PROBABILISTIC COST MODELS

FOR LIFECYCLE DESIGN OF BUILDINGS

by

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Abstract

This thesis presents a collection of numerical models that predict the total lifetime cost of buildings. Different models are developed for different phases in the life of a building, i.e., extraction and manufacturing of materials, construction, operation, hazards, demolition, and recycling. Models forecast direct costs, environmental impact costs, and human health costs related to each such phase. The variability in the parameters that enter the cost models is addressed using random variables. The estimate of the total cost of a building can be used in future work to optimize the structural design.

Despite powerful new optimization algorithms, the answer to what is holistically the optimal choice of materials, dimensions, and configurations is often unanswered in practice. One reason is that developers, architects, users, and societies may have different objectives, ranging from the cost of construction to aesthetic appeal and environmental impact. Another problem is the lack of unbiased models to predict the costs and benefits that matter to private and public stakeholders. Thus, concerns such as environmental impacts and cost of potential earthquakes are rarely quantified in an explicit and comprehensive manner. This issue is addressed in this thesis through the development of a collection of unified probabilistic cost models for a broad range of costs and benefits. The models proposed in this thesis are implemented in a computer program for simulation of building behaviour.

Preface

Chapters 1 and 3 of this thesis are developed by the author of this thesis under the direct supervision of Dr. Terje Haukaas. The implementation of the proposed models in Chapter 5 has been carried out by Dr. Haukaas using the software framework Rts. Chapters 2, 3, 4, and 5 are the basis for a conference paper:

Haukaas, T., Gill, G., Gavrilovic, S. (2017) "Probabilistic Cost Models and Computational Framework for Life-cycle Design of Buildings" Proceedings of the 12th International Conference on Structural Safety & Reliability, Vienna, Austria, 6-10 August (10 pages)

The above-mentioned paper is prepared in a collaborative effort with Dr. Terje Haukaas and Stevan Gavrilovic, both from the University of British Columbia.

The author of this thesis is responsible for the literature review, deriving equations, developing models, data collection, performing analysis, and interpreting the results. This thesis is drafted by the author and finalized in an iterative process with the research supervisor, Dr. Terje Haukaas.

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F_{fuel}	Conversion from energy source to environmental/health cost	$/L $/J	Table 2-1	15	(Shindell 2015)
D_{fuel}	Energy density of energy source	J/L	Table 2-2	17	(U.S Deparment of Energy 2014)
P_{fuel}	Fuel split for extraction and manufacturing phase	-	Table 2-4 Table 2-5	19	(Hammond and Jones 2006)
i_p	Energy required for extraction and manufacturing of material	J/kg	Table 2-3	18	(Hammond and Jones 2006)
i_{wt}	Energy required to transport workers	J/worker/km	Table 2-6	21	(Poudenx and Merida 2007)
i_{mt}	Energy required to transport materials	j/kg/km	Table 2-7	22	(Office of Energy Efficiency 2006)
R_{rec}	Recycling rate of a material	-	Table 2-8	26	(Townsend et al. 2014)
ec_{lf}	Environmental cost of landfilling	$/ton	13.0		(Rabl et al. 2008)
e_{rec}	Energy for recycling materials compared to their primary production energy	-	Table 2-9	26	(Environmental Council of Concrete Organizations 1997; Rankin 2012)
$P_{severity\text{-}x\|DS}$	Probability of experiencing severity level *x* given a damage state	-	Table 4-7 Table 4-8 Table 4-9	47, 49	(Federal Emergency Management Agency 2003)
$C_{severity}$	Cost of injury	$/person	Table 4-6	47	(Duval and Gribbin 2008)
$P_{collapse}$	Probability of building collapse	-	Table 4-4	45	(Federal Emergency Management Agency 2003)

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I am eternally indebted and grateful to my father, Gurdip Singh Gill, and my mother, Manjit Kaur Gill, for their unconditional love, support, and encouragement in every step in my life. I would like to thank my brother, Harvinder Singh Gill, who has always been my intellectual sparring partner, for allowing me to bounce ideas off him. I would also like to thank my maternal family for providing me with so much love and support while I have been in Canada.

Finally, and most importantly, I would like to thank my wife, Navjot Kaur Romana. Her support, encouragement, patience, and unwavering love for the past one year have been the inspiration and motivation for continuing this research work.

Dedication

To my beloved father and mother

Chapter 1: Introduction

Until recently the primary factor considered when assessing the risk of buildings and infrastructure projects was human safety. However, the occurrence of earthquakes in urban areas and the realization of the importance of environmental costs have broadened the scope of impacts considered. In this thesis, all concerns are translated into cost-values. It is controversial to assign monetary values to the potential for injuries and loss of life; to put a price-tag on environmental impacts can come under similar criticism. However, the society, owners, developers, and architects must prioritize limited resources. Design decisions ultimately involve trade-offs in allocating finite resources towards ensuring structural integrity, human safety, ecosystem preservation, and user experience. Instead of considering this a multi-objective decision problem, all concerns are here quantified by a unified measure, i.e., cost. Regardless of the approach, weights must be applied to different concerns. The cost-based approach adopted here implies that the weights, i.e., the translation of concerns into costs, are transparent and open for discussion.

1.1 Objectives

The objective in this thesis is to develop cost models that enable lifecycle cost estimation and holistic design optimization of buildings and their components. The models are implemented in the computer program Rts, an extension of the computer program Rt (Mahsuli and Haukaas 2012). An important purpose of Rt was to facilitate probabilistic analysis with many interacting models for hazards, buildings, and costs. Until now Rt has been used for regional seismic risk analysis with relatively simple models for each building. The extended program, Rts, addresses detailed building analysis using finite elements to model the structure. The details of these implementations are outside the scope of this thesis but it is useful to be aware of three “classes” in the object-oriented framework: 1) the detailed building model, 2) the building information model, and 3) the component. The detailed building model orchestrates the analysis and contains a database of variables defined in this thesis. The second model reads information from a building information model (BIM) file and creates the building components. A component contains information about its volume of different materials, as well as construction cost and cost of repairing the potential damage. The models developed in this thesis are implemented in the components and in the detailed building model.

<table>
<tr><th></th><th>Direct Cost</th><th>Environmental Impact</th><th>Human Health</th><th>Functionality</th><th>Human Experience</th></tr>
<tr><td>Manufacturing</td><td rowspan="2">3.3</td><td colspan="2">2.3</td><td></td><td></td></tr>
<tr><td>Construction</td><td colspan="2">2.4</td><td></td><td></td></tr>
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</table>

Figure 1-1: Matrix of costs

An overview of the costs considered in this study is shown in Figure 1-1. Each cell in the matrix represents one cost. The matrix is organized such that each row addresses one phase in the life of the building. For example, the manufacturing of the construction materials is addressed by the first row. The columns of the matrix separate the costs in each phase into direct cost, environmental impact cost, etc. The numbers within the table are references to sections in this thesis where those models are addressed. The blank cells are either not meaningful, such as building functionality before the building is built, or not yet addressed, such as the direct cost of demolition.

1.2 Limitations and Assumptions

Evaluating the cost of life, the cost of nature, and other social constructs is challenging for two reasons. One is related to the moral questions that can be raised when associating lives or nature with dollar values. The other is the lack of robust data to estimate these costs; many uncertainties remain in this type of analysis. Some of these uncertainties are explicitly included in the models in this thesis, while the others are hard to quantify. In the future, the models created in this thesis should be subjected to continuous discussion and improvement. Regarding the potential moral questions about cost-based modeling, it is recognized that all decision approaches must ultimately weigh different concerns. Using cost-values makes this weighing exercise more transparent. In fact, this kind of analysis, involving a wide range of costs, allows an unbiased exploration of how society values various aspects of building design. The cost models in this thesis are developed to demonstrate the feasibility of this concept, not to provide conclusive results. In other words, the cost models presented in this thesis should be regarded as initial estimates and the methodology can be seen as a "proof of concept."

Several factors that affect building performance are sensitive to geographical locations. This makes the optimal building design location-specific. Among the models proposed in this thesis, the environmental impact models have the highest sensitivity to geographical locations. In general, the pollutants have more impact around the locations from where they are emitted (Fuglestvedt et al. 2010). The models proposed in this thesis are fundamentally based on global average emissions and hence, provide only a broad overview of the environmental impacts. However, those values are modified to provide better estimates for the United States (Shindell

2015). In addition, the environmental impact valuation also depends on local energy preferences and recycling practices. These variations can be reflected in the results by using local data in the models. For some of the model parameters employed in this thesis, location specific data was unavailable and hence, national, or global average values were used instead.

1.3 Background

A considerable amount of research has already been done on estimating the construction cost of buildings. Commercial software programs are available in the market for obtaining such estimates. These software programs require the user to identify the items being used in the construction along with their quantities. By accessing a cost database, these programs estimate the cost of the items. However, conventional construction cost estimation methods are challenging in the context of this thesis. The component-based framework in Rts is designed to import a BIM file and then work independently, without any more user inputs.

BIM files contain a lot of information pertaining to the specific components and also about the project as a whole (Eastman et al. 2008). There are a variety of ways to get these quantities and material definitions out of a BIM file into a cost estimating software. One way is to use an Application Programming Interface (API) to directly link a BIM software, like Revit, to a costing system, like Innovaya. However, it is still difficult to automatically compute construction cost estimates. Although the computable information at the heart of a BIM makes quantification easier, manual input is still required (Revit 2006). As it currently stands, using an API would certainly offer significant advantages. However, the need for user input makes it harder to develop a program that automatically calculates the construction cost for each trial design in an optimization analysis. An alternative cost estimation approach is proposed in this thesis, in which only the geometry of a building component is required to estimate the cost.

This approach is described in detail in this thesis and demonstrated using a reinforced concrete (RC) column as an example.

In this thesis, RS Means has been used as a source of construction-related cost data (RS Means 2012). The RS Means booklet that was used in this work was published in 2012 and uses imperial units of measurements. Thus, all the construction costs quoted in this thesis are in 2012 US Dollars, and measurement units for most of the parameters defined and used are imperial. However, in all the final models the units are translated into metric units.

For determining the environmental impact of a specific building lifecycle phase, the approach adopted in this thesis is to first estimate the energy consumed in that phase. The fuel consumption patterns for that energy consumption are also determined. This information is used to estimate the quantities of different fuels consumed, which in turn is used to estimate the cost of damage to the environment using appropriate conversion factors. Although this approach works well for the operational phase and construction phase, some steps might feel unnecessary for other lifecycle phases like the manufacturing and extraction phase. It would make more sense to directly estimate fuel usage for the manufacturing and extraction phase, without the intermediate energy calculation steps. There are two main reasons for adopting the same approach for all the phases. First, the required data for developing such energy based models is readily available. Second, the environmental impact cost models for phases like repair and end of life are indeed similar in a few aspects to the models for other phases, such as manufacturing phase or construction phase. For example, the repair phase model is a combination of the manufacturing model and the construction model. Thus, to simplify the process of developing these models, and to obtain a uniform set of models, the same approach was used for all the phases.

Another method that has been employed in this thesis is to use "intensity" values for calculating the energy usage part of the cost models. These intensity values provide energy usage data per unit of concerned activity (Guerra 2010). For example, product energy intensity (i_p) values, also known as embodied energy, for a material have units of joule per kilogram. They show how much energy in joules is required to manufacture a kilogram of that material (Hammond and Jones 2006). Similarly, passenger transportation intensity values (i_{wt}) provide the amount of energy needed in joules to transport one passenger over a distance of one kilometer (Poudenx and Merida 2007). Most of these intensity values depend upon the usage patterns, and social and technological preferences of a region. Hence, they vary from country to country and sometimes even within a country. In this thesis, wherever possible, the intensity values have been taken from the studies representing the US and Canada regions. Sometimes, due to unavailability of data, the values from similar research conducted in other parts of the world are used. In such cases, an effort was made to ensure that the conditions under which such data was obtained were not too different from US or Canada. For example, the product energy intensity data has been estimated from studies performed in the United Kingdom.

