.000622767
Chlorides (Cl-) (unspecified)	water	kg	0.268254142	0.00012	0.008469752	0.007003249
Chlorides (methyl chloride)	water	kg	2.91403E-10		9.43693E-12	7.80476E-12
Chromium (Cr III, Cr VI)	water	kg	1.02262E-05		2.17851E-07	4.73669E-07
Cobalt	water	kg	1.604E-07		5.19445E-09	4.29604E-09
COD	water	kg	0.003184016	0.006	5.65494E-05	1.44939E-05
Copper (Cu+, Cu++)	water	kg	1.62445E-06		5.99568E-08	5.4633E-08
Cresols	water	kg	4.2467E-07		1.3678E-08	1.14463E-08
Cyanide (CN-)	water	kg	0.000632836		1.69214E-11	1.39947E-11
Cymene	water	kg	7.23484E-10		2.34296E-11	1.93773E-11
Dibenzofuran	water	kg	1.37663E-09		4.45813E-11	3.68708E-11
Dibenzothiophene	water	kg	1.11537E-09		3.61206E-11	2.98734E-11
Dissolved Solids (unspecified)	water	kg	0.322577872		0.010447891	0.008637669
Ethylbenzene	water	kg	6.83207E-07		2.21253E-08	1.82986E-08
Fluorines/Fluorides (F-)	water	kg	0.000188813		1.29601E-06	1.37353E-08
Halogenated Matters (organic)	water	kg				
Hardness	water	kg	0.071663247		0.002320774	0.001919384
Hydrocarbons (unspecified)	water	kg	6.98558E-06	0.0001	4.71529E-08	3.87068E-08
Inorganic Dissolved Matters (unspecified)	water	kg		0.0004		
Iron (Fe++, Fe3+)	water	kg	0.001143527		2.52055E-05	3.33176E-05
Lead (Pb++, Pb4+)	water	kg	0.000138104		9.03791E-08	1.11451E-07
Lithium	water	kg	0.003507219		0.000199583	1.07635E-05
Magnesium	water	kg	0.004547768		0.000147308	0.000121775
Manganese	water	kg	1.97328E-05		2.01437E-06	2.11185E-07
Mercury (Hg+, Hg++)	water	kg	4.58123E-09		1.11694E-10	1.83025E-10
Metals (unspecified)	water	kg	0.050652585	0.0003	0.002885133	0.000152779
Methyl Ethyl Ketone (MEK)	water	kg	5.82806E-10		1.88739E-11	1.56095E-11
Molybdenum	water	kg	1.66431E-07		5.38979E-09	4.4576E-09
Naphthalene	water	kg			4.2609E-09	3.533E-09
Nickel (Ni++, Ni3+)	water	kg	3.13506E-06		4.58875E-08	5.23232E-08

Nitrates (NO3-)	water	kg	2.10313E-07	0.000005	1.99165E-07	2.07079E-09
Nitrogen (ammonia)	water	kg	6.24022E-08		6.96887E-08	7.24579E-10
Nitrogenous Matter (unspecified, as N)	water	kg	0.000690165	0.00001		
Oils (unspecified)	water	kg	0.017993192	0.0001	4.69713E-06	4.44999E-06
Organic Carbons (unspecified)	water	kg	1.64987E-05		9.39783E-07	4.97652E-08
Organic Dissolved Matters (unspecified)	water	kg	9.1728E-06	0.00002		
Pentamethyl Benzene	water	kg	5.42613E-10		1.75722E-11	1.4533E-11
Phenanthrene	water	kg	1.55257E-09		3.76752E-11	5.37722E-11
Phenol (C6H5CH)	water	kg	4.74075E-09	0.000001		
Phenolic Compounds	water	kg	1.00032E-05		1.07796E-07	9.77358E-08
Phosphates (PO4 3-, HPO4-, H2PO4, H3PO4, as P)	water	kg		0.000005		
Polycyclic Aromatic Hydrocarbons (PAH, unspecified)	water	kg				
Radionuclides (unspecified)	water	curie	2.79341E-10		3.11315E-10	3.25244E-12
Salts (unspecified)	water	kg				
Selenium	water	kg	7.55304E-08		2.89466E-08	2.31288E-09
Silver	water	kg	1.51915E-05		4.91545E-07	4.07289E-07
Sodium (Na+)	water	kg	0.073744471		0.002388802	0.001974725
Strontium	water	kg	0.000394691		1.27819E-05	1.05712E-05
Sulfate (SO4-)	water	kg	0.000780255	0.00001	0.000147071	1.54521E-05
Sulfide (S-)	water	kg	0.001863427		2.46289E-09	9.32993E-09
Sulfur	water	kg	1.91817E-05		6.21189E-07	5.13752E-07
Sulfuric Acid	water	kg	2.27115E-06			
Surfactants	water	kg	6.56402E-06		2.2572E-07	1.63092E-07
Suspended Solids (unspecified)	water	kg	0.048607881	0.0003	0.000281246	0.000513659
TDS	water	kg				
Thallium	water	kg	5.47039E-08		1.01531E-09	2.19649E-09
Tin	water	kg	1.25339E-06		3.13894E-08	4.2468E-08
Titanium	water	kg	3.98585E-06		7.39367E-08	1.60081E-07
TOC (Total Organic Carbon)	water	kg				
Toluene (C6H5CH3)	water	kg	1.14748E-05		3.71605E-07	3.07334E-07
Total Alkalinity	water	kg	0.000575924		1.87961E-05	1.52848E-05
Total Biphenyls	water	kg	1.47335E-08		2.72951E-10	5.92075E-10

Total Dibenzo-thiophenes	water	kg	4.54739E-11		8.42442E-13	1.82739E-12
Vanadium	water	kg	1.96598E-07		6.3667E-09	5.26555E-09
Water, chemically polluted	water	kg	0.00262395			
Xylenes	water	kg	6.09158E-06		1.97532E-07	1.62902E-07
Yttrium	water	kg	4.87905E-08		1.58005E-09	1.30677E-09
Zinc (Zn++)	water	kg			2.31123E-07	3.85493E-07
Non-Allocated by products	solid waste	kg				
Recovered Matter:Aluminum Scrab	solid waste	kg				
Recovered Matter:Ash	solid waste	kg				
Recovered Matters (total)	solid waste	kg				
Waste (hazardous)	solid waste	kg		0.000000007		
Waste (municipal and industrial)	solid waste	kg		0.00000031		
Waste (unspecified)	solid waste	kg				
waste (unspecified, to incineration)	solid waste	kg				
Waste:Bauxite Residues (red mud)	solid waste	kg				
Waste:FGD sludge	solid waste	kg				
Waste:Mineral (inert)	solid waste	kg		0.000022		
waste:Mining+Tailing	solid waste	kg				
Waste:Non Toxic Chemicals (unspecified)	solid waste	kg		0.0000002		
waste:Slags and Ash (unspecified)	solid waste	kg	0.304996	0.000007		
Wastes (total)	solid waste	kg	0.295886366	0.00003417	0.062863742	0.002523061

Emissions per unit table (cont'd)

emissions /unit table	location	unit	combination truck (1 TKM)	<11 (1 hp.hr)	≥11 - <25 (1 hp.hr)	≥25 - <50 (1 hp.hr)
output to nature	air	kg				
1,3Butadiene	air	kg	1.11085E-11	1.60573E-05	1.60573E-05	1.60573E-05
Acenaphthene (C12H10)	air	kg	2.97744E-13	4.14546E-06	4.14546E-06	4.14546E-06
Acenaphthylene (C12H8)	air	kg	1.45953E-13	0.000161694	0.000161694	0.000161694
Acetaldehyde (CH3CHO)	air	kg	5.27354E-10	0.00010079	0.00010079	0.00010079
Acetophenone (C8H8O)	air	kg	4.68177E-15	6.40384E-06	6.40384E-06	6.40384E-06
Acid (organic)	air	kg		1.37009E-07	1.37009E-07	1.37009E-07
Acrolein (CH2CHCHO)	air	kg	1.62386E-09	9.02163E-05	9.02163E-05	9.02163E-05
Aldehydes (unspecified)	air	kg	9.821E-07	0.000138633	0.000138633	0.000138633
Aluminum (Al)	air	kg				
Ammonia (NH3)	air	kg	4.9091E-07	0.000682046	0.000682046	0.000682046
Ammonia Chloride (NH3Cl)	air	kg	4.84081E-10	0.02103058	0.02103058	0.02103058
Anthanthrene	air	kg		0.00014746	0.00014746	0.00014746
Anthracene (C14H10)	air	kg	1.226E-13	1.43835E-08	1.43835E-08	1.43835E-08
Antimony(Sb)	air	kg	1.3325E-11	1.11859E-09	1.11859E-09	1.11859E-09
Aromatic Hydrocarbons (unspecified)	air	kg				
Arsenic (As)	air	kg	3.65449E-10	2.51576E-13	2.51576E-13	2.51576E-13
Barium (Ba)	air	kg				
Benzene (C6H6)	air	kg	1.02977E-07	2.08316E-06	2.08316E-06	2.08316E-06
Benzo(a)anthracene	air	kg	4.67049E-14	7.55291E-09	7.55291E-09	7.55291E-09
Benzo(a)pyrene (C20H12)	air	kg	2.21848E-14	1.04128E-06	1.04128E-06	1.04128E-06
Benzo(b)fluoranthene	air	kg				
Benzo(e)pyrene	air	kg		0.00022553	0.00022553	0.00022553
Benzo(g,h,i)perylene	air	kg	1.57629E-14	1.84442E-09	1.84442E-09	1.84442E-09
Benzo(j)fluoranthene	air	kg	6.42192E-14	1.0268E-09	1.0268E-09	1.0268E-09
Benzo(k)fluoranthene	air	kg				
Benzyl Chloride (C7H7Cl)	air	kg	2.18482E-13	5.97401E-10	5.97401E-10	5.97401E-10
Beryllium (Be)	air	kg	1.73786E-11	1.63234E-06	1.63234E-06	1.63234E-06
Biphenyl	air	kg	9.92479E-13	1.85723E-07	1.85723E-07	1.85723E-07
Bromoform (CHBr3)	air	kg	1.21726E-14	3.23429E-08	3.23429E-08	3.23429E-08