One of the most critical parameters used in these environmental impact models is called fuel-to-cost conversion factor. It converts fuels consumption to environmental impact cost. As has been already mentioned, it is hard to assign a monetary value to nature or its degradation and limited research has been done in this regard. A study performed in 2015 named "Social Cost of Atmospheric Release" attempted to describe the environmental damage in terms of dollar value (Shindell 2015). The final value incorporates health impacts of air quality as well as climate damages. It also includes the cost of efforts to mitigate such damages. The study was targeted towards pollution due to electricity generation and vehicular transportation specifically. Although, electricity is one of the prime fuels and transportation an important activity in the lifecycle of a building, there are some lifecycle phases where this data might seem unreasonable to be used. Moreover, the said study admits to having uncertainties in the results, which have been specifically discussed and presented as part of the models.

Abbas Yazdi has worked with Dr. Haukaas developing a software framework for the assessment of seismic damage and loss to building components (Yazdi 2015). The seismic damage model proposed by Abbas determines the damage state of a component after a hazard based on visual damage cues like cracks or deformations. Damage states of individual components can be used to assign a similar overall damage state to the building as a whole. Damage state of the building determines the probability of severity of injuries (Federal Emergency Management Agency 2003). More the damage to the building, more the chance of life threating or fatal injuries. Finally, the cost of injuries is directly related to their severity (Duval and Gribbin 2008). The health impact model proposed in this thesis estimates the preventive cost of casualties for a particular damage state and not the treatment cost. As already stated, assigning a value to life is controversial, and there is little consensus on the value of life estimates (Mrozek and Taylor 2001). Still, such a model can clarify how the monetary resources should be allocated towards ensuring human safety during hazards.

1.4 Overview of the Thesis

In this section, the general overview of the organization of the thesis is laid out. In the second chapter, the environmental impact cost models have been developed for different lifecycle phases of a building. In the third chapter, the effort has been made to develop a general approach for obtaining construction cost models for various building components. The fourth chapter deals with the calculation of prevention costs of injuries or fatalities in case of a hazard like an earthquake. Analysis of an example building has been provided in the fifth chapter. Conclusions and summary of the work are provided in the sixth chapter. A procedure for estimating average fuel usage for manufacturing and mining industry, used in the second chapter, has been discussed in Appendix A. Appendix B describes the procedure used to obtain the cost data table for regression analysis. A small part of this data table is included in Appendix C. Appendix D discusses the potential issues related to regression analysis and their solution.

Chapter 2: Environmental Impact Cost

Putting a price on pollution is difficult even though the damage to the environment is something everyone ends up paying for. Thus, the objective of this chapter is to present a basic framework for incorporating environmental cost into structural engineering decisions. Typically, the engineers only concern themselves with structural considerations while designing, even though, the materials selected have significant environmental consequences.

In 2009, United Nations Environment Program published a report, “Buildings & Climate Change: A Summary for Decision-makers” under their sustainable buildings and climate initiative (United Nations Environment Programme 2009). Some of the major points highlighted by the report included:

- 40 percent of global energy use and 30 percent of global greenhouse gas emissions are caused directly or indirectly by buildings, both in developed and developing countries.
- Building Sector can contribute significantly in reducing greenhouse gas emission.
- Owing to longer lifespans of buildings, any corrective measures taken now will have a long-time impact.

North America is one of the largest contributors towards building related energy consumption, which is expected to increase even more in coming years (Blok et al. 2007). Space heating consumes most energy in residential buildings while lighting consumes most in commercial buildings. Both space heating and lighting requirements of a building can be mitigated with proper building design and material usage. Thus, in addition to structural safety and integrity, adequate emphasis must also be given to the environmental cost considerations during building design and construction.

2.1 Building Lifecycle

One of the best ways to visualize and evaluate the environmental performance of a building is by its entire lifecycle (Cabeza et al. 2014). The lifecycle of a building includes various stages starting from the extraction of raw materials, manufacturing of construction materials, on-site construction activities, operational phase, maintenance, repair, and stopping at end-of-life phase. It is important to note that transportation occurs between and within each phase (Khasreen et al. 2009). Figure 2-1 below summarizes the stages of a building's lifecycle graphically.

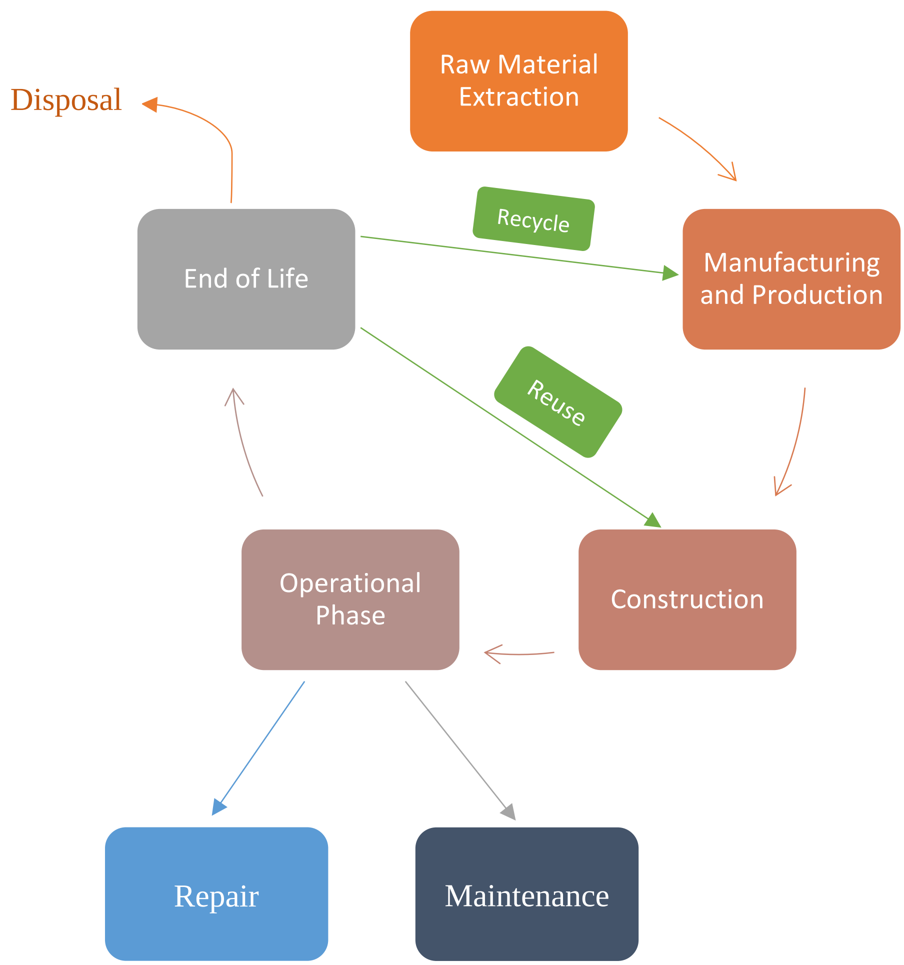


Figure 2-1: Building lifecycle

Extraction of raw materials for producing construction materials is the first stage of lifecycle of a building. This extraction could be open pit mining for different ores to produce metals, extracting oil from wells to produce plastics or extracting gypsum from open pit quarries to produce cement. The energy and other inputs and outputs vary depending on the materials being produced. The environmental impact of the extraction stage can be minimized by selecting building materials that require less energy in their extraction and require less transportation.

After extraction, the raw materials are transported to a facility where they are further processed or manufactured. For example, limestone, shells, chalk or shale, and clay are carried to cement manufacturing plants after extraction from quarries. These materials, along with some other necessary ingredients, are then heated in kilns after converting to a fine powder. At the end of the manufacturing stage, the materials are ready to be transported to the construction sites for use. The environmental impact of this stage can be minimized by selecting building materials that require less energy in production/manufacturing, less transportation, and minimal wastage. In this thesis, the process of extracting raw materials and then manufacturing products, is considered one phase in the overall building lifecycle.

The manufactured/processed materials are then transported to distribution centers and eventually to the construction sites where workers assemble the building as designed. At the construction site, heavy machinery such as cranes, backhoes, generators, and pumps are quite likely to be used. Fossil fuels account for the majority of the energy sources used at this stage (Sharrard 2007). Additionally, transportation of workers could have a significant impact if construction occurs over extended periods of time. Other than this, construction stage also results in a significant amount of waste generation. The environmental implications of the construction stage can be minimized by optimizing structures for quick assembly, reducing worker transportation and minimizing wastage.

The operational phase is by far the longest stage of building life cycle as it is quite common for buildings to exceed 50 years of operation. Due to its length in time, the operation phase is usually the biggest contributor to the environmental impacts. The environmental impact of this phase can be reduced by selecting a favorable orientation of the building. Reducing the natural heat loss and increasing natural lighting would also result in energy savings.

The maintenance phase is associated with maintaining adequate building assemblies. Certain elements of the building envelope such as paneling, carpet, paint, roof tiles, and windows usually have shorter life spans than the building's design life. Such elements are usually replaced after wear and tear or due to changes in style. Thus, during a building's lifecycle, maintenance can be of both structural and non-structural nature. Lack of maintenance is one of the main reasons for poor physical condition of buildings (The Athena Institute 2004). Each building, which must be replaced due to poor maintenance, is adding extra unnecessary environmental impact. Thus, regular maintenance and care take of buildings is vital even from the environmental point of view. Reducing the environmental impact of this phase is not as much in the hands of the structural engineers as the homeowners. Still, a building can be designed to allow for easier maintenance and repair. Moreover, it can be ensured that the products commonly used in maintenance like paints are eco-friendly.

In this thesis, repair and maintenance are considered different activities. Maintenance addresses regular wear and tear and non-structural changes. Repair corresponds to the corrective measures taken in case of damage due to hazard occurrences, poor structural design or poor workmanship during the construction phase. Repairs are a significant aspect of building lifecycle and should not be ignored. Unlike maintenance, structural engineers can contribute much more to ensure repair phase does not have an excessive environmental impact. A proper structural design and good workmanship during construction will ensure an adequately resilient building, which can stand the test of time and hazards. Moreover, the environmental impact can also be reduced by using recycled and reused materials for repair works if possible.

The final phase of the building lifecycle is end of life phase. Since end of life stage happens decades after construction, it is very hard to predict. Normally, when a building is demolished, the debris generated can either be reused, or transported and deposited in a landfill. Usually, steel and wood materials can be recycled, sometimes even more than once, and used again as construction material. On the other hand, a concrete beam can be crushed and reused as aggregate. Structural engineers can reduce environmental impact at this stage by designing members for easy and convenient disassembly. This will ensure that such structural members can be recycled or reused when a building reaches its design life.

Thus, structural engineers and designers can influence almost each stage of a building. Optimizing a single stage of a building's lifecycle is generally neither sufficient nor advisable. Changes in one stage have consequences throughout the other stages of lifecycle. It is common to find materials that have characteristics that are favorable in one stage of a building's lifecycle, but not another. For example, steel may be favorable in end of life stage due to its recyclable nature, but it is highly energy intensive material during production. Thus, for determining which materials are best, we need to look at the specific project, location, and must consider all lifecycle stages. A numerical model for each lifecycle stage would be helpful in comparing and identifying better materials and procedures.

2.2 Energy Usage to Cost Conversion

The environmental impact models proposed in this thesis are based on environmental damages due to energy consumption in different phases of the building lifecycle. This energy is then converted into cost by the simple formula F_{fuel}/D_{fuel}. Here F_{fuel} is a factor with units $ per litre fuel or $ per kWh electricity, which converts fuel or electricity usage into dollar costs. As described below, the factor F_{fuel} includes both environmental impact costs and health costs. D_{fuel} specifies how much energy, measured in Joule, is contained in a litre of fuel or a kWh of electricity. The result of the division F_{fuel}/D_{fuel} is a conversion factor with unit: dollar per Joule.

In 2015, a study named “The Social Cost of Atmospheric Release (SCAR)” addressed the factor F_{fuel} using a multi-impact economic evaluation framework. That study estimated environmental costs for fossil fuels that are used in electricity production and transportation (Shindell 2015). The environmental damage values calculated in the study included health impacts of air quality. Damages associated with aerosols, sulfur dioxide (SO_2), nitrogen oxides (NO_x), products of incomplete combustion (PIC), carbon dioxide (CO_2), ammonia, and methane are included.

However, before these values can be used for fuel-to-cost conversion the underlying uncertainties in the computation of these values need to be addressed. Figure 2-2 shows the probability distribution of the various pollutants considered by the study. This means the environment damage cost values proposed by SCAR study should not be taken in absolute terms and should be used in models as variables with inherent uncertainty. The final F_{fuel} factors for conventional fuels are provided in Table 2-1, taking into account this variability.

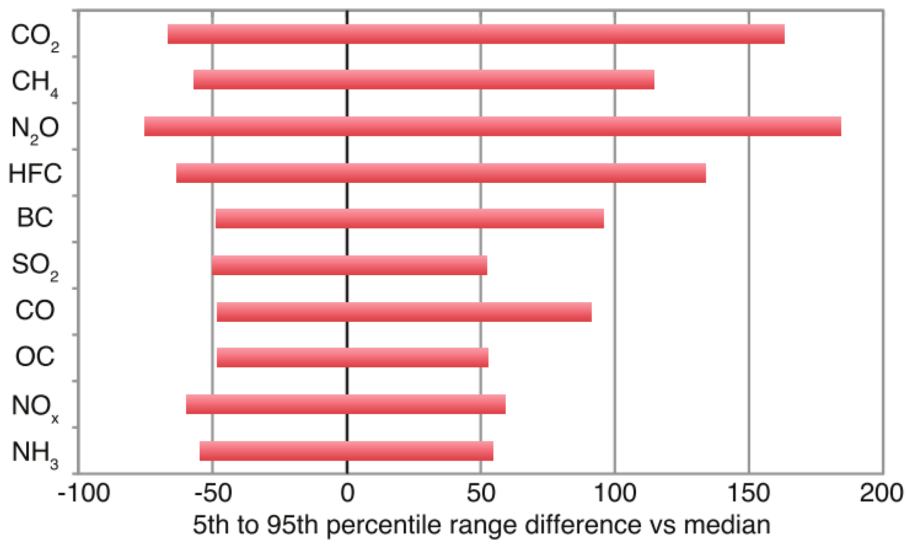


Figure 2-2: Probability distribution of the SCAR valuation for each pollutant (Shindell 2015)

Table 2-1: Fuel-to-cost conversion factor for common fuels (US national average)

Fuel type	Conversion factor, F_{fuel}	Data model	Parameters
Gasoline	$F_{gasoline}$	Normal distribution	μ = \$1.2 per litre cov = 20%
Diesel	F_{diesel}	Normal distribution	μ = \$1.5 per litre cov = 30%
Coal	F_{coal}	Uniform distribution	a = \$45/GJ b = \$108/GJ
Natural gas	F_{ngas}	Uniform distribution	a = \$13/GJ b = \$57/GJ
Electricity	$F_{electric}$	$0.40(F_{coal}) + 0.27(F_{ngas})$	
Fuel oil	$F_{fueloil}$	$1.0(F_{diesel})$	
LPG	F_{lpg}	$0.9(F_{gasoline})$	

The conversion factor F_{fuel} for gasoline and diesel is normally distributed with mean (μ) and coefficient of variation (cov) as presented in Table 2-1. For coal and natural gas, the conversion factor is assumed to be uniformly distributed with lower bound (a) and upper bound (b). Required data is not readily available to estimate F_{fuel} factors for many commonly used fuels like fuel oil, liquefied petroleum gas (LPG) and electricity. Approximate models based on meaningful assumptions are proposed for such fuels.

F_{fuel} conversion factor for electricity generation has been derived using coal and natural gas data. As per Figure 2-3, on an average 40% of electricity is generated using coal as fuel and 27% is generated using natural gas. Nuclear and renewable sources of electricity generation are assumed to create negligible pollution and hence ignored here. Taking this fuel type distribution of electricity generation into account, the F_{fuel} factor for electricity has been approximated as shown in Table 2-1.

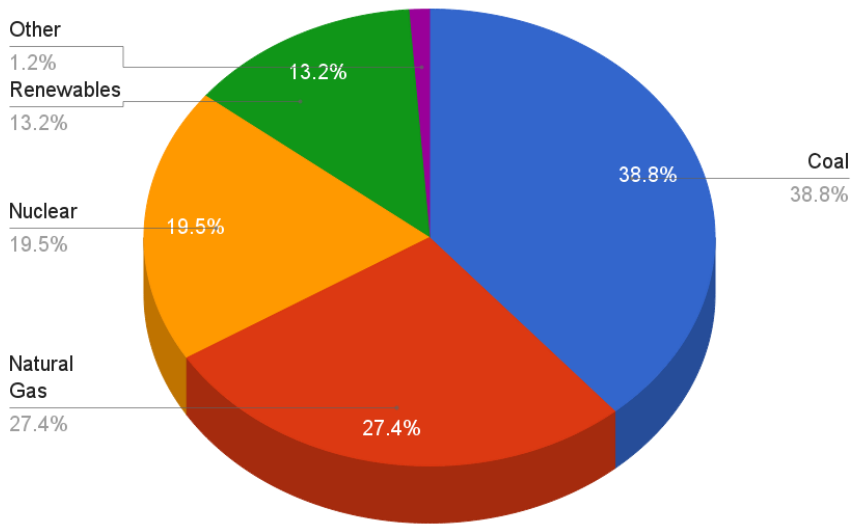


Figure 2-3: Electricity generation by type (EIA 2016)

As already mentioned the D_{fuel} factor specifies how much energy, measured in Joule, is contained in a litre of fuel or a kWh of electricity. This is the energy density of a fuel. Table 2-2 provides D_{fuel} values for common fuels considered in this thesis. Fuel Energy Densities are not needed for natural gas and coal in this case as the available F_{fuel} factors for both natural gas and coal (Table 2-1) can be directly used to convert the energy usage to environmental impact cost. The energy density for electricity is just the MJ-kWh relationship. The following section presents the numerical models used to estimate the cost of environmental impact through energy usage in a building for individual lifecycle stages.

Table 2-2: Fuel energy densities for common fuel types

Fuel type	**Fuel energy density (D_{fuel})**	**Source**
Diesel	35.8 MJ/L (D_{diesel})	(U.S Deparment of Energy 2014)
Gasoline	34.2 MJ/L ($D_{gasoline}$)	
Fuel Oil	35.8 MJ/L ($D_{fueloil}$)	
LPG	26 MJ/L (D_{lpg})	
Electricity	3.6 MJ/kWh ($D_{electric}$)	MJ-kWh conversion factor

2.3 Extraction and Manufacturing Phase

The environmental impact cost due to the extraction and manufacturing phase of a building is expressed as,

$$EC_{E\&M} = \sum \left(q \cdot i_p \cdot \sum \left(P_{fuel} \cdot \frac{F_{fuel}}{D_{fuel}} \right) \right) \tag{2-1}$$

where $EC_{E\&M}$ = the environmental impact cost associated with the extraction & manufacturing phase of the materials considered in a building in dollars; q = the quantity of a given material in kilograms (kg); i_p = the process energy intensity for a given material's extraction and manufacture (J/kg), also known as embodied energy; D_{fuel} = the energy densities of fuels as per Table 2-2; F_{fuel} = the fuel-to-cost conversion factors as per Table 2-1, and P_{fuel} = relative contribution of each energy source as per Table 2-4 or Table 2-5. In the implementation in Rts, the parameter q would be provided by the component. Parameters i_p, P_{fuel}, D_{fuel}, and F_{fuel}, would be available in a database accessible by the model that calculates environmental cost of manufacturing and extraction phase.

F_{fuel} and D_{fuel} are already discussed in section 2.2 and q being the quantity of a given material is self-explanatory. The quantity of a given material should be increased by a "waste factor" to account for the material wastages. The process energy intensity (i_p) of a material is the sum of all energy required to produce that material. Buildings and building products are constructed with a variety of materials and each material consumes energy during extraction and manufacture (Dixit et al. 2012). This energy is also known as embodied energy. The embodied energy estimates have been obtained from the Inventory of Carbon and Energy, which is freely available (Hammond and Jones 2006). Table 2-3 shows the average process energy intensities for some of the common building materials. As per the original study, the accuracy of these values depends upon the data availability. Some of these values are less accurate due to poor data availability or difficulty in selecting a representative value due to large standard deviation in results. To account for these uncertainties, a coefficient of variation of 20% has been assumed here.

Table 2-3: Process energy intensities, i_p (Hammond and Jones 2006) (UK)

Building material	**Process energy intensity (i_p) in MJ/kg**	**Coefficient of variation (cov)**
Aggregate	0.10	20%
Bitumen	47.00	
Bricks	3.00	
Cement	4.60	
Concrete	0.95	
Glass	15.00	
Insulation	45.00	
Paint	68.00	
Paperboard	24.80	
Plaster	1.80	
Plastics	80.50	
Rubber	101.70	
Sand	0.10	
Steel	24.40	
Timber	8.50	

P_{fuel} is the relative contribution of each energy source (fuel split) during extraction and manufacturing of a material. This data is also provided in Inventory of Carbon and Energy. P_{fuel} values for some of the building materials are provided in Table 2-4.

Table 2-4: Relative contribution of each energy source towards embodied energy (Hammond and Jones 2006)

Material	**Fuel split (P_{fuel})**			
	Coal	Fuel oil	Natural gas	Electricity
Aggregate	0.0%	19.8%	14.9%	65.3%
Bitumen	*--Data unavailable--*			
Bricks	0.0%	1.9%	72.1%	26.0%
Cement	70.9%	1.2%		27.9%
Concrete	47.1%	15.4%	3.1%	34.4%
Glass	0.0%	0.2%	72.8%	27.0%
Insulation	*--Data unavailable--*			
Paint	0.0%	2.0%	25.5%	72.5%
Paperboard	4.3%	0.3%	31.8%	63.6%
Plaster	*--Data unavailable--*			
Plastics	*--Data unavailable--*			
Rubber	12.3%	11.3%	11.1%	65.3%
Sand	0.0%	19.8%	14.9%	65.3%
Steel	*--Data unavailable--*			
Timber	0.0%	19.3%	28.5%	52.2%

Table 2-4 shows that required data is unavailable for some of the building materials. For these materials, an average fuel split (P_{fuel}) is estimated based on Canadian mining and manufacturing industry data. The calculation procedure used to derive this data has been duly explained in Appendix A. Table 2-5 gives the average contributions (P_{fuel}) for different energy sources. These values will be used for the materials missing in Table 2-4.