Butane (C4H10)	air	kg				9.12583E-11	1.34598E-10	1.34598E-10	1.34598E-10
Cadmium (Cd)	air	kg							
Calcium (Ca)	air	kg							
Carbon Dioxide (CO2)	air	kg				0.089860396	0.61444144	0.61444144	0.61444144
Carbon Disulfide (CS2)	air	kg				4.05753E-14	7.75166E-10	7.75166E-10	7.75166E-10
Carbon Monoxide (CO)	air	kg				0.000448511	0.006	0.0049	0.0041
Carbon Tetrachloride	air	kg				1.63153E-11	1.93571E-10	1.93571E-10	1.93571E-10
CFC12	air	kg				2.69358E-12	9.78289E-11	9.78289E-11	9.78289E-11
Chlorides (Cl-)	air	kg							
Chlorine (Cl2)	air	kg				2.81643E-10	5.58955E-10	5.58955E-10	5.58955E-10
Chloroacetophenone (2-C8H7ClO)	air	kg				2.18482E-15	1.20649E-09	1.20649E-09	1.20649E-09
Chlorobenzene (C6H5Cl)	air	kg				6.86659E-15	9.01068E-12	9.01068E-12	9.01068E-12
Chloroform (CHCl3, HC-20)	air	kg				1.84149E-14	8.70465E-10	8.70465E-10	8.70465E-10
Chromium (Cr III, CrVI)	air	kg				3.09638E-10	1.60004E-08	1.60004E-08	1.60004E-08
Chrysene (C18H12)	air	kg				5.83811E-14	2.37864E-09	2.37864E-09	2.37864E-09
Cobalt (Co)	air	kg				5.68796E-10	1.43143E-10	1.43143E-10	1.43143E-10
Copper (Cu)	air	kg				4.24805E-12	1.55474E-08	1.55474E-08	1.55474E-08
Coronene	air	kg					1.75744E-09	1.75744E-09	1.75744E-09
Cumene (C9H12)	air	kg				1.65422E-15	6.00712E-12	6.00712E-12	6.00712E-12
Cyanide (CN-)	air	kg				7.80294E-13	9.93064E-15	9.93064E-15	9.93064E-15
Di(2-ethylhexyl)phalate (DEHP, C24H38O4)	air	kg				2.27846E-14	3.44442E-09	3.44442E-09	3.44442E-09
Dibenzo(a,h)anthracene	air	kg							
Dichlorobenzene (1,4-C6H4Cl2)	air	kg							
Dimethyl Benzanthrane (7,12-C20H16)	air	kg							
Dimethyl Sulfate (C2H6O4S)	air	kg				1.49817E-14			
Dinitrotoluene (2,4-C7H6N2O4)	air	kg				8.7393E-17	2.18427E-07	2.18427E-07	2.18427E-07
Dioxins (unspecified) (Teq)	air	kg				5.97111E-13	4.6343E-13	4.6343E-13	4.6343E-13
Diphenyl ((C6H5)2)	air	kg							
Ethane (C2H6)	air	kg							
Ethyl Benzene(C6H5C2H5)	air	kg				1.19849E-08			
Ethyl Chloride (C2H5Cl)	air	kg				1.31089E-14	2.35626E-11	2.35626E-11	2.35626E-11
Ethylene Dibromide (C2H4Br2)	air	kg				3.74541E-16	4.6343E-15	4.6343E-15	4.6343E-15

Ethylene Dichloride (C2H4Cl2)	air	kg	1.24847E-14	1.45649E-14	1.45649E-14	1.45649E-14
Fluoranthene	air	kg	4.14506E-13	1.85372E-16	1.85372E-16	1.85372E-16
Fluorene (C13H10)	air	kg	5.31268E-13	2.78058E-14	2.78058E-14	2.78058E-14
Fluorides (F-)	air	kg	5.38283E-11	2.54216E-08	2.54216E-08	2.54216E-08
Formaldehyde (CH2O)	air	kg	6.78104E-09	7.94452E-16	7.94452E-16	7.94452E-16
Furan (C4H4O)	air	kg				
Furans (unspecified)	air	kg	2.65875E-15			
Halogenated Hydrocarbons (unspecified)	air	kg				
Halon 1301 (CF3Br)	air	kg				
Hexane (C6H14)	air	kg	2.09119E-14			
Hydrocarbons (NMHC)	air	kg		0.0067	0.00635	0.0054
Hydrocarbons (unspecified)	air	kg	4.7517E-05	1.05927E-13	1.05927E-13	1.05927E-13
Hydrogen (H2)	air	kg				
Hydrogen Chloride (HCl)	air	kg	7.6956E-07			
Hydrogen Fluoride (HF)	air	kg	8.75584E-08	2.58197E-13	2.58197E-13	2.58197E-13
Hydrogen Sulfide (H2S)	air	kg				
Indeno (1,2,3-cd)pyrene	air	kg	3.56125E-14			
Iron (Fe)	air	kg				
Isophorone (C9H14O)	air	kg	1.81028E-13			
Kerosene	air	kg	8.69545E-10	1.32409E-14	1.32409E-14	1.32409E-14
Lead (Pb)	air	kg	4.10378E-10	2.31715E-14	2.31715E-14	2.31715E-14
Magnesium (Mg)	air	kg	6.42192E-09	3.04799E-10	3.04799E-10	3.04799E-10
Manganese (Mn)	air	kg	1.1214E-09			
Mercaptan	air	kg	6.34558E-11			
Mercury (Hg)	air	kg	6.74844E-11	1.65511E-14	1.65511E-14	1.65511E-14
Metals (unspecified)	air	kg	1.52479E-08	3.28823E-07	3.28823E-07	3.28823E-07
Methane (CH4)	air	kg	0.000107615	4.82793E-12	4.82793E-12	4.82793E-12
Methyl Bromide (CH3Br)	air	kg	4.99388E-14	5.03153E-15	5.03153E-15	5.03153E-15
Methyl Chloride (CH3Cl)	air	kg	1.65422E-13			
Methyl Cholanthrene (3-C21H16)	air	kg				
Methyl Chrysene (5-C19H15)	air	kg	1.28438E-14			
Methyl Ethyl Ketone (MEK, C4H8O)	air	kg	1.21726E-13	2.58197E-14	2.58197E-14	2.58197E-14

Methyl Hydrazine (CH6N2)	air	kg	5.306E-14	3.90605E-14	3.90605E-14	3.90605E-14
Methyl Methacrylate (CH2C(CH3)COOCH3)	air	kg	6.24235E-15	8.60656E-14	8.60656E-14	8.60656E-14
Methyl Naphthalene (2-C11H10)	air	kg				
Methyl Tert Butyl Ether (MTBE, C5H12O)	air	kg	1.09241E-14			
Methylene Chloride (CH2Cl2, HC130)	air	kg	7.06304E-10	3.50883E-15	3.50883E-15	3.50883E-15
Molybdenum (Mo)	air	kg				
Naphthalene (C10H8)	air	kg	1.51286E-10			
Naphthalene	air	kg	7.58955E-12	6.66874E-11	6.66874E-11	6.66874E-11
Nickel (Ni)	air	kg	7.32976E-09			
Nitrogen Oxides (NOx)	air	kg	0.000608512	1.49816E-09	1.49816E-09	1.49816E-09
Nitrous Oxide (N2O)	air	kg	2.17352E-06	3.4607E-11	3.4607E-11	3.4607E-11
Organic Matter (unspecified)	air	kg	3.56079E-09	7.42864E-10	7.42864E-10	7.42864E-10
Particulates (PM10)	air	kg	1.95436E-06	0.00055	0.0005	0.001275
Particulates (PM2.5)	air	kg				
Particulates (unspecified)	air	kg	7.57014E-06			
Penanthrene (C14H10)	air	kg				
Pentane (C5H12)	air	kg				
Perchloroethylene	air	kg	3.14395E-11			
Perylene	air	kg		6.31554E-13	6.31554E-13	6.31554E-13
Phenanthrene	air	kg	1.57629E-12	3.09585E-13	3.09585E-13	3.09585E-13
Phenol (C6H5OH)	air	kg				
Phenols	air	kg	3.50221E-10			
Phosphorus (P)	air	kg				
Polyaromatic hydrocarbons (total)	air	kg	5.99977E-11			
Polycyclic Aromatic Hydrocarbons (PAH, unspecified)	air	kg				
Propane (C3H8)	air	kg				
Propionaldehyde (CH3CH2CHO)	air	kg	1.18605E-13			
Propylene	air	kg	7.33257E-10	4.70569E-14	4.70569E-14	4.70569E-14
Propylene Oxide	air	kg				
Pyrene (C16H10)	air	kg	1.92658E-13	1.36217E-13	1.36217E-13	1.36217E-13
Radionuclides (unspecified)	air	curie	1.08078E-07	2.29248E-07	2.29248E-07	2.29248E-07