Table 2-5: Average P_{fuel} values for materials missing in Table 2-4 (US)

Energy source	**Contribution (P_{fuel})**
Electricity	50%
Natural gas	33%
Coal	14%
Diesel	3%

2.4 Construction Phase

The environmental impact cost for construction phase can be modeled as

$$EC_{HM} = r_h \cdot t_{wh} \cdot i_{hm} \cdot \sum \left(P_{fuel} \cdot \frac{F_{fuel}}{D_{fuel}} \right) \tag{2-2}$$

$$EC_{LT} = \frac{t_{wh}}{t_s} \cdot d_{wt} \cdot \sum \left(i_{wt} \cdot \frac{F_{fuel}}{D_{fuel}} \right) \tag{2-3}$$

$$EC_{MT} = \sum \left(q \cdot i_{mt} \cdot d_{mt} \cdot \frac{F_{fuel}}{D_{fuel}} \right) \tag{2-4}$$

$$EC_{const.} = EC_{HM} + EC_{LT} + EC_{MT} \tag{2-5}$$

where $EC_{const.}$ = the environmental impact cost for construction phase in US dollars; $EC_{HM.}$ = the environmental impact cost due to use of heavy machinery; $EC_{LT.}$ = the environmental impact due to labour transportation; $EC_{MT.}$ = the environmental impact cost due to material transportation; D_{fuel} = the energy densities for the fuels used for heavy machinery work and labor & material transportation, which can be obtained from Table 2-2; F_{fuel} = the fuel-to-cost conversion factors as defined in Section 2.2 and specifically in Table 2-1; r_h = the ratio of worker-hours allocated to the use of heavy machinery to the total worker hours; t_{wh} = the total worker hours assigned to construction work; t_s = the worker shift in hours, typically 8 hours; d_{wt} = the distance travelled by workers including return trips in kilometers (km); i_{hm} = the energy intensity due to heavy machinery use (J/worker-hour); i_{wt} = the worker transportation energy intensity (J/passenger/km) as per Table 2-6; q = the quantity of a given material in kilograms (kg); i_{mt} = the material transportation energy intensity for a given mode (J/kg/km) as per Table 2-7; d_{mt} = the distance between manufacturing plant and the construction site. In the implementation in Rts, the parameters i_{hm}, D_{fuel}, F_{fuel}, i_{mt}, and i_{wt} will be available in a database accessible by the model that calculates the total environmental cost of the construction phase, while q, r_h, t_{wh}, t_s, and d_{wt} are provided by the concerned component.

The energy model for construction phase has three basic components: 1) contributions from heavy machinery usage during construction process, which predominately uses diesel as fuel;

2) contributions from material transportation where diesel is the primary fuel; and 3) contributions from labor transportation where gasoline is used as primary fuel. Like the previous model, the energy consumed in this phase can be estimated using energy intensities, which is then converted to various fuel contributions. Table 2-6 summarizes some published intensity values for passenger transportation in British Columbia. Most of the process and fuel inefficiencies are accounted for during the estimation of these energy intensities (Poudenx and Merida 2007). Fuel usage obtained here is then converted to environmental impact cost using the F_{fuel} factors discussed in section 2.2. Contributions from energy use and CO_2 emissions by labor workers are being ignored here.

Table 2-6: Sample passenger transportation intensity

Mode	**Passenger transportation intensity, i_{wt} (J/passenger/km)**	**Location of study and source**
Light truck	3,560,000	British Columbia, Canada (Poudenx and Merida 2007)
Automobile	2,730,000	
Sea bus	1,840,000	
Diesel bus	920,000	
West coast express	570,000	
Trolley bus	410,000	
Sky train	390,000	

The environmental impact cost of extraction and manufacturing phase included the impact of the transportation of raw materials from the extraction site to the manufacturing plant. It was included in the process intensity values used in the model. The environmental impact of the transportation of finished goods and materials from the manufacturing plant to the construction site is included with the construction phase model. Table 2-7 summarizes some published intensity values for material transportation in Canada.

Table 2-7: Transportation energy intensity for common freight transport

Mode	Transportation energy intensity, i_{mt}, J/kg/km	Location of study and source
Light truck (0-4 tons)	7640	Canada, (Office of Energy Efficiency 2006)
Medium truck (4-15 tons)	6600	
Heavy trucks (+15 tons)	2400	
Rails	230	
Marine	430	

2.5 Operational Phase

The operation phase of buildings uses energy to provide the necessary conditions that facilitate the activities performed in a building. The environmental cost for the operational phase can be modeled as

$$EC_{oper} = t_{des} \cdot \sum (E_{fuel} \cdot F_{fuel}) \tag{2-6}$$

where EC_{oper} = the environmental impact costs of operational phase in US Dollars; E_{fuel} = the annual energy demand (J/year) for a particular fuel; t_{des} = the expected design life of the building in years; F_{fuel} = the fuel-to-cost conversion factors as per Table 2-1. In Rts implementation, E_{fuel} needs to be estimated using already available building energy modeling software like eQuest, while F_{fuel} will be provided in the form of a database. t_{des} will be provided by the building component.

E_{fuel} can be determined by a separate building energy modeling software like eQuest, Energy Plus, ESP-r, IES VE. For Canadian buildings, CAN-QUEST should be used, which is a Canadian adaptation of eQUEST. Most of the software products are open source and freely available.

2.6 Maintenance Phase

A rough model is being proposed for maintenance phase using the manufacturing and extraction phase energy usage approximations as shown below,

$$EC_M = \sum \left\{ \left(\frac{t_{des}}{t_{mat}} - 1\right) \cdot i_{mat} \cdot \left(P_{fuel} \cdot \frac{F_{fuel}}{D_{fuel}} \right) \right\} \forall t_{mat} < t_{des} \quad (2\text{-}7)$$

$$EC_M = 0 \ \forall t_{mat} \geq t_{des} \quad (2\text{-}8)$$

where EC_M = the environmental impact cost associated with the maintenance phase of a building in US dollars; t_{des} = the design life of building in years; t_{mat} = the design life of the assembly of interest in years; i_{mat} = the energy intensity of each assembly of interest (J/replacement) (Adalberth 1997); D_{fuel} = the energy densities of fuel as per Table 2-2; F_{fuel} = the fuel-to-cost conversion factors as per Table 2-1 and P_{fuel} = relative contribution of each energy source as per Table 2-5. In the implementation in Rts, the parameter t_{mat}, t_{des} would be provided by the component in question. i_{mat}, D_{fuel}, and F_{fuel} would be present in a database accessible to the model calculating environmental cost due to building maintenance.

It is to be noted here that this model only approximates environmental impact of assembly replacement. Assembly replacement is only a part of total maintenance process and thus it will underestimate the impact of the maintenance phase. It has been observed that different studies assume different nature of building materials. Moreover, replacement life depends strongly on caretaking of the property. Thus, the maintenance phase of building lifecycle deserves more research.

2.7 Repair Phase

Repair here means corrective measures undertaken in case of damage due to hazards, poor workmanship during construction or improper design. It does not include any maintenance performed due to regular wear and tear of building components. The model for estimating energy usage due to building repair is of the form,

$$EC_R = \sum q_r \cdot i_p \cdot \sum\left(P_{fuel} \cdot \frac{F_{fuel}}{D_{fuel}}\right) + \frac{t_r}{t_s} \cdot d_{wt} \cdot \sum\left(i_{wt} \cdot \frac{F_{fuel}}{D_{fuel}}\right) + \sum\left(q_r \cdot i_{mt} \cdot d_{mt} \cdot \frac{F_{fuel}}{D_{fuel}}\right) \quad (2\text{-}9)$$

where EC_R = the environmental impact cost associated with the repair phase of the building in US dollars; q_r = the quantity of a material in kg required for repair as provided by the repair manager (Rts); i_p = the process energy intensity or embodied energy for a given material's extraction and manufacture (J/kg); i_{mt} = the material transportation energy intensity for a given mode (J/kg/km) (Table 2-7); t_r = the total worker hours required for repair work as provided by repair manager (hours); t_s = the worker shift (hours), typically 8 hours; d_{wt} = the distance travelled by workers including return trips (km); i_{wt} = the worker transportation energy intensity (J/passenger/km); D_{fuel} = the energy densities of fuel as per Table 2-2; F_{fuel} = the fuel-to-cost conversion factors as per Table 2-1; d_{mt} = the distance between manufacturing plant and the construction site and P_{fuel} = relative contribution of each energy source as per Table 2-5. In the implementation in Rts, the parameters i_p, i_t, D_{fuel}, F_{fuel}, and i_{wt} will be available in a database accessible by the model that calculates the total environmental cost of repair phase.

2.8 End of Life Phase

The equation for estimating the energy at the end-of-life of a building is,

$$EC_{EOL-1} = \sum\left\{q_{eol} \cdot \left(1 - \frac{R_{rec}}{100}\right) \cdot \frac{ec_{lf}}{1000}\right\} + \sum\left(q_{eol} \cdot i_{mt} \cdot d_{mt} \cdot \frac{F_{fuel}}{D_{fuel}}\right) \quad (2\text{-}10)$$

$$EC_{EOL-2} = \sum\left\{q_{eol} \cdot \frac{R_{rec}}{100} \cdot \left(1 - \frac{e_{rec}}{100}\right) \cdot i_p \cdot \sum\left(P_{fuel} \cdot \frac{F_{fuel}}{D_{fuel}}\right)\right\} \quad (2\text{-}11)$$

$$EC_{EOL} = EC_{EOL-1} - EC_{EOL-2} \quad (2\text{-}12)$$

where EC_{EoL} = the environmental impact cost associated with the end of life phase of a building in US dollars; EC_{EoL-1} = the environmental impact cost due to landfilling and transporting materials to either the landfill site or the recycling plants; EC_{EoL-2} = the energy saved in the production of certain materials by using recycled materials; q_{eol} = the material mass (kg); R_{rec} = average recycling rates in percent for various materials as given in Table 2-8; ec_{lf} = environmental damage cost of landfills per ton; i_t = the material transportation energy intensity for a given mode (J/kg/km) (Table 2-7); d_{mt} = the average distance between demolition site and recycling plant or landfill (km); D_{fuel} = the energy densities for the fuels used for labor and material transportation, which can be obtained from Table 2-2; F_{fuel} = the fuel-to-cost conversion factors as per Table 2-1; e_{rec} = energy for recycling materials in terms of percent of their primary production energy as provided in Table 2-9; i_p = the process energy intensity for a given material's extraction and manufacture (J/kg) as per Table 2-3; and P_{fuel} = relative contribution of each energy source as per Table 2-4 or Table 2-5. In the implementation in Rts, parameter q_{eol} can be provided by respective components. The remaining factors will be provided by a database accessible to model calculating environmental cost of end of life phase.

Buildings produce waste and cause significant environmental impact when the end of life phase is reached. It is not easy to estimate the cost of end-of-life phase as it is not clear how the benefits and burdens are to be distributed. Still, an effort has been made to get a reasonable impact cost. Depending upon the type of material, location and local waste policies, a percentage of demolition waste is recycled and reused while the remaining is transported to a landfill. Thus, to estimate environmental impact of the end of life phase, the percentage of total material recycled and dumped is needed. In addition to this, approximate environmental impact cost of landfills and recycling process of materials is also required. Environmental damage cost of landfills (ec_{lf}) has been taken as $13/ton (Rabl et al. 2008). Approximate average recycling rates (R_{rec}) for various common building materials have been provided in Table 2-8. The remaining material is assumed to be dumped in a landfill.

Table 2-8: Approximate average recycling rates for building materials in the US (Townsend et al. 2014)

Building material	**Approx. average recycling rate (R_{rec})**
Aggregate (Cement/Concrete)	85%
Wood	98%
Drywall	100%
Metals	98%
Cardboard	83%
Glass	50%
Plastic	50%

Recycling is also an energy intensive process, but it consumes less energy than manufacturing a material from scratch. Energy for recycling (e_{rec}) some common building materials after collection and sorting in terms of percent of their primary production energy has been provided in Table 2-9.

Table 2-9: Energy used in production using recycled material (Environmental Council of Concrete Organizations 1997; Rankin 2012)

Building material	**Embodied energy as % of primary production (e_{rec})**
Aggregate (Cement/Concrete)	50%
Steel	20-40%
Glass	70%
Plastic	30%
Copper	15%
Aluminum	5-10%
Paper and Cardboard	60%

2.9 Example Setup

The methodology proposed in the current chapter is being demonstrated using a typical 10-feet tall RC column having a round shape with 16” nominal diameter and 2” cover. It is reinforced with six 0.75” diameter longitudinal steel bars and 0.375” diameter circular stirrups @ 1’ c/c. Dimensions are duly shown in Figure 2-4.

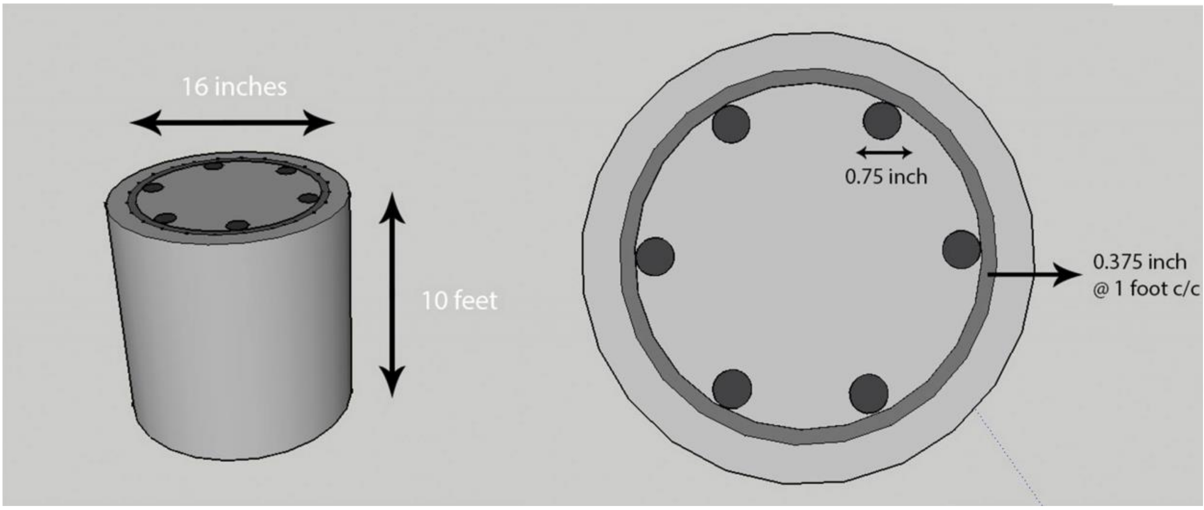


Figure 2-4: RC column example

Column is assumed to be in Vancouver. Some of the data values being used in the example are not based on local studies and ideally should have been modified for Vancouver. However, as this is just a demonstration example, there values are being used as they are.

Rts software has been used for performing the analysis. When information is not available, reasonable assumptions have been made. If the uncertainty values have been specifically assigned to the proposed values of factors being used, they have been included as they are. Otherwise, a coefficient of variation (cov) of 5% has been assigned to those factors that reflect consistent agreement among various studies, a cov of 10% to the values those are fairly variable and a cov of 20% to estimates that are highly uncertain. Table 2-10 summarizes the material and their quantities from the RC column example.

Table 2-10: Material quantity used in RC column example

Material	Quantity (kg)	Waste factor	Final quantity (kg)
Concrete	948	5%	995
Steel	46.63	5%	49
Paperboard (Formwork)	1.98	2%	2
Jute blanket (Curing)	3.5	2%	3.5

The intensity values are input as lognormal distributions with the properties identified in Table 2-11. These embodied energies include cradle-to-gate contributions and hence include energy usage during extraction, material transportation to the manufacturing plant and manufacturing phases. The coefficient of variation of 20% is being assumed as the values reported in Inventory of Carbon and Energy show significant variation.

Table 2-11: Process energy intensities, i_p (Hammond and Jones 2006)

Material	Process energy intensity, i_p (MJ/kg)	Coefficient of variation (Cov)
Concrete	0.95	20%
Steel	36.40	
Paperboard	24.80	
Jute blanket	18.60	

The relative contribution of each energy source towards embodied energy (Table 2-12) has also been provided in Inventory of Carbon and Energy for some materials. If the required information was missing, the average values as per Table 2-5 have been used.

Table 2-12: Relative contribution of each energy source towards embodied energy (Hammond and Jones 2006)

Material	Relative fuel contributions in percentage (P_{fuel})				
	Coal	LPG	Fuel oil	Natural gas	Electricity
Concrete	47.1	-	15.4	3.1	34.4
Steel	17	-	-	33	50
Paperboard	4.3	-	0.3	31.8	63.6
Jute blanket	-	-	8.0	36.3	55.7

D_{fuel} and F_{fuel} values can be obtained from Table 2-2 and Table 2-1 respectively. The assumptions made for material transportation have been summarized in Table 2-13. The distances are assumed here and include backhaul. The transportation energy intensities are modeled as lognormal distributions, and the values are taken from Table 2-7. Transportation energy intensity data for ready-mix trucks was not available, so an assumed value of 1.5 times the value for heavy trucks has been taken. Diesel has been assumed to be the fuel used for material transportation.

Table 2-13: Material transportation assumptions during construction

Material	**Mode**	**Distance from manufacturing plant to construction site (km)**	**Transportation energy intensity (i_t) (J/kg/km)**	**Cov**
Concrete	Ready-Mix Truck	30	3600	10%
Steel	Heavy Truck	40	2400	
Paperboard	Light Truck	60	7640	
Jute blanket	Light Truck	60	7640	

RS Means also provide data related to the number of hours required for a certain kind of work. Table 2-14 shows that about 3.76 hours are needed for constructing our example RC column. Contributions from concrete are not included as it is assumed to be ready-mix concrete. Curing data was not provided and was assumed to take 0.24 hours. This gives an approximation of total worker hours (t_{wh}) needed for our example to be 4 hours.

Table 2-14: Calculating total worker hours using RS means

Activity	**Per unit labour hours**	**Unit**	**Quantity**	**Total labour hours**
Formwork	0.23	L.F.	10	2.29
Concrete	-			
Reinforcement	21.33	Ton	0.05	1.10
Placing	0.71	C.Y.	0.5	0.37
Curing	-			0.24
Total (t_{wh})				4.00

In this example, the only activity which required the use of heavy machinery was placing concrete using a pump. Thus, the ratio of worker-hours assigned to heavy machinery to total worker-hours comes out to be 0.09. Assuming a 100 HP pump working for 0.37 hours gives 99 MJ as energy usage due to heavy machinery. This means the heavy machinery energy intensity is 268 MJ/worker-hour. Table 2-15 summarizes the heavy machinery usage data.

Table 2-15: Heavy machinery usage related inputs

Parameter	**Distribution type**	**Mean**	**Cov**
Total worker-hours (t_{wh})	Lognormal	4.00 hours	5%
Ratio of heavy machinery to total worker-hours (r_h)	Constant	0.09	-
Heavy machinery energy intensity (i_{hm})	Lognormal	268 MJ/worker-hour	10%
Number of workers (n_w)	Constant	4 workers	-

Passenger transportation data has been developed using Table 2-6 presented earlier. Mode share contributions have been assumed to be 50% automobile, 30% sky train, and 20% diesel bus. The passenger transportation data has been summarized in Table 2-16.

Table 2-16: Passenger transportation related inputs

Mode	**Contribution**	**Passenger transportation intensity, i_{wt} (MJ/passenger/km)**	**CoV**	**Worker travel distance including back trips, d_{wt} (km)**
Automobile	50%	2.73	10%	30 km
Diesel bus	20%	0.92		
Sky train	30%	0.39		

For the end of life phase, Table 2-8 and Table 2-9 provide most of the data required. Remaining data has been summarized in Table 2-17. Mode of transportation of demolished material has been assumed to be a heavy truck with diesel being the primary fuel.

Table 2-17: End of life phase related inputs

Parameter	Distribution type	Mean value	C.o.v.
Environmental cost of landfilling (ec_{lf})	Normal	$13/ton	20%
Distance traveled from demolition site to landfill or recycling plant (km)	Constant	50 km	-

Remaining parameters have already been defined and given appropriate valuation in their respective sections discussed previously. The results of this RC column example are presented in the next section.

2.10 Example Results

Total environmental impact cost has been calculated by introducing all relevant variables into the Rts implementation of the cost models proposed. Figure 2-5 shows the total environmental cost of the RC column as a probability density function (PDF). Mean environmental impact cost comes out to be $68 with a coefficient of variation of 16%. The cost calculated includes contributions from extraction and manufacturing phase, construction phase, and end of life phase only. Operation phase has not been included as the basic factors, on which the energy usage during this phase depends, cannot be attributed to a column in any sensible way. Repair phase was ignored as no hazard event was assumed in our example. Maintenance phase was not included as the proposed model for maintenance phase depends on assembly replacement and in the current example there was no assembly to replace. Table 2-18 summarizes the contributions from each lifecycle phase towards the overall impact.

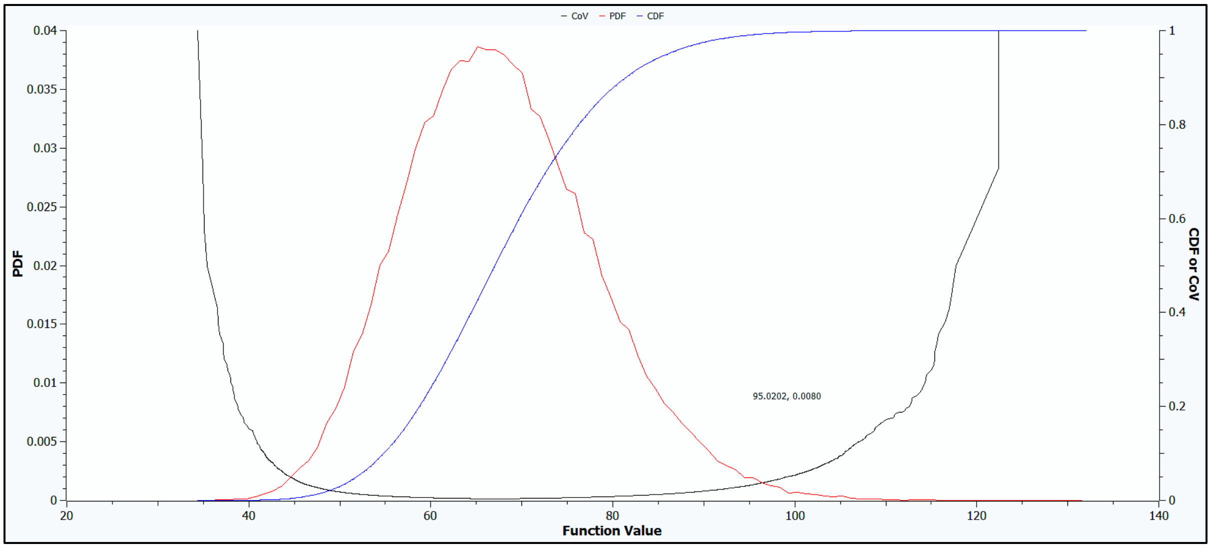


Figure 2-5: Environmental impact cost for RC column

Table 2-18: Environmental impact cost for individual lifecycle phases

Building Lifecycle Phase	Mean Environmental Impact Cost	Coefficient of Variation
Extraction and Manufacturing Phase	$118	20%
Construction Phase	$11	24%
End of Life Phase	-$60	23%
Overall Cost	$68	16%
Overall Cost, excluding recycling	$146	16%

As can be seen from Table 2-18, end of life has a negative impact cost, which means it has a net positive impact on the environment. This is the case when recycling is considered in the calculations. If recycling is completely ignored and replaced with landfilling, the environmental impact cost increases considerably to $146 (Figure 2-6). This shows the importance recycling towards the environment.