Selenium (Se)	air	kg	8.2854E-10	1.23834E-13	1.23834E-13	1.23834E-13
Silicon (Si)	air	kg				
Sodium (Na)	air	kg				
Styrene (C6H5CHCH2)	air	kg	7.80294E-15			
Sulfur Dioxide	air	kg	4.25321E-05	8.79222E-13	8.79222E-13	8.79222E-13
Sulfur Oxides (SOx as SO2)	air	kg	6.5358E-05	1.12689E-12	1.12689E-12	1.12689E-12
Tetrachloroethylene (C2Cl4)	air	kg				
TNMOC (unspecified)	air	kg	6.45925E-08			
Toluene (C6H5CH3)	air	kg	1.55023E-07	1.60984E-11	1.60984E-11	1.60984E-11
Trichloroethane (1, 1, 1-CH3CCl3)	air	kg	2.27611E-12			
Trichloroethylene	air	kg		3.34352E-12	3.34352E-12	3.34352E-12
Vanadium (V)	air	kg				
Vinyl Acetate (C4H6O2)	air	kg	2.37209E-15			
VOC (unspecified)	air	kg	2.93191E-05	2.72435E-14	2.72435E-14	2.72435E-14
Xylene (C6H4(CH3)2)	air	kg				
Xylenes	air	kg	9.04982E-08			
Zinc (Zn)	air	kg	2.83203E-12	5.63955E-15	5.63955E-15	5.63955E-15
1-Methylfluorene	water	kg	1.02987E-11	1.19309E-08	1.19309E-08	1.19309E-08
2,4 Dimethylphenol	water	kg	2.53471E-09	1.94715E-07	1.94715E-07	1.94715E-07
2-Hexanone	water	kg	5.90862E-10	4.03235E-08	4.03235E-08	4.03235E-08
2-Methyl Naphthalene	water	kg	1.43262E-09	0.00015123	0.00015123	0.00015123
4-Methyl 2-Pentanone	water	kg	3.80298E-10	0.008550097	0.008550097	0.008550097
Acetone	water	kg	9.04904E-10	0.000508452	0.000508452	0.000508452
Acid (benzoic)	water	kg	9.17977E-08	4.84889E-06	4.84889E-06	4.84889E-06
Acid (H+) (unspecified)	water	kg	5.62479E-09	1.4347E-05	1.4347E-05	1.4347E-05
Acid (hexanoic)	water	kg	1.90103E-08	9.67449E-08	9.67449E-08	9.67449E-08
Alkylated Benzenes	water	kg	4.26733E-09	5.08543E-07	5.08543E-07	5.08543E-07
Alkylated Fluorenes	water	kg	2.47307E-10	1.52954E-05	1.52954E-05	1.52954E-05
Alkylated Naphthalenes	water	kg	6.99282E-11	9.23534E-09	9.23534E-09	9.23534E-09
Alkylated Phenanthrenes	water	kg	2.89946E-11	4.40487E-06	4.40487E-06	4.40487E-06
Aluminium (Al3+)	water	kg	7.79028E-06			
Ammonia (NH3)	water	kg	1.65015E-06	3.83143E-08	3.83143E-08	3.83143E-08
Ammonium (NH4+)	water	kg	3.88185E-10	3.50018E-06	3.50018E-06	3.50018E-06

Antimony	water	kg	4.86458E-09	8.23392E-10	8.23392E-10	8.23392E-10
AOX (Adsorbable Organic Halogenes)	water	kg				
Aromatic Hydrocarbons (unspecified)	water	kg				
Arsenic	water	kg	2.47894E-08	1.65242E-05	1.65242E-05	1.65242E-05
Barium (Ba++)	water	kg	0.000106759	1.03184E-08	1.03184E-08	1.03184E-08
Benzene	water	kg	1.51806E-07	5.25817E-08	5.25817E-08	5.25817E-08
Beryllium	water	kg	1.379E-09	0.00022645	0.00022645	0.00022645
BOD	water	kg	2.28599E-06	2.92504E-09	2.92504E-09	2.92504E-09
Boron	water	kg	2.84013E-07	7.76613E-09	7.76613E-09	7.76613E-09
Bromide	water	kg	1.93874E-05	4.68867E-07	4.68867E-07	4.68867E-07
Cadmium (Cd++)	water	kg	3.66131E-09	4.25249E-09	4.25249E-09	4.25249E-09
Calcium	water	kg	0.000290625	5.40791E-08	5.40791E-08	5.40791E-08
Chlorides (Cl-) (unspecified)	water	kg	0.003268183	3.29798E-05	3.29798E-05	3.29798E-05
Chlorides (methyl chloride)	water	kg	3.64222E-12	1.10321E-07	1.10321E-07	1.10321E-07
Chromium (Cr III, Cr VI)	water	kg	2.21046E-07	1.06544E-05	1.06544E-05	1.06544E-05
Cobalt	water	kg	2.00482E-09	0.00012054	0.00012054	0.00012054
COD	water	kg	6.76382E-06	2.09044E-07	2.09044E-07	2.09044E-07
Copper (Cu+, Cu++)	water	kg	2.54954E-08	1.81169E-10	1.81169E-10	1.81169E-10
Cresols	water	kg	5.34162E-09	4.4124E-09	4.4124E-09	4.4124E-09
Cyanide (CN-)	water	kg	6.53088E-12	5.17928E-08	5.17928E-08	5.17928E-08
Cymene	water	kg	9.04276E-12	2.28943E-09	2.28943E-09	2.28943E-09
Dibenzofuran	water	kg	1.72064E-11	4.03159E-07	4.03159E-07	4.03159E-07
Dibenzothiophene	water	kg	1.39409E-11	0.001954704	0.001954704	0.001954704
Dissolved Solids (unspecified)	water	kg	0.004030912	1.0464E-05	1.0464E-05	1.0464E-05
Ethylbenzene	water	kg	8.53934E-09	2.17423E-09	2.17423E-09	2.17423E-09
Fluorines/Fluorides (F-)	water	kg	6.40981E-09	4.20374E-08	4.20374E-08	4.20374E-08
Halogenated Matters (organic)	water	kg				
Hardness	water	kg	0.000895713	1.58458E-07	1.58458E-07	1.58458E-07
Hydrocarbons (unspecified)	water	kg	1.80632E-08	5.21216E-09	5.21216E-09	5.21216E-09
Inorganic Dissolved Matters (unspecified)	water	kg				
Iron (Fe++, Fe3+)	water	kg	1.55482E-05	1.29353E-09	1.29353E-09	1.29353E-09
Lead (Pb++, Pb4+)	water	kg	5.20105E-08	3.81584E-07	3.81584E-07	3.81584E-07

Lithium	water	kg	5.02299E-06	0.006932248	0.006932248	0.006932248
Magnesium	water	kg	5.68282E-05	7.72563E-12	7.72563E-12	7.72563E-12
Manganese	water	kg	9.85531E-08	0.000616453	0.000616453	0.000616453
Mercury (Hg+, Hg++)	water	kg	8.54115E-11	1.35961E-08	1.35961E-08	1.35961E-08
Metals (unspecified)	water	kg	7.12969E-05	2.0498E-09	2.0498E-09	2.0498E-09
Methyl Ethyl Ketone (MEK)	water	kg	7.28445E-12	7.17233E-10	7.17233E-10	7.17233E-10
Molybdenum	water	kg	2.08021E-09	4.11233E-05	4.11233E-05	4.11233E-05
Naphthalene	water	kg	1.64873E-09	6.02429E-07	6.02429E-07	6.02429E-07
Nickel (Ni++, Ni3+)	water	kg	2.44175E-08	4.92606E-08	4.92606E-08	4.92606E-08
Nitrates (NO3-)	water	kg	9.6637E-10	1.38529E-11	1.38529E-11	1.38529E-11
Nitrogen (ammonia)	water	kg	3.38137E-10	0.001899925	0.001899925	0.001899925
Nitrogenous Matter (unspecified, as N)	water	kg				
Oils (unspecified)	water	kg	2.07666E-06	1.51298E-05	1.51298E-05	1.51298E-05
Organic Carbons (unspecified)	water	kg	2.32237E-08	1.61438E-07	1.61438E-07	1.61438E-07
Organic Dissolved Matters (unspecified)	water	kg				
Pentamethyl Benzene	water	kg	6.78207E-12	1.91942E-09	1.91942E-09	1.91942E-09
Phenanthrene	water	kg	2.50937E-11	9.05157E-09	9.05157E-09	9.05157E-09
Phenol (C6H5CH)	water	kg				
Phenolic Compounds	water	kg	4.561E-08	5.24571E-10	5.24571E-10	5.24571E-10
Phosphates (PO4 3-, HPO4-, H2PO4, H3PO4, as P)	water	kg				
Polycyclic Aromatic Hydrocarbons (PAH, unspecified)	water	kg				
Radionuclides (unspecified)	water	curie	1.5178E-12	3.21946E-12	3.21946E-12	3.21946E-12
Salts (unspecified)	water	kg				
Selenium	water	kg	1.07934E-09	6.15015E-11	6.15015E-11	6.15015E-11
Silver	water	kg	1.90068E-07	3.22E-07	3.22E-07	3.22E-07
Sodium (Na+)	water	kg	0.000921538	1.13303E-08	1.13303E-08	1.13303E-08
Strontium	water	kg	4.93321E-06	1.91809E-11	1.91809E-11	1.91809E-11
Sulfate (SO4-)	water	kg	7.21096E-06	3.6497E-11	3.6497E-11	3.6497E-11
Sulfide (S-)	water	kg	4.35397E-09	2.95705E-11	2.95705E-11	2.95705E-11
Sulfur	water	kg	2.39751E-07	5.37646E-09	5.37646E-09	5.37646E-09
Sulfuric Acid	water	kg		1.81131E-08	1.81131E-08	1.81131E-08
Surfactants	water	kg	7.61094E-08	1.2533E-09	1.2533E-09	1.2533E-09

Suspended Solids (unspecified)	water	kg	0.000239708	1.54513E-11	1.54513E-11	1.54513E-11
TDS	water	kg				
Thallium	water	kg	1.02503E-09	2.18449E-11	2.18449E-11	2.18449E-11
Tin	water	kg	1.98184E-08	3.03877E-09	3.03877E-09	3.03877E-09
Titanium	water	kg	7.47046E-08	8.06663E-10	8.06663E-10	8.06663E-10
TOC (Total Organic Carbon)	water	kg				
Toluene (C6H5CH3)	water	kg	1.43423E-07	3.49718E-09	3.49718E-09	3.49718E-09
Total Alkalinity	water	kg	7.13291E-06	1.43857E-11	1.43857E-11	1.43857E-11
Total Biphenyls	water	kg	2.76302E-10	5.3227E-11	5.3227E-11	5.3227E-11
Total Dibenzo-thiophenes	water	kg	8.52783E-13	3.04218E-07	3.04218E-07	3.04218E-07
Vanadium	water	kg	2.45726E-09	5.86073E-10	5.86073E-10	5.86073E-10
Water, chemically polluted	water	kg				
Xylenes	water	kg	7.60209E-08	1.80887E-12	1.80887E-12	1.80887E-12
Yttrium	water	kg	6.09828E-10	1.6125E-07	1.6125E-07	1.6125E-07
Zinc (Zn++)	water	kg	1.79897E-07	1.46032E-12	1.46032E-12	1.46032E-12
Non-Allocated by products	solid waste	kg				
Recovered Matter:Aluminum Scrab	solid waste	kg				
Recovered Matter:Ash	solid waste	kg				
Recovered Matters (total)	solid waste	kg				
Waste (hazardous)	solid waste	kg				
Waste (municipal and industrial)	solid waste	kg				
Waste (unspecified)	solid waste	kg				
waste (unspecified, to incineration)	solid waste	kg				
Waste:Bauxite Residues (red mud)	solid waste	kg				
Waste:FGD sludge	solid waste	kg				