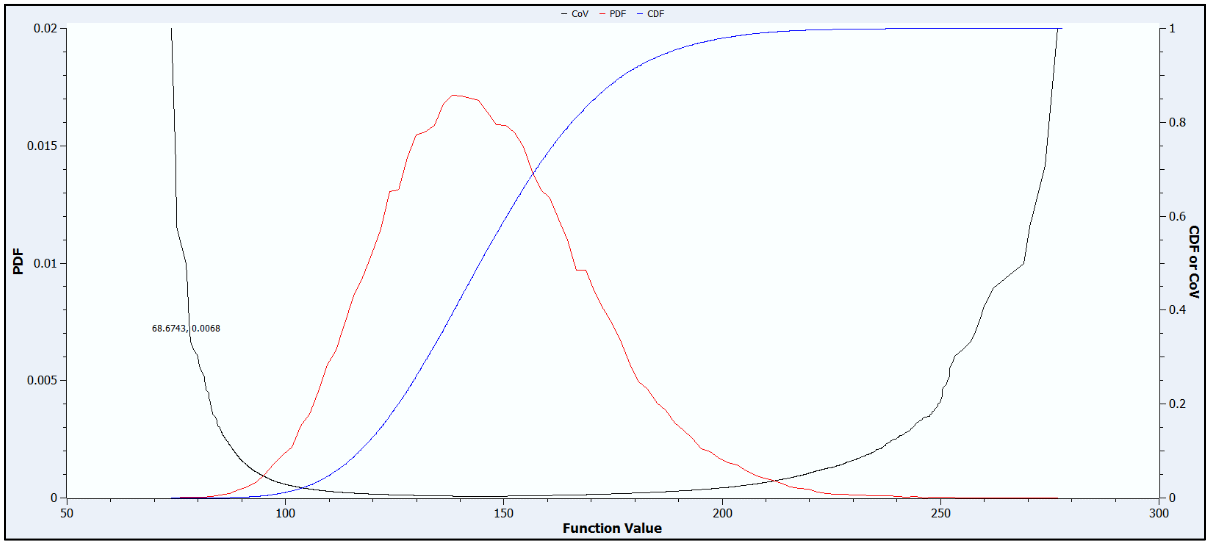


Figure 2-6: Environmental impact cost for RC column, excluding recycling

Table 2-19: Gamma importance measures

Parameter	Gamma Importance Measure
Process energy intensities, i_p	0.60
Fuel-to-cost conversion factors, F_{fuel}	0.40
Fuel densities, D_{fuel}	-0.08
Material transportation energy intensities, i_t	0.04
Heavy machinery energy intensity, i_{hm}	0.03
Damage cost for landfills, ec_{lf}	0.03
Total worker hours, t_{wh}	0.03
Passenger transportation energy intensities, i_{wt}	0.02

Table 2-19 lists the gamma importance measures of the variable parameters used in the environmental impact cost models as input. It indicates that the process energy intensities and the fuel-to-cost conversion factors have considerable influence on the results. This means that research targeted at making these values better would have the most significant impact towards reducing the uncertainty of these models.

Chapter 3: Construction Cost

The objective of this chapter is to explain a common procedure for estimating the construction cost of a building. The procedure is then used to create a database of cost values from which new probabilistic models are developed. A demonstration application is also included, calculating the cost of constructing a reinforced concrete column.

Construction cost estimation is usually performed in two steps. First step is to roughly calculate how many units of different materials or activities is required to get the job done. This requires a working knowledge of construction materials, methods, and current industrial practices. Second step is to approximate a reasonable cost for those units. A reasonable understanding of the labor and material markets and their probable future fluctuations is required here. Detailed construction plans, with necessary material and procedural specifications, make sure that the quantities calculated during estimation are considerably accurate. On the other hand, labour rates and even material costs vary from city to city and even from supplier to supplier within the same town. These fluctuations result in variations in estimates. To overcome this problem, standard cost databases like RS Means, Cost Works, and Innovaya are used.

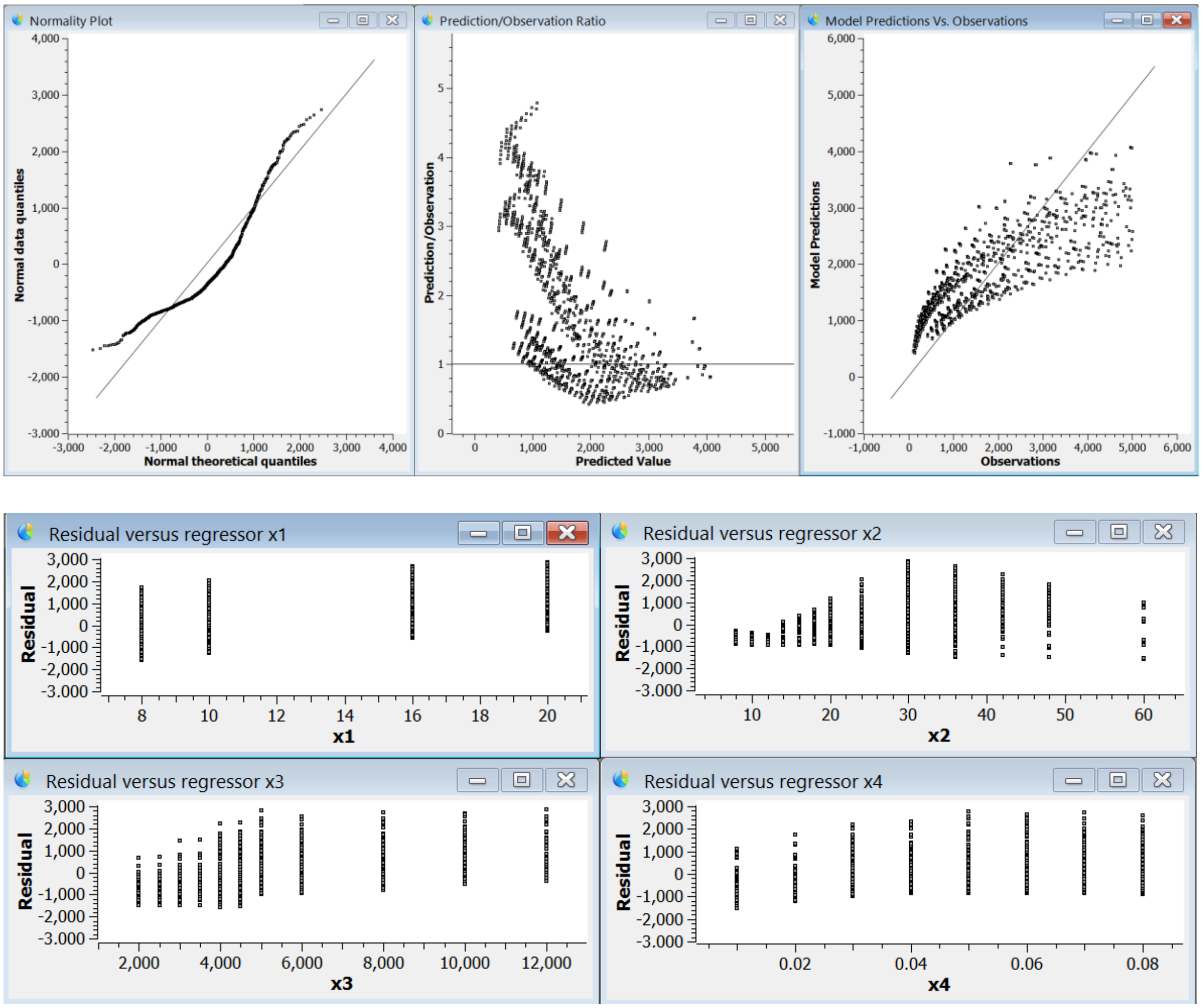
3.1 RC Column Component

In this section, a linear regression model for estimating construction cost of a reinforced concrete (RC) column is proposed. Concrete is one of the most versatile and widely used materials in the construction industry. Concrete is durable, comparatively easy to work with, and virtually maintenance-free. Concrete cost estimation is relatively straightforward as most of the materials and methods used are listed in building cost construction (RS Means 2012) data, which is being used here.

Cost of a building depends primarily on the geometric and material properties. For the considered RC column, height and diameter are the said geometric properties. Moreover, concrete strength and steel reinforcement ratio also affect construction cost. Data required for the regression model was obtained by varying these four independent variables and calculating the cost of RC column by using RS Means. The complete data table has 1324 data entries. It is difficult to include in the thesis document. Still, a part of the data is provided in Appendix C as a sample. The complete detailed procedure explaining how the data was obtained is provided in Appendix B.

3.2 Model Construction using Raw Data

A regression model was constructed from the data table using Rts software. Trial results (Figure 3-1) show the model predictions deviating considerably from the observations. This indicates that this model is not an appropriate representation of the raw data. Usually, building a regression model is an iterative process as several things can go wrong while trying to build a model from observations. These imperfections are then corrected in subsequent trials. The potential issues include collinearity, heteroskedasticity, and correlation and non-normality of errors. These issues, along with the techniques with which they are detected and corrected, have been discussed in Appendix D. The final linear regression model proposed for cost estimation of a RC column is presented in the next section.




```
Mean of the model parameters:
|     -13.7459 |
|      64.1831 |
|   -0.0114335 |
|      9176.35 |

Coefficient of variation (in percent) of the model parameters:
|      24.7715 |
|      2.88221 |
|      112.832 |
|      13.6732 |

Correlation matrix of the model parameters:
|            1     -0.381531     -0.208219     -0.145678 |
|    -0.381531             1     -0.492138      0.117129 |
|    -0.208219     -0.492138             1       -0.6946 |
|    -0.145678      0.117129       -0.6946             1 |

R-factor: 0.840373
Mean of sigma: 778.814
Coefficient of variation of sigma: 0.019492
```