Waste:Mineral (inert)	solid waste	kg					
waste:Mining+Tailing	solid waste	kg					
Waste:Non Toxic Chemicals (unspecified)	solid waste	kg					
waste:Slags and Ash (unspecified)	solid waste	kg					
Wastes (total)	solid waste	kg	0.001177428	0.002497481	0.002497481	0.002497481	0.002497481

Emissions per unit table (cont'd)

emissions /unit table	location	unit	≥50 - <75 (1 hp.hr)	≥75 - <100 (1 hp.hr)	≥100 - <175 (1 hp.hr)	≥175 - <300 (1 hp.hr)
output to nature	air	kg				
1,3Butadiene	air	kg	1.60573E-05	1.60573E-05	1.44907E-05	1.44907E-05
Acenaphthene (C12H10)	air	kg	4.14546E-06	4.14546E-06	3.74102E-06	3.74102E-06
Acenaphthylene (C12H8)	air	kg	0.000161694	0.000161694	0.000145919	0.000145919
Acetaldehyde (CH3CHO)	air	kg	0.00010079	0.00010079	9.09566E-05	9.09566E-05
Acetophenone (C8H8O)	air	kg	6.40384E-06	6.40384E-06	5.77907E-06	5.77907E-06
Acid (organic)	air	kg	1.37009E-07	1.37009E-07	1.23642E-07	1.23642E-07
Acrolein (CH2CHCHO)	air	kg	9.02163E-05	9.02163E-05	8.14147E-05	8.14147E-05
Aldhydes (unspecified)	air	kg	0.000138633	0.000138633	0.000125108	0.000125108
Aluminum (Al)	air	kg				
Ammonia (NH3)	air	kg	0.000682046	0.000682046	0.000615505	0.000615505
Ammonia Chloride (NH3Cl)	air	kg	0.02103058	0.02103058	0.018978816	0.018978816
Anthanthrene	air	kg	0.00014746	0.00014746	0.000133074	0.000133074
Anthracene (C14H10)	air	kg	1.43835E-08	1.43835E-08	1.29802E-08	1.29802E-08
Antimony(Sb)	air	kg	1.11859E-09	1.11859E-09	1.00946E-09	1.00946E-09
Aromatic Hydrocarbons (unspecified)	air	kg				
Arsenic (As)	air	kg	2.51576E-13	2.51576E-13	2.27032E-13	2.27032E-13
Barium (Ba)	air	kg				

Benzene (C6H6)	air	kg	2.08316E-06	2.08316E-06	1.87993E-06	1.87993E-06
Benzo(a)anthracene	air	kg	7.55291E-09	7.55291E-09	6.81604E-09	6.81604E-09
Benzo(a)pyrene (C20H12)	air	kg	1.04128E-06	1.04128E-06	9.39695E-07	9.39695E-07
Benzo(b)fluoranthene	air	kg				
Benzo(e)pyrene	air	kg	0.00022553	0.00022553	0.000203527	0.000203527
Benzo(g,h,i)perylene	air	kg	1.84442E-09	1.84442E-09	1.66448E-09	1.66448E-09
Benzo(j)fluoranthene	air	kg	1.0268E-09	1.0268E-09	9.26624E-10	9.26624E-10
Benzo(k)fluoranthene	air	kg				
Benzyl Chloride (C7H7Cl)	air	kg	5.97401E-10	5.97401E-10	5.39118E-10	5.39118E-10
Beryllium (Be)	air	kg	1.63234E-06	1.63234E-06	1.47309E-06	1.47309E-06
Biphenyl	air	kg	1.85723E-07	1.85723E-07	1.67604E-07	1.67604E-07
Bromoform (CHBr3)	air	kg	3.23429E-08	3.23429E-08	2.91875E-08	2.91875E-08
Butane (C4H10)	air	kg				
Cadmium (Cd)	air	kg	1.34598E-10	1.34598E-10	1.21467E-10	1.21467E-10
Calcium (Ca)	air	kg				
Carbon Dioxide (CO2)	air	kg	0.61444144	0.61399484	0.55404948	0.55312438
Carbon Disulfide (CS2)	air	kg	7.75166E-10	7.75166E-10	6.9954E-10	6.9954E-10
Carbon Monoxide (CO)	air	kg	0.0037	0.0037	0.0037	0.00456
Carbon Tetrachloride	air	kg	1.93571E-10	1.93571E-10	1.74686E-10	1.74686E-10
CFC12	air	kg	9.78289E-11	9.78289E-11	8.82846E-11	8.82846E-11
Chlorides (Cl-)	air	kg				
Chlorine (Cl2)	air	kg	5.58955E-10	5.58955E-10	5.04423E-10	5.04423E-10
Chloroacetophenone (2-C8H7ClO)	air	kg	1.20649E-09	1.20649E-09	1.08879E-09	1.08879E-09
Chlorobenzene (C6H5Cl)	air	kg	9.01068E-12	9.01068E-12	8.13159E-12	8.13159E-12
Chloroform (CHCl3, HC-20)	air	kg	8.70465E-10	8.70465E-10	7.85542E-10	7.85542E-10
Chromium (Cr III, CrVI)	air	kg	1.60004E-08	1.60004E-08	1.44394E-08	1.44394E-08
Chrysene (C18H12)	air	kg	2.37864E-09	2.37864E-09	2.14658E-09	2.14658E-09
Cobalt (Co)	air	kg	1.43143E-10	1.43143E-10	1.29178E-10	1.29178E-10
Copper (Cu)	air	kg	1.55474E-08	1.55474E-08	1.40306E-08	1.40306E-08
Coronene	air	kg	1.75744E-09	1.75744E-09	1.58599E-09	1.58599E-09
Cumene (C9H12)	air	kg	6.00712E-12	6.00712E-12	5.42106E-12	5.42106E-12
Cyanide (CN-)	air	kg	9.93064E-15	9.93064E-15	8.9618E-15	8.9618E-15
Di(2-ethylhexyl)phthalate (DEHP, C24H38O4)	air	kg	3.44442E-09	3.44442E-09	3.10838E-09	3.10838E-09
Dibenzo(a,h)anthracene	air	kg				
Dichlorobenzene (1,4-C6H4Cl2)	air	kg				

Dimethyl Benzanthrane (7,12-C20H16)	air	kg							
Dimethyl Sulfate (C2H6O4S)	air	kg							
Dinitrotoluene (2,4-C7H6N2O4)	air	kg	2.18427E-07	2.18427E-07	1.97117E-07	1.97117E-07	1.97117E-07	1.97117E-07	1.97117E-07
Dioxins (unspecified) (Teq)	air	kg	4.6343E-13	4.6343E-13	4.18217E-13	4.18217E-13	4.18217E-13	4.18217E-13	4.18217E-13
Diphenyl ((C6H5)2)	air	kg							
Ethane (C2H6)	air	kg							
Ethyl Benzene(C6H5C2H5)	air	kg							
Ethyl Chloride (C2H5Cl)	air	kg	2.35626E-11	2.35626E-11	2.12638E-11	2.12638E-11	2.12638E-11	2.12638E-11	2.12638E-11
Ethylene Dibromide (C2H4Br2)	air	kg	4.6343E-15	4.6343E-15	4.18217E-15	4.18217E-15	4.18217E-15	4.18217E-15	4.18217E-15
Ethylene Dichloride (C2H4Cl2)	air	kg	1.45649E-14	1.45649E-14	1.3144E-14	1.3144E-14	1.3144E-14	1.3144E-14	1.3144E-14
Fluoranthene	air	kg	1.85372E-16	1.85372E-16	1.67287E-16	1.67287E-16	1.67287E-16	1.67287E-16	1.67287E-16
Fluorene (C13H10)	air	kg	2.78058E-14	2.78058E-14	2.5093E-14	2.5093E-14	2.5093E-14	2.5093E-14	2.5093E-14
Fluorides (F-)	air	kg	2.54216E-08	2.54216E-08	2.29415E-08	2.29415E-08	2.29415E-08	2.29415E-08	2.29415E-08
Formaldehyde (CH2O)	air	kg	7.94452E-16	7.94452E-16	7.16944E-16	7.16944E-16	7.16944E-16	7.16944E-16	7.16944E-16
Furan (C4H4O)	air	kg							
Furans (unspecified)	air	kg							
Halogenated Hydrocarbons (unspecified)	air	kg							
Halon 1301 (CF3Br)	air	kg							
Hexane (C6H14)	air	kg							
Hydrocarbons (NMHC)	air	kg	0.0042	0.00455	0.00455	0.00455	0.00455	0.00395	0.00395
Hydrocarbons (unspecified)	air	kg	1.05927E-13	0.00014	0.00014	0.00014	0.00014	0.00043	0.00043
Hydrogen (H2)	air	kg							
Hydrogen Chloride (HCl)	air	kg							
Hydrogen Fluoride (HF)	air	kg	2.58197E-13	2.58197E-13	2.33007E-13	2.33007E-13	2.33007E-13	2.33007E-13	2.33007E-13
Hydrogen Sulfide (H2S)	air	kg							
Indeno (1,2,3-cd)pyrene	air	kg							
Iron (Fe)	air	kg							
Isophorone (C9H14O)	air	kg							
Kerosene	air	kg	1.32409E-14	1.32409E-14	1.19491E-14	1.19491E-14	1.19491E-14	1.19491E-14	1.19491E-14
Lead (Pb)	air	kg	2.31715E-14	2.31715E-14	2.09109E-14	2.09109E-14	2.09109E-14	2.09109E-14	2.09109E-14
Magnesium (Mg)	air	kg	3.04799E-10	3.04799E-10	2.75063E-10	2.75063E-10	2.75063E-10	2.75063E-10	2.75063E-10
Manganese (Mn)	air	kg							
Mercaptan	air	kg							
Mercury (Hg)	air	kg	1.65511E-14	1.65511E-14	1.49363E-14	1.49363E-14	1.49363E-14	1.49363E-14	1.49363E-14
Metals (unspecified)	air	kg	3.28823E-07	3.28823E-07	2.96743E-07	2.96743E-07	2.96743E-07	2.96743E-07	2.96743E-07