Figure 3-1: Raw data results obtained using Rts software

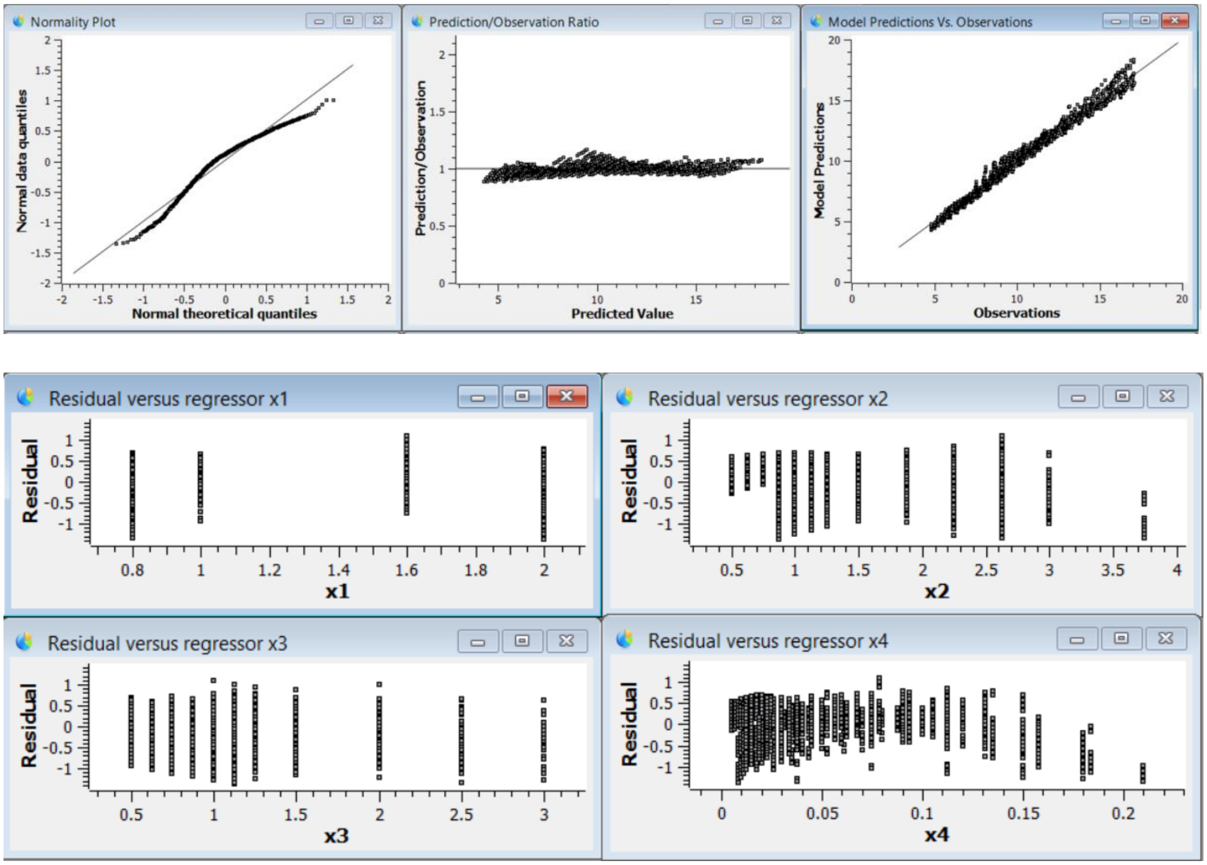
3.3 Linear Regression Model for RC Column

The final linear regression model with unit-less regression coefficients would be of the form:

$$\sqrt[3]{y} = \theta_1 \cdot h + \theta_2 \cdot d + \theta_3 \cdot f_c + \theta_4 \cdot \rho \cdot d + \varepsilon \qquad (3\text{-}1)$$

where y = the cost of RC Column in 2012 US Dollars; θ_1 = a unit less regression coefficient with 3.0 as mean and 0.6% as coefficient of variation; h = the height of RC Column in metre divided by standard height of 3.0 metre; θ_2 = a unit less regression coefficient with 2.7 as mean and 0.7% as coefficient of variation; d = the diameter of the RC Column in metres divided by standard diameter of 0.4 metre; θ_3 = a unit less regression coefficient with 0.8 as mean and 3.3% as coefficient of variation; f_c = the strength of ready mix concrete in MPa divided by 27 MPa as standard strength; θ_4 = a unit less regression coefficient with 33.0 as mean and 1.3% as coefficient of variation; ρ = the steel reinforcement ratio, and ε = the model error with 0.4 as standard deviation. In the implementation in Rts, the parameters height (h), diameter (d), concrete strength (f_c), and reinforcement ratio (ρ) are envisaged being provided by the RC Column component.

Once again Rts software was used to perform the regression analysis on the data and the results obtained are provided below in Figure 3-2. As compared to the raw data trial results (Figure 3-1), these results are a considerable improvement.




```
Mean of the model parameters:
|      3.00889 |
|      2.67121 |
|     0.759252 |
|      33.0622 |

Coefficient of variation (in percent) of the model parameters:
|     0.644758 |
|      0.70074 |
|       3.2507 |
|       1.2874 |

Correlation matrix of the model parameters:
|            1    -0.478816    -0.533489     0.346833 |
|    -0.478816            1   -0.0873888    -0.529652 |
|    -0.533489   -0.0873888            1     -0.58307 |
|     0.346833    -0.529652     -0.58307            1 |

R-factor: 0.992166
Mean of sigma: 0.420666
Coefficient of variation of sigma: 0.019492
```

Figure 3-2: Final model results

3.4 Rts Sampling Analysis

Both, the regression equation derived above and the regression method used for the purpose, are a little complex and difficult to understand due to the presence of random variables as coefficients. Each of these regression coefficients is a variable with different "coefficient of variation," and even the model itself has a variable "error." All this makes the model difficult to visualize and response harder to interpret. To understand the model better, a sampling analysis has been run, once again using the RC column example. The result has been shown in Figure 3-3.

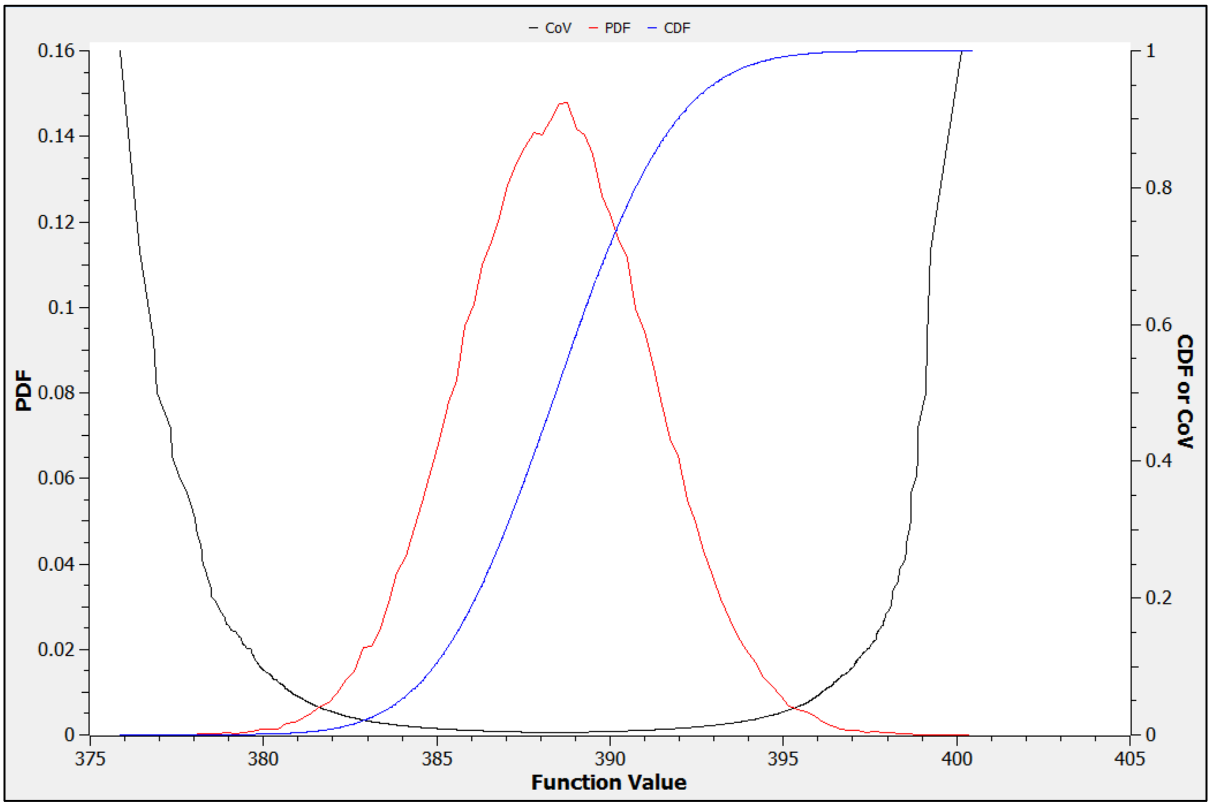


Figure 3-3: Sampling analysis of RC column example

Figure 3-3 represents the final regression model for RC column construction cost as a probability density function (PDF). This describes the relative likelihood for the RC column to have a given cost value. The mean cost value comes out to be $388 with a standard deviation of $3. Moreover, we can also see from the pdf graph above that the probable cost values mostly lie between $380 and $397. Although the model seems to estimate on a little higher side (Appendix B), it can be used rather successfully for relatively fast first draft estimates.

Chapter 4: Cost of Injuries and Fatalities

The conservation of life is the central goal of any structural design. Whenever new rules and regulations of engineering practice or building codes are enacted, benefits are weighed versus costs, with safety being one of the most important parameters. The regulators enacting these rules are supposed to answer questions such as: Should all buildings be made as much fireproof and earthquake resistant as possible? Should the inspection and assessment of new and existing structures be made more frequent and stringent? Should certain significant parameters in code be changed to increase the structural safety irrespective of the costs? Regulators are supposed to put numbers on the pros and cons of these questions. Technical as it sounds, what underlies all these questions is something that is far from just technical. It is, in fact, a deeply ethical issue: How to assess the value of a Human life in financial terms? How much money could be logically spent to save a single life, considering the finite resources? Until this is addressed, the cost-benefit questions asked above cannot be answered.

The value of life is estimated by considering the risks that people are voluntarily willing to take in return for some extra cash or benefits (Mankiw 2011). It is called value of statistical life (VSL). It is important to note that VSL is somewhat different from the value of an actual life. VSL is the value placed on changes in the likelihood of death, not the price a person would willingly pay to avoid death. However, they are being considered the same here.

In VSL studies, most of the researchers look at how the wages change with the changes in job characteristics like the risk of death, occupation, industry, and location of work. The inherent trade-offs made by workers, between incremental increases in the risk of dying on the job and the additional wages required to accept such riskier jobs, are estimated and converted into corresponding estimates of the VSL (Mrozek and Taylor 2001).

4.1 Value of Statistical Life

Since January 1993, the US department of transportation has adopted a guidance memorandum, "Treatment of Value of Life and Injuries in Preparing Economic Evaluations." This document set forth recommended economic values to be used in department regulatory and investment analyses (Duval and Gribbin 2008). The initial value was set at $2.5 million and directed periodic adjustments have been made since then. In 2008, the value of life estimate was adjusted again taking into consideration some of the major studies performed on the subject in the early 2000s. Table 4-1 shows the studies those were chosen to be considered for VSL estimate adjustment (values adjusted to 2007 dollar):

Table 4-1: Studies considered for VSL estimation

(Mrozek and Taylor 2001)	$2.6 million
(Viscusi and Aldy 2003)	$8.5 million
(Miller et al. 2000)	$5.2 million
(Viscusi 2004)	$6.1 million
(Kochi et al. 2006)	$6.6 million

The mean of these five values ($5.8 million) was chosen to be the adjusted VSL estimate in 2008. This value was further increased to $6 million in 2009 (Duval and Gribbin 2008). In this thesis, $6 million would be considered as the VSL.

4.2 Value of Preventing Injuries

Usually, non-fatal injuries are far more common than fatal ones. A standardized method is used by US department of transportation to estimate the value of injuries, scaled in proportion to VSL. Relative value coefficients for preventing injuries of varying severity and duration used by US transportation department are based on the abbreviated injury scale (AIS), which categorizes injuries into levels ranging from minor (AIS 1) to critical (AIS 5). Table 4-2 contains the schedule of coefficients for each category of injuries:

Table 4-2: Schedule of coefficients for different category of injuries (Duval and Gribbin 2008)

AIS level	Severity	Fraction of VSL
AIS 1	Minor	0.002
AIS 2	Moderate	0.016
AIS 3	Serious	0.057
AIS 4	Severe	0.188
AIS 5	Critical	0.762
	Fatal	1.000

These estimates have been developed by a panel of experienced physicians by relating injuries to possible loss of quality and quantity of life. Lost market earnings and household productivity are included in these estimates.