Methane (CH4)	air	kg	4.82793E-12	4.82793E-12	4.35691E-12	4.35691E-12
Methyl Bromide (CH3Br)	air	kg	5.03153E-15	5.03153E-15	4.54065E-15	4.54065E-15
Methyl Chloride (CH3Cl)	air	kg				
Methyl Chloranthrene (3-C21H16)	air	kg				
Methyl Chrysene (5-C19H15)	air	kg				
Methyl Ethyl Ketone (MEK, C4H8O)	air	kg	2.58197E-14	2.58197E-14	2.33007E-14	2.33007E-14
Methyl Hydrazine (CH6N2)	air	kg	3.90605E-14	3.90605E-14	3.52498E-14	3.52498E-14
Methyl Methacrylate (CH2C(CH3)COOCH3)	air	kg	8.60656E-14	8.60656E-14	7.76689E-14	7.76689E-14
Methyl Naphthalene (2-C11H10)	air	kg				
Methyl Tert Butyl Ether (MTBE, C5H12O)	air	kg				
Methylene Chloride (CH2Cl2, HC130)	air	kg	3.50883E-15	3.50883E-15	3.1665E-15	3.1665E-15
Molybdenum (Mo)	air	kg				
Naphthalene (C10H8)	air	kg				
Naphthylene	air	kg	6.66874E-11	6.66874E-11	6.01813E-11	6.01813E-11
Nickel (Ni)	air	kg				
Nitrogen Oxides (NOx)	air	kg	0.006900002	0.002500002	0.002500001	0.002500001
Nitrous Oxide (N2O)	air	kg	3.4607E-11	3.4607E-11	3.12307E-11	3.12307E-11
Organic Matter (unspecified)	air	kg	7.42864E-10	7.42864E-10	6.7039E-10	6.7039E-10
Particulates (PM10)	air	kg	0.00018	0.00011	8.00001E-05	0.00014
Particulates (PM2.5)	air	kg				
Particulates (unspecified)	air	kg				
Penanthrene (C14H10)	air	kg				
Pentane (C5H12)	air	kg				
Perchloroethylene	air	kg				
Perylene	air	kg	6.31554E-13	6.31554E-13	5.69939E-13	5.69939E-13
Phenanthrene	air	kg	3.09585E-13	3.09585E-13	2.79382E-13	2.79382E-13
Phenol (C6H5OH)	air	kg				
Phenols	air	kg				
Phosphorus (P)	air	kg				
Polycyclic Aromatic Hydrocarbons (total)	air	kg				
Polycyclic Aromatic Hydrocarbons (PAH, unspecified)	air	kg				
Propane (C3H8)	air	kg				
Propionaldehyde (CH3CH2CHO)	air	kg				
Propylene	air	kg	4.70569E-14	4.70569E-14	4.2466E-14	4.2466E-14

AOX (Adsorbable Organic Halogenes)	water	kg							
Aromatic Hydrocarbons (unspecified)	water	kg							
Arsenic	water	kg						1.49121E-05	1.49121E-05
Barium (Ba++)	water	kg		1.65242E-05				1.03184E-08	9.31175E-09
Benzene	water	kg		5.25817E-08				5.25817E-08	4.74518E-08
Beryllium	water	kg		0.00022645				0.00022645	0.000204357
BOD	water	kg		2.92504E-09				2.92504E-09	2.63967E-09
Boron	water	kg		7.76613E-09				7.76613E-09	7.00846E-09
Bromide	water	kg		4.68867E-07				4.68867E-07	4.23124E-07
Cadmium (Cd++)	water	kg		4.25249E-09				4.25249E-09	3.83761E-09
Calcium	water	kg		5.40791E-08				5.40791E-08	4.88031E-08
Chlorides (Cl-) (unspecified)	water	kg		3.29798E-05				3.29798E-05	2.97623E-05
Chlorides (methyl chloride)	water	kg		1.10321E-07				1.10321E-07	9.95582E-08
Chromium (Cr III, Cr VI)	water	kg		1.06544E-05				1.06544E-05	9.61497E-06
Cobalt	water	kg		0.00012054				0.00012054	0.00010878
COD	water	kg		2.09044E-07				2.09044E-07	1.8865E-07
Copper (Cu+, Cu++)	water	kg		1.81169E-10				1.81169E-10	1.63494E-10
Cresols	water	kg		4.4124E-09				4.4124E-09	3.98192E-09
Cyanide (CN-)	water	kg		5.17928E-08				5.17928E-08	4.67398E-08
Cymene	water	kg		2.28943E-09				2.28943E-09	2.06607E-09
Dibenzofuran	water	kg		4.03159E-07				4.03159E-07	3.63827E-07
Dibenzothiophene	water	kg		0.001954704				0.001954704	0.001764001
Dissolved Solids (unspecified)	water	kg		1.0464E-05				1.0464E-05	9.44312E-06
Ethylbenzene	water	kg		2.17423E-09				2.17423E-09	1.96211E-09
Fluorines/Fluorides (F-)	water	kg		4.20374E-08				4.20374E-08	3.79362E-08
Halogenated Matters (organic)	water	kg							
Hardness	water	kg		1.58458E-07				1.58458E-07	1.42999E-07
Hydrocarbons (unspecified)	water	kg		5.21216E-09				5.21216E-09	4.70366E-09
Inorganic Dissolved Matters (unspecified)	water	kg							
Iron (Fe++, Fe3+)	water	kg		1.29353E-09				1.29353E-09	1.16733E-09
Lead (Pb++, Pb4+)	water	kg		3.81584E-07				3.81584E-07	3.44357E-07
Lithium	water	kg		0.006932248				0.006932248	0.006255931
Magnesium	water	kg		7.72563E-12				7.72563E-12	6.97191E-12
Manganese	water	kg		0.000616453				0.000616453	0.000556312
Mercury (Hg+, Hg++)	water	kg		1.35961E-08				1.35961E-08	1.22696E-08
Metals (unspecified)	water	kg		2.0498E-09				2.0498E-09	1.84982E-09

Methyl Ethyl Ketone (MEK)	water	kg	7.17233E-10	7.17233E-10	6.47259E-10	6.47259E-10
Molybdenum	water	kg	4.11233E-05	4.11233E-05	3.71113E-05	3.71113E-05
Naphthalene	water	kg	6.02429E-07	6.02429E-07	5.43656E-07	5.43656E-07
Nickel (Ni++, Ni3+)	water	kg	4.92606E-08	4.92606E-08	4.44547E-08	4.44547E-08
Nitrates (NO3-)	water	kg	1.38529E-11	1.38529E-11	1.25014E-11	1.25014E-11
Nitrogen (ammonia)	water	kg	0.001899925	0.001899925	0.001714566	0.001714566
Nitrogenous Matter (unspecified, as N)	water	kg				
Oils (unspecified)	water	kg	1.51298E-05	1.51298E-05	1.36538E-05	1.36538E-05
Organic Carbons (unspecified)	water	kg	1.61438E-07	1.61438E-07	1.45688E-07	1.45688E-07
Organic Dissolved Matters (unspecified)	water	kg				
Pentamethyl Benzene	water	kg	1.91942E-09	1.91942E-09	1.73216E-09	1.73216E-09
Phenanthrene	water	kg	9.05157E-09	9.05157E-09	8.16849E-09	8.16849E-09
Phenol (C6H5CH)	water	kg				
Phenolic Compounds	water	kg	5.24571E-10	5.24571E-10	4.73394E-10	4.73394E-10
Phosphates (PO4 3-, HPO4-, H2PO4, H3PO4, as P)	water	kg				
Polycyclic Aromatic Hydrocarbons (PAH, unspecified)	water	kg				
Radionuclides (unspecified)	water	curie	3.21946E-12	3.21946E-12	2.90537E-12	2.90537E-12
Salts (unspecified)	water	kg				
Selenium	water	kg	6.15015E-11	6.15015E-11	5.55013E-11	5.55013E-11
Silver	water	kg	3.22E-07	3.22E-07	2.90586E-07	2.90586E-07
Sodium (Na+)	water	kg	1.13303E-08	1.13303E-08	1.02249E-08	1.02249E-08
Strontium	water	kg	1.91809E-11	1.91809E-11	1.73096E-11	1.73096E-11
Sulfate (SO4-)	water	kg	3.6497E-11	3.6497E-11	3.29363E-11	3.29363E-11
Sulfide (S-)	water	kg	2.95705E-11	2.95705E-11	2.66856E-11	2.66856E-11
Sulfur	water	kg	5.37646E-09	5.37646E-09	4.85193E-09	4.85193E-09
Sulfuric Acid	water	kg	1.81131E-08	1.81131E-08	1.63459E-08	1.63459E-08
Surfactants	water	kg	1.2533E-09	1.2533E-09	1.13102E-09	1.13102E-09
Suspended Solids (unspecified)	water	kg	1.54513E-11	1.54513E-11	1.39438E-11	1.39438E-11
TDS	water	kg				
Thallium	water	kg	2.18449E-11	2.18449E-11	1.97137E-11	1.97137E-11
Tin	water	kg	3.03877E-09	3.03877E-09	2.7423E-09	2.7423E-09
Titanium	water	kg	8.06663E-10	8.06663E-10	7.27964E-10	7.27964E-10
TOC (Total Organic Carbon)	water	kg				
Toluene (C6H5CH3)	water	kg	3.49718E-09	3.49718E-09	3.15599E-09	3.15599E-09

Total Alkalinity	water	kg	1.43857E-11	1.43857E-11	1.29822E-11	1.29822E-11
Total Biphenyls	water	kg	5.3227E-11	5.3227E-11	4.80341E-11	4.80341E-11
Total Dibenzo-thiophenes	water	kg	3.04218E-07	3.04218E-07	2.74538E-07	2.74538E-07
Vanadium	water	kg	5.86073E-10	5.86073E-10	5.28895E-10	5.28895E-10
Water, chemically polluted	water	kg				
Xylenes	water	kg	1.80887E-12	1.80887E-12	1.63239E-12	1.63239E-12
Yttrium	water	kg	1.6125E-07	1.6125E-07	1.45519E-07	1.45519E-07
Zinc (Zn++)	water	kg	1.46032E-12	1.46032E-12	1.31785E-12	1.31785E-12
Non-Allocated by products	solid	kg				
Recovered Matter:Aluminum Scrab	waste	kg				
Recovered Matter:Ash	solid	kg				
Recovered Matters (total)	waste	kg				
Waste (hazardous)	solid	kg				
Waste (municipal and industrial)	waste	kg				
Waste (unspecified)	solid	kg				
waste (unspecified, to incineration)	waste	kg				
Waste:Bauxite Residues (red mud)	solid	kg				
Waste:FGD sludge	waste	kg				
Waste:Mineral (inert)	solid	kg				
waste:Mining+Tailing	waste	kg				
Waste:Non Toxic Chemicals (unspecified)	solid	kg				
waste:Slags and Ash (unspecified)	solid	kg				
Wastes (total)	solid	kg	0.002497481	0.002497481	0.002253824	0.002253824

Emissions per unit table (cont'd)

emissions /unit table							
output to nature	location	unit	≥300 - <600 (1 hp.hr)	≥600 - ≤750 (1 hp.hr)	>750 (1 hp.hr)		
1,3Butadiene	air	kg	1.44907E-05	1.44907E-05	1.44907E-05		
Acenaphthene (C12H10)	air	kg	3.74102E-06	3.74102E-06	3.74102E-06		
Acenaphthylene (C12H8)	air	kg	0.000145919	0.000145919	0.000145919		
Acetaldehyde (CH3CHO)	air	kg	9.09566E-05	9.09566E-05	9.09566E-05		
Acetophenone (C8H8O)	air	kg	5.77907E-06	5.77907E-06	5.77907E-06		
Acid (organic)	air	kg	1.23642E-07	1.23642E-07	1.23642E-07		
Acrolein (CH2CHCHO)	air	kg	8.14147E-05	8.14147E-05	8.14147E-05		
Aldhydes (unspecified)	air	kg	0.000125108	0.000125108	0.000125108		
Aluminum (Al)	air	kg					
Ammonia (NH3)	air	kg	0.000615505	0.000615505	0.000615505		
Ammonia Chloride (NH3Cl)	air	kg	0.018978816	0.018978816	0.018978816		
Anthanthrene	air	kg	0.000133074	0.000133074	0.000133074		
Anthracene (C14H10)	air	kg	1.29802E-08	1.29802E-08	1.29802E-08		
Antimony(Sb)	air	kg	1.00946E-09	1.00946E-09	1.00946E-09		
Aromatic Hydrocarbons (unspecified)	air	kg					
Arsenic (As)	air	kg	2.27032E-13	2.27032E-13	2.27032E-13		
Barium (Ba)	air	kg					
Benzene (C6H6)	air	kg	1.87993E-06	1.87993E-06	1.87993E-06		
Benzo(a)anthracene	air	kg	6.81604E-09	6.81604E-09	6.81604E-09		
Benzo(a)pyrene (C20H12)	air	kg	9.39695E-07	9.39695E-07	9.39695E-07		
Benzo(b)fluoranthene	air	kg					
Benzo(e)pyrene	air	kg	0.000203527	0.000203527	0.000203527		
Benzo(g,h,i)perylene	air	kg	1.66448E-09	1.66448E-09	1.66448E-09		
Benzo(i)fluoranthene	air	kg	9.26624E-10	9.26624E-10	9.26624E-10		
Benzo(k)fluoranthene	air	kg					
Benzyl Chloride (C7H7Cl)	air	kg	5.39118E-10	5.39118E-10	5.39118E-10		
Beryllium (Be)	air	kg	1.47309E-06	1.47309E-06	1.47309E-06		
Biphenyl	air	kg	1.67604E-07	1.67604E-07	1.67604E-07		
Bromoform (CHBr3)	air	kg	2.91875E-08	2.91875E-08	2.91875E-08		

Ethylene Dichloride (C2H4Cl2)	air	kg	1.3144E-14	1.3144E-14	1.3144E-14
Fluoranthene	air	kg	1.67287E-16	1.67287E-16	1.67287E-16
Fluorene (C13H10)	air	kg	2.5093E-14	2.5093E-14	2.5093E-14
Fluorides (F-)	air	kg	2.29415E-08	2.29415E-08	2.29415E-08
Formaldehyde (CH2O)	air	kg	7.16944E-16	7.16944E-16	7.16944E-16
Furan (C4H4O)	air	kg			
Furans (unspecified)	air	kg			
Halogenated Hydrocarbons (unspecified)	air	kg			
Halon 1301 (CF3Br)	air	kg			
Hexane (C6H14)	air	kg			
Hydrocarbons (NMHC)	air	kg	0.0039	0.0039	0.0048
Hydrocarbons (unspecified)	air	kg	0.00043	0.00128	0.00048
Hydrogen (H2)	air	kg			
Hydrogen Chloride (HCl)	air	kg			
Hydrogen Fluoride (HF)	air	kg	2.33007E-13	2.33007E-13	2.33007E-13
Hydrogen Sulfide (H2S)	air	kg			
Indeno (1,2,3-cd)pyrene	air	kg			
Iron (Fe)	air	kg			
Isophorone (C9H14O)	air	kg			
Kerosene	air	kg	1.19491E-14	1.19491E-14	1.19491E-14
Lead (Pb)	air	kg	2.09109E-14	2.09109E-14	2.09109E-14
Magnesium (Mg)	air	kg	2.75063E-10	2.75063E-10	2.75063E-10
Manganese (Mn)	air	kg			
Mercaptan	air	kg			
Mercury (Hg)	air	kg	1.49363E-14	1.49363E-14	1.49363E-14
Metals (unspecified)	air	kg	2.96743E-07	2.96743E-07	2.96743E-07
Methane (CH4)	air	kg	4.35691E-12	4.35691E-12	4.35691E-12
Methyl Bromide (CH3Br)	air	kg	4.54065E-15	4.54065E-15	4.54065E-15
Methyl Chloride (CH3Cl)	air	kg			
Methyl Cholanthrene (3-C21H16)	air	kg			
Methyl Chrysene (5-C19H15)	air	kg			
Methyl Ethyl Ketone (MEK, C4H8O)	air	kg	2.33007E-14	2.33007E-14	2.33007E-14
Methyl Hydrazine (CH6N2)	air	kg	3.52498E-14	3.52498E-14	3.52498E-14

Methyl Methacrylate (CH ₂ C(CH ₃)COOCH ₃)	air	kg	7.76689E-14	7.76689E-14	7.76689E-14
Methyl Naphthalene (2-C11H10)	air	kg			
Methyl Tert Butyl Ether (MTBE, C ₅ H ₁₂ O)	air	kg			
Methylene Chloride (CH ₂ Cl ₂ , HC130)	air	kg	3.1665E-15	3.1665E-15	3.1665E-15
Molybdenum (Mo)	air	kg			
Naphthalene (C ₁₀ H ₈)	air	kg			
Naphthalene	air	kg	6.01813E-11	6.01813E-11	6.01813E-11
Nickel (Ni)	air	kg			
Nitrogen Oxides (NO _x)	air	kg	0.002500001	0.002500001	0.004030001
Nitrous Oxide (N ₂ O)	air	kg	3.12307E-11	3.12307E-11	3.12307E-11
Organic Matter (unspecified)	air	kg	6.7039E-10	6.7039E-10	6.7039E-10
Particulates (PM ₁₀)	air	kg	0.00014	0.00014	0.00016
Particulates (PM _{2.5})	air	kg			
Particulates (unspecified)	air	kg			
Penanthrene (C ₁₄ H ₁₀)	air	kg			
Pentane (C ₅ H ₁₂)	air	kg			
Perchloroethylene	air	kg			
Perylene	air	kg	5.69939E-13	5.69939E-13	5.69939E-13
Phenanthrene	air	kg	2.79382E-13	2.79382E-13	2.79382E-13
Phenol (C ₆ H ₅ OH)	air	kg			
Phenols	air	kg			
Phosphorus (P)	air	kg			
Polyaromatic hydrocarbons (total)	air	kg			
Polycyclic Aromatic Hydrocarbons (PAH, unspecified)	air	kg			
Propane (C ₃ H ₈)	air	kg			
Propionaldehyde (CH ₃ CH ₂ CHO)	air	kg			
Propylene	air	kg	4.2466E-14	4.2466E-14	4.2466E-14
Propylene Oxide	air	kg			
Pyrene (C ₁₆ H ₁₀)	air	kg	1.22928E-13	1.22928E-13	1.22928E-13
Radionuclides (unspecified)	air	curie	2.06883E-07	2.06883E-07	2.06883E-07
Selenium (Se)	air	kg	1.11753E-13	1.11753E-13	1.11753E-13