It should be noted here that these estimates present cost of "preventing" injuries and does not mean cost of "treating" injuries. The former term relates to the idea of using cost-benefit analysis to assist in safer designs based on informed decision making while the later term estimates the post-hazard costs. Thus, as a structural engineer or designer, using cost of preventing injuries here makes more sense than using cost of treating injuries.

4.3 Uncertainty in Value of Statistical Life

Although $6 million has been assigned as value of statistical life (VSL), numerous studies show VSLs within the range of $1 million to $10 million cannot be ruled out. US department of transportation recommends using a standard deviation of $2.6 million, together with mean of $6 million (Duval and Gribbin 2008). Moreover, it was recommended to use Weibull or lognormal distribution as normal distribution includes both positive and unrealistic negative values. A standard deviation of 2.6 million for an average VSL of 6 million means a coefficient of variation (cov) of 43%.

4.4 Casualty Cost Model

The main objective of this chapter is to develop a cost model for estimating economic cost of preventing injuries and fatalities in case of a hazard. For a typical building, such a cost would depend upon parameters like the number of occupants at the time of hazard and the severity of their injuries. Severity of injuries depends upon the extent of damage suffered by the building in question, which depends upon the type of building and severity of the hazard.

In the aftermath of an actual hazard, the damage suffered by buildings varies from "none" to "complete" as continuous function of building deformations (Federal Emergency Management Agency 2003). But is not practical to model building damage as a continuous function and hence, various "damage states" are used to describe generalized range of building damage. In this thesis, the injuries due to non-structural damage are being ignored, and emphasis has been given to structural damage only.

Multi-hazard loss estimation methodology (Hazus) developed by Federal Emergency Management Agency (FEMA) describes in detail various generalized damage states a typical building can be assumed to be in depending upon the extent of damage and deformations. Table 4-3 describes damage states for RC moment resisting frames. As described in the table, the "Complete Structural Damage" state may or may not lead to a building collapse. Only a certain percentage of buildings in complete damage state are considered to be collapsed as per Hazus methodology. Table 4-4 provides general collapse rates for several types of buildings.

Table 4-3: Damage states for RC moment resisting frames (Federal Emergency Management Agency 2003)

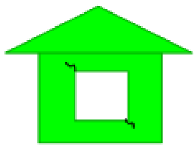
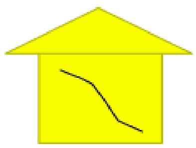
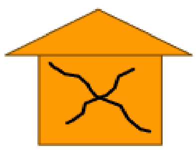
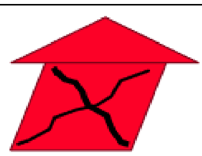
Damage State		**Description**
	Slight	Flexural or shear type hairline cracks in some beams and columns near joints or within joints
	Moderate	Most beams and columns exhibit hairline cracks. In ductile frames, some of the frame elements have reached yield capacity indicated by larger flexural cracks and some concrete spalling. Non-ductile frames may exhibit larger shear cracks and spalling.
	Extensive	Some of the frame elements have reached their ultimate capacity indicated in ductile frames by large flexural cracks, spalled concrete and buckled main reinforcement; non-ductile frame elements may have suffered shear failures or bond failures at reinforcement splices, or broken ties or buckled main reinforcement in columns, which may result in partial collapse.
	Complete Structural Damage	The structure is collapsed or in imminent danger of collapse due to brittle failure of non-ductile frame elements or loss of frame stability.

Table 4-4: Collapse rates in the event of complete structural failure for generic building types (Federal Emergency Management Agency 2003)

Model building type	**Collapse rate**
wood, steel high-rise, mobile home	3%
steel mid-rise, concrete high-rise, reinforced masonry high-rise	5%
steel low-rise	8%
concrete mid-rise, pre-cast concrete high-rise, reinforced masonry mid-rise	10%
concrete low-rise, pre-cast concrete mid-rise, reinforced masonry low-rise	13%
concrete low-rise, pre-cast concrete low-rise, unreinforced masonry	15%

In Rts implementation, the repair manager is supposed to know the visual damage elements like crack width or deformation for a component. Thus, repair manager can assign a damage state to a component as per the damage states defined in Hazus methodology. The global building component can then estimate the overall damage state of the building depending upon the damage states of various components.

Next step is to relate the building damage state to the severity of injuries. We have already discussed the different categories of injuries as defined by US Transportation Department for use in the cost of injury estimations in Section 4.2. The 5-level Abbreviated Injury Scale (AIS) described in Table 4-2 does not properly match with the 4-level severity scale (Table 4-5) proposed in Hazus. Thus, it cannot properly correspond to the various damage states defined in Hazus. It has been appropriately modified as in Table 4-6. The final relationship between building damage state and injury severity level for a low-rise concrete building has been provided in Table 4-7 as probability values. These probability values vary depending upon the type of building (Federal Emergency Management Agency 2003). This table gives the probability of experiencing injuries of a given severity level when the building is in a particular damage state due to a hazard.

Table 4-5: Casualty classification scale (Federal Emergency Management Agency 2003)

Casualty level	Casualty description
Severity 1	Injuries requiring basic medical aid, but without hospitalization (treat and release)
Severity 2	Injuries requiring medical attention and hospitalization, but not considered to be life-threatening
Severity 3	Casualties that include entrapment and require expeditious rescue and medical treatment to avoid death
Severity 4	Immediate deaths

Table 4-6: Modified cost of injury table

Casualty severity	**Corresponding AIS level**	**Fraction of VSL**	**Cost of severity in US dollars ($C_{severity}$)**	**Coefficient of variation (cov)**
Severity-1	AIS-1	0.002	12,000	43%
Severity-2	AIS-2, AIS-3	0.037	219,000	
Severity-3	AIS-4, AIS-5	0.475	2,850,000	
Severity-4	Fatal	1.000	6,000,000	

Table 4-7: Indoor concrete frame low-rise building (Federal Emergency Management Agency 2003)

Building damage state	**Casualty severity level (x10^{-3})**			
	$P_{Severity\text{-}1}$	$P_{Severity\text{-}2}$	$P_{Severity\text{-}3}$	$P_{Severity\text{-}4}$
Slight	0.5	0	0	0
Moderate	2.5	0.3	0	0
Extensive	10	1	0.01	0.01
Complete (no collapse)	50	10	0.1	0.1
Complete (with collapse)	400	200	50	100

Finally, the last parameter needed for the model is the number of people present in the building at the time of hazard. The final casualty cost model can be presented as

$$C_{cas|DS} = \sum_{Severity-1}^{Severity-n} \left(P_{Severity-x|DS} \cdot C_{Severity-x} \right) \cdot P_{present} \quad \forall (\text{DS} \neq \text{CSD}) \tag{4-1}$$

$$C_{cas|CSD} = \sum_{Severity-1}^{Severity-n} \left[\left\{ P_{Severity-x|CDS-nc} \cdot \left(1 - P_{collapse}\right) + P_{Severity-x|CDS-c} \cdot P_{collapse} \right\} C_{Severity-x} \right] \cdot P_{present} \tag{4-2}$$

where $C_{cas|DS}$ = cost of casualty for a particular building damage state in US dollars; *Severity* = severity level of injury experienced by a person due to a hazard as per Table 4-5; $P_{Severity\text{-}x|DS}$ = probability of different casualty severity levels given a damage state and building type as given in Table 4-7; $C_{Severity}$ = cost of injury per person for a particular injury severity level as per Table 4-6; $P_{Severity\text{-}x|CSD\text{-}nc}$ = probability of different casualty severity levels given a complete structural damage state but no collapse; $P_{Severity\text{-}x|CSD\text{-}c}$ = probability of different casualty severity levels given a complete structural damage state, which also resulted in collapse; $P_{collapse}$ = probability of building collapse in case of complete structural damage as per Table 4-4; $P_{present}$ = number of people present in the building at the time of hazard, which can be estimated as

$$P_{present} = P_{\max} \cdot O_{avg} \qquad (4\text{-}3)$$

where P_{max} = maximum population of the building and O_{avg} = average occupancy of the building at the time of hazard.

4.5 Example

The proposed model is being used to estimate the casualty prevention cost for a hypothetical scenario involving three single story buildings made of concrete, steel, and wood. All three structures will have different structural properties due to different materials and hence, will have a different response to a hazard. Similarly, the damage state descriptions for these structures would also be different as per Hazus methodology. But, these marked differences are not important for this example. The cost estimates are being calculated assuming a structure to be in particular damage state while not caring about how it got there.

In the model proposed in section 4.4, probability of casualty severity levels ($P_{Severity}$) and collapse rate in case of complete structural damage ($P_{collapse}$) depend upon the type of building. $P_{Severity}$ values for a single-story concrete building have already been provided in Table 4-7 while Table 4-8 and Table 4-9 contain similar values for wood and steel buildings respectively. Table 4-4 provides the $P_{collapse}$ values for different building types. It is assumed that same number of people were present inside the building at the time of hazard and let it be 2 people ($P_{present}$ = 2).

Table 4-8: Wood light frame low-rise (W1) building (Federal Emergency Management Agency 2003)

Building damage state	**Casualty severity level ($x10^{-3}$)**			
	$P_{Severity-1}$	$P_{Severity-2}$	$P_{Severity-3}$	$P_{Severity-4}$
Slight	0.5	0	0	0
Moderate	2.5	0.3	0	0
Extensive	10	1	0.01	0.01
Complete (no collapse)	50	10	0.1	0.1
Complete (with collapse)	400	200	30	50

Table 4-9: Steel frame low-rise (S1L) building (Federal Emergency Management Agency 2003)

Building damage state	**Casualty severity level ($x10^{-3}$)**			
	$P_{Severity-1}$	$P_{Severity-2}$	$P_{Severity-3}$	$P_{Severity-4}$
Slight	0.5	0	0	0
Moderate	2	0.25	0	0
Extensive	10	1	0.01	0.01
Complete (no collapse)	50	10	0.1	0.1
Complete (with collapse)	400	200	50	100

Rts software has been used for the calculations and the results obtained are being presented in Table 4-10. Respective coefficients of variation are also provided in parenthesis along with the dollar values.

Table 4-10: Casualty prevention cost in US dollars

Damage state	**Building type**		
	Concrete	Steel	Wood
Slight	13 (43%)	13 (43%)	13 (43%)
Moderate	210 (33%)	170 (33%)	210 (33%)
Extensive	930 (26%)	930 (26%)	930 (26%)
Complete	115000 (33%)	72500 (32%)	18000 (28%)

The coefficient of variation values for the results obtained varies from higher 20s to lower 40s. These values signify that there is large uncertainty in the results obtained, which stems from the uncertainty and lack of consensus in fixing a value of life. As already discussed in section 4.2, cost estimates being used for this model are prevention costs rather than treatment costs. Therefore, in a way, these results provide a theoretical upper limit of monetary resources that can be spent on casualty prevention measures. As per above results, for a single-story concrete frame house occupied by two people, it is justifiable to spend US$100000 on injury preventing safety measures alone, if there is a chance of the building suffering complete structural damage due to potential hazards. Another way to look at this situation is by noticing that preventive cost in case of extensive damage (~$930) is significantly lower than complete damage case (~$100000). It might be a better alternative to spend more on improving the structural strength and integrity of the building to reduce the chances of experiencing complete structural damage. Thus, this model can be used as a decision