Silicon (Si)	air	kg				
Sodium (Na)	air	kg				
Styrene (C6H5CHCH2)	air	kg				
Sulfur Dioxide	air	kg	7.93444E-13	7.93444E-13	7.93444E-13	7.93444E-13
Sulfur Oxides (SOx as SO2)	air	kg	1.01695E-12	1.01695E-12	1.01695E-12	1.01695E-12
Tetrachloroethylene (C2Cl4)	air	kg				
TNMOC (unspecified)	air	kg				
Toluene (C6H5CH3)	air	kg	1.45278E-11	1.45278E-11	1.45278E-11	1.45278E-11
Trichloroethane (1, 1, 1-CH3CCl3)	air	kg				
Trichloroethylene	air	kg	3.01732E-12	3.01732E-12	3.01732E-12	3.01732E-12
Vanadium (V)	air	kg				
Vinyl Acetate (C4H6O2)	air	kg				
VOC (unspecified)	air	kg	2.45856E-14	2.45856E-14	2.45856E-14	2.45856E-14
Xylene (C6H4(CH3)2)	air	kg				
Xylenes	air	kg				
Zinc (Zn)	air	kg	5.08935E-15	5.08935E-15	5.08935E-15	5.08935E-15
1-Methylfluorene	water	kg	1.07669E-08	1.07669E-08	1.07669E-08	1.07669E-08
2,4 Dimethylphenol	water	kg	1.75718E-07	1.75718E-07	1.75718E-07	1.75718E-07
2-Hexanone	water	kg	3.63895E-08	3.63895E-08	3.63895E-08	3.63895E-08
2-Methyl Naphthalene	water	kg	0.000136476	0.000136476	0.000136476	0.000136476
4-Methyl 2-Pentanone	water	kg	0.007715942	0.007715942	0.007715942	0.007715942
Acetone	water	kg	0.000458846	0.000458846	0.000458846	0.000458846
Acid (benzoic)	water	kg	4.37583E-06	4.37583E-06	4.37583E-06	4.37583E-06
Acid (H+) (unspecified)	water	kg	1.29473E-05	1.29473E-05	1.29473E-05	1.29473E-05
Acid (hexanoic)	water	kg	8.73064E-08	8.73064E-08	8.73064E-08	8.73064E-08
Alkylated Benzenes	water	kg	4.58929E-07	4.58929E-07	4.58929E-07	4.58929E-07
Alkylated Fluorenes	water	kg	1.38032E-05	1.38032E-05	1.38032E-05	1.38032E-05
Alkylated Naphthalenes	water	kg	8.33433E-09	8.33433E-09	8.33433E-09	8.33433E-09
Alkylated Phenanthrenes	water	kg	3.97513E-06	3.97513E-06	3.97513E-06	3.97513E-06
Aluminum (Al3+)	water	kg				
Ammonia (NH3)	water	kg	3.45763E-08	3.45763E-08	3.45763E-08	3.45763E-08
Ammonium (NH4+)	water	kg	3.1587E-06	3.1587E-06	3.1587E-06	3.1587E-06
Antimony	water	kg	7.43061E-10	7.43061E-10	7.43061E-10	7.43061E-10

AOX (Adsorbable Organic Halogenes)	water	kg				
Aromatic Hydrocarbons (unspecified)	water	kg				
Arsenic	water	kg	1.49121E-05	1.49121E-05	1.49121E-05	1.49121E-05
Barium (Ba++)	water	kg	9.31175E-09	9.31175E-09	9.31175E-09	9.31175E-09
Benzene	water	kg	4.74518E-08	4.74518E-08	4.74518E-08	4.74518E-08
Beryllium	water	kg	0.000204357	0.000204357	0.000204357	0.000204357
BOD	water	kg	2.63967E-09	2.63967E-09	2.63967E-09	2.63967E-09
Boron	water	kg	7.00846E-09	7.00846E-09	7.00846E-09	7.00846E-09
Bromide	water	kg	4.23124E-07	4.23124E-07	4.23124E-07	4.23124E-07
Cadmium (Cd++)	water	kg	3.83761E-09	3.83761E-09	3.83761E-09	3.83761E-09
Calcium	water	kg	4.88031E-08	4.88031E-08	4.88031E-08	4.88031E-08
Chlorides (Cl-) (unspecified)	water	kg	2.97623E-05	2.97623E-05	2.97623E-05	2.97623E-05
Chlorides (methyl chloride)	water	kg	9.95582E-08	9.95582E-08	9.95582E-08	9.95582E-08
Chromium (Cr III, Cr VI)	water	kg	9.61497E-06	9.61497E-06	9.61497E-06	9.61497E-06
Cobalt	water	kg	0.00010878	0.00010878	0.00010878	0.00010878
COD	water	kg	1.8865E-07	1.8865E-07	1.8865E-07	1.8865E-07
Copper (Cu+, Cu++)	water	kg	1.63494E-10	1.63494E-10	1.63494E-10	1.63494E-10
Cresols	water	kg	3.98192E-09	3.98192E-09	3.98192E-09	3.98192E-09
Cyanide (CN-)	water	kg	4.67398E-08	4.67398E-08	4.67398E-08	4.67398E-08
Cymene	water	kg	2.06607E-09	2.06607E-09	2.06607E-09	2.06607E-09
Dibenzofuran	water	kg	3.63827E-07	3.63827E-07	3.63827E-07	3.63827E-07
Dibenzothiophene	water	kg	0.001764001	0.001764001	0.001764001	0.001764001
Dissolved Solids (unspecified)	water	kg	9.44312E-06	9.44312E-06	9.44312E-06	9.44312E-06
Ethylbenzene	water	kg	1.96211E-09	1.96211E-09	1.96211E-09	1.96211E-09
Fluorines/Fluorides (F-)	water	kg	3.79362E-08	3.79362E-08	3.79362E-08	3.79362E-08
Halogenated Matters (organic)	water	kg				
Hardness	water	kg	1.42999E-07	1.42999E-07	1.42999E-07	1.42999E-07
Hydrocarbons (unspecified)	water	kg	4.70366E-09	4.70366E-09	4.70366E-09	4.70366E-09
Inorganic Dissolved Matters (unspecified)	water	kg				
Iron (Fe++, Fe3+)	water	kg	1.16733E-09	1.16733E-09	1.16733E-09	1.16733E-09
Lead (Pb++, Pb4+)	water	kg	3.44357E-07	3.44357E-07	3.44357E-07	3.44357E-07
Lithium	water	kg	0.006255931	0.006255931	0.006255931	0.006255931
Magnesium	water	kg	6.97191E-12	6.97191E-12	6.97191E-12	6.97191E-12

Manganese	water	kg		0.000556312	0.000556312	0.000556312
Mercury (Hg+, Hg++)	water	kg		1.22696E-08	1.22696E-08	1.22696E-08
Metals (unspecified)	water	kg		1.84982E-09	1.84982E-09	1.84982E-09
Methyl Ethyl Ketone (MEK)	water	kg		6.47259E-10	6.47259E-10	6.47259E-10
Molybdenum	water	kg		3.71113E-05	3.71113E-05	3.71113E-05
Naphthalene	water	kg		5.43656E-07	5.43656E-07	5.43656E-07
Nickel (Ni++, Ni3+)	water	kg		4.44547E-08	4.44547E-08	4.44547E-08
Nitrates (NO3-)	water	kg		1.25014E-11	1.25014E-11	1.25014E-11
Nitrogen (ammonia)	water	kg		0.001714566	0.001714566	0.001714566
Nitrogenous Matter (unspecified, as N)	water	kg				
Oils (unspecified)	water	kg		1.36538E-05	1.36538E-05	1.36538E-05
Organic Carbons (unspecified)	water	kg		1.45688E-07	1.45688E-07	1.45688E-07
Organic Dissolved Matters (unspecified)	water	kg				
Pentamethyl Benzene	water	kg		1.73216E-09	1.73216E-09	1.73216E-09
Phenanthrene	water	kg		8.16849E-09	8.16849E-09	8.16849E-09
Phenol (C6H5CH)	water	kg				
Phenolic Compounds	water	kg		4.73394E-10	4.73394E-10	4.73394E-10
Phosphates (PO4 3-, HPO4-, H2PO4, H3PO4, as P)	water	kg				
Polycyclic Aromatic Hydrocarbons (PAH, unspecified)	water	kg				
Radionuclides (unspecified)	water	curie		2.90537E-12	2.90537E-12	2.90537E-12
Salts (unspecified)	water	kg				
Selenium	water	kg		5.55013E-11	5.55013E-11	5.55013E-11
Silver	water	kg		2.90586E-07	2.90586E-07	2.90586E-07
Sodium (Na+)	water	kg		1.02249E-08	1.02249E-08	1.02249E-08
Strontium	water	kg		1.73096E-11	1.73096E-11	1.73096E-11
Sulfate (SO4-)	water	kg		3.29363E-11	3.29363E-11	3.29363E-11
Sulfide (S-)	water	kg		2.66856E-11	2.66856E-11	2.66856E-11
Sulfur	water	kg		4.85193E-09	4.85193E-09	4.85193E-09
Sulfuric Acid	water	kg		1.63459E-08	1.63459E-08	1.63459E-08
Surfactants	water	kg		1.13102E-09	1.13102E-09	1.13102E-09
Suspended Solids (unspecified)	water	kg		1.39438E-11	1.39438E-11	1.39438E-11
TDS	water	kg				

Thallium	water	kg	1.97137E-11	1.97137E-11	1.97137E-11
Tin	water	kg	2.7423E-09	2.7423E-09	2.7423E-09
Titanium	water	kg	7.27964E-10	7.27964E-10	7.27964E-10
TOC (Total Organic Carbon)	water	kg			
Toluene (C6H5CH3)	water	kg	3.15599E-09	3.15599E-09	3.15599E-09
Total Alkalinity	water	kg	1.29822E-11	1.29822E-11	1.29822E-11
Total Biphenyls	water	kg	4.80341E-11	4.80341E-11	4.80341E-11
Total Dibenzo-thiophenes	water	kg	2.74538E-07	2.74538E-07	2.74538E-07
Vanadium	water	kg	5.28895E-10	5.28895E-10	5.28895E-10
Water, chemically polluted	water	kg			
Xylenes	water	kg	1.63239E-12	1.63239E-12	1.63239E-12
Yttrium	water	kg	1.45519E-07	1.45519E-07	1.45519E-07
Zinc (Zn++)	water	kg	1.31785E-12	1.31785E-12	1.31785E-12
Non-Allocated by products	solid				
	waste	kg			
Recovered Matter:Aluminum Scrab	solid				
	waste	kg			
Recovered Matter:Ash	solid				
	waste	kg			
Recovered Matters (total)	solid				
	waste	kg			
Waste (hazardous)	solid				
	waste	kg			
Waste (municipal and industrial)	solid				
	waste	kg			
Waste (unspecified)	solid				
	waste	kg			
waste (unspecified, to incineration)	solid				
	waste	kg			
Waste:Bauxite Residues (red mud)	solid				
	waste	kg			
Waste:FGD sludge	solid				
	waste	kg			
Waste:Mineral (inert)	solid				
	waste	kg			

waste:Mining+Tailing	solid waste	kg				
Waste:Non Toxic Chemicals (unspecified)	solid waste	kg				
waste:Slags and Ash (unspecified)	solid waste	kg				
Wastes (total)	solid waste	kg	0.002253824	0.002253824	0.002253824	0.002253824

Appendix (B)

Energy and raw materials consumption per unit table

energy and raw material consumption /unit table									
consumption name	location	unit	fine agg. (1 kg)	coarse agg. (1 kg)	cement (1 kg)	sp.aa (1 kg)	steel (1kg)	plastic fibers (1 kg)	
energy		mj	0.2285956	0.2287306	5.701214699	115.747188	24.89531279	298.2435246	
coal	in ground	kg			0.12982722		0.7062615		
crude oil	in ground	litre	0.018918567	0.018918567	0.014932753	2.091398212	0.072232759	5.816855127	
natural gas	in ground	m3			0.005567881	0.004226	0.06118875	0.0001875	
uranium	in ground	kg					3.85875E-07		
fine aggregate (sand)	in ground	kg	1		0.040497481				
coarse aggregate	in ground	kg		1					
calcite ore	in ground	kg			1.399465412		0.1910853		
shale & clay	in ground	kg			0.111919109				
iron ore	in ground	kg			0.013525321		1.228185		
anhydrous gypsum	in ground	kg			0.0485971				
water	water source	kg	5.058E-08	5.058E-08	0.84061268	0.0000000416			

Energy and raw materials consumption per unit table (cont'd)

energy and raw material consumption /unit table									
consumption name	location	unit	Electricity (1 kwh)	single unit truck (1 TKM)	combination truck (1 TKM)	<11 (1 hp.hr)	≥11 - <25 (1 hp.hr)	≥25 - <50 (1 hp.hr)	
energy		mj	28.77026021	2.131667999	0.994778399	14.9814	14.9814	14.9814	
coal	in ground	kg	0.26263						
crude oil	in ground	litre	0.180005652	0.319606213	0.149149566	2.246198061	2.246198061	2.246198061	
natural gas	in ground	m3	0.05153666						
uranium	in ground	kg	6.35029E-07						

fine aggregate (sand)	in ground	kg							
coarse aggregate	in ground	kg							
calcite ore	in ground	kg							
shale & clay	in ground	kg							
iron ore	in ground	kg							
anhydrous gypsum	in ground	kg							
water	water								
	source	kg							

Energy and raw materials consumption per unit table (cont'd)

energy and raw material consumption /unit		table							
consumption name	location	unit	≥50 - <75 (1 hp.hr)	≥75 - <100 (1 hp.hr)	≥100 - <175 (1 hp.hr)	≥175 - <300 (1 hp.hr)	≥300 - <600 (1 hp.hr)		
energy		mj	14.9814	14.9814	13.5198	13.5198	13.5198		
coal	in ground	kg							
crude oil	in ground	litre	2.246198061	2.246198061	2.027056787	2.02705679	2.0270568		
natural gas	in ground	m3							
uranium	in ground	kg							
fine aggregate (sand)	in ground	kg							
coarse aggregate	in ground	kg							
calcite ore	in ground	kg							
shale & clay	in ground	kg							
iron ore	in ground	kg							
anhydrous gypsum	in ground	kg							
water	water								
	source	kg							

Energy and raw materials consumption per unit table (cont'd)

energy and raw material consumption /unit table				
consumption name	location	unit	≥600 - ≤750 (1 hp.hr)	>750 (1 hp.hr)
energy		mj	13.5198	13.5198
coal	in ground	kg		
crude oil	in ground	litre	2.027056787	2.027056787
natural gas	in ground	m3		
uranium	in ground	kg		
fine aggregate (sand)	in ground	kg		
coarse aggregate	in ground	kg		
calcite ore	in ground	kg		
shale & clay	in ground	kg		
irone ore	in ground	kg		
anhydrated gypsum	in ground	kg		
water	water source	kg		

APPENDIX (C)

Snapshots of input tables of the model

life cycle definition		
cycle type	repetition (yr)	
construction		
resurfacing		
maintenance and repair		

cast in situ construction materials		
component	unit	quantity
<i>volume of cast in situ concrete</i>	m ³	
<i>density of concrete</i>	kg/m ³	
<i>fine aggregate</i>	kg/m ³	
<i>coarse aggregate</i>	kg/m ³	
<i>cement</i>	kg/m ³	
<i>fly ash</i>	kg/m ³	
<i>silica fume</i>	kg/m ³	
<i>slag</i>	kg/m ³	
<i>super plasticizer</i>	kg/m ³	
<i>air entraining agent</i>	kg/m ³	
<i>steel rebar</i>	kg/m ³	
<i>prestressing steel</i>	kg/m ³	
<i>steel fibers</i>	kg/m ³	
<i>plastic fibers</i>	kg/m ³	

precast construction materials		
component	unit	quantity
<i>volume of precast concrete</i>	m3	
<i>density of concrete</i>	kg/m3	
<i>fine aggregate</i>	kg/m3	
<i>coarse aggregate</i>	kg/m3	
<i>cement</i>	kg/m3	
<i>fly ash</i>	kg/m3	
<i>silica fume</i>	kg/m3	
<i>slag</i>	kg/m3	
<i>super plasticizer</i>	kg/m3	
<i>air entraining agent</i>	kg/m3	
<i>steel rebar</i>	kg/m3	
<i>prestressing steel</i>	kg/m3	
<i>steel fibers</i>	kg/m3	
<i>plastic fibers</i>	kg/m3	

resurfacing layer materials		
component	unit	quantity
<i>volume of resurfacing layer concrete</i>	m3	
<i>density of concrete</i>	kg/m3	
<i>fine aggregate</i>	kg/m3	
<i>coarse aggregate</i>	kg/m3	
<i>cement</i>	kg/m3	
<i>fly ash</i>	kg/m3	
<i>silica fume</i>	kg/m3	
<i>slag</i>	kg/m3	
<i>super plasticizer</i>	kg/m3	
<i>air entraining agent</i>	kg/m3	
<i>steel rebar</i>	kg/m3	
<i>prestressing steel</i>	kg/m3	
<i>steel fibers</i>	kg/m3	
<i>plastic fibers</i>	kg/m3	

maintenance & repair materials		
component	unit	quantity
<i>volume of maintenance and repair concrete</i>	m3	
<i>density of concrete</i>	kg/m3	
<i>fine aggregate</i>	kg/m3	
<i>coarse aggregate</i>	kg/m3	
<i>cement</i>	kg/m3	
<i>fly ash</i>	kg/m3	
<i>silica fume</i>	kg/m3	
<i>slag</i>	kg/m3	
<i>super plasticizer</i>	kg/m3	
<i>air entraining agent</i>	kg/m3	
<i>steel rebar</i>	kg/m3	
<i>prestressing steel</i>	kg/m3	
<i>steel fibers</i>	kg/m3	
<i>plastic fibers</i>	kg/m3	

construction equipment (cast in situ construction)						
equip. #	pieces used (no.)	horse power rating (hp)	usage time/piece (hr)	weight (kg)		
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						
19						
20						
21						

construction equipment (precast construction)							
equip.#	pieces used (no.)	horse power rating (hp)	usage time/piece (hr)	weight (kg)			
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							
19							
20							
21							

construction equipment (resurfacing layer)							
equip.#	pieces used (no.)	horse power rating (hp)	usage time/piece (hr)	weight (kg)			
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							
19							
20							
21							

construction equipment (maintenance & repair)							
equip.#	pieces used (no.)	horse power rating (hp)		usage time/piece (hr)		weight (kg)	
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							
19							
20							
21							

construction equipment (demolishing)							
equip.#	pieces used (no.)	horse power rating (hp)		usage time/piece (hr)		weight (kg)	
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							
19							
20							
21							

transportation distances input		
transportation of	unit	distance
<i>fine aggregate to batch plant</i>	km	
<i>coarse aggregate to batch plant</i>	km	
<i>cement to batch plant</i>	km	
<i>fly ash to batch plant</i>	km	
<i>silica fume to batch plant</i>	km	
<i>slag to batch plant</i>	km	
<i>additives to batch plant</i>	km	
<i>steel to fabricator</i>	km	
<i>fabricated steel to site</i>	km	
<i>prestressing steel to site</i>	km	
<i>concrete to site</i>	km	
<i>precast concrete to site</i>	km	
<i>construction equipment to site</i>	km	
<i>site to landfill site</i>	km	
<i>site to crusher</i>	km	
<i>scrap steel to yard</i>	km	
<i>steel fibers to batch plant</i>	km	
<i>plastic fibers to batch plant</i>	km	

wastage	
wastage percentage (in decimal)	

electricity usage		
activity type	unit	value
<i>precast plant</i>	kwh/m3	
<i>batch plant</i>	kwh/m3	21.8584
<i>steel fabrication</i>	kwh/kg	
<i>crusher</i>	kwh/kg	
<i>fly ash preparation</i>	kwh/kg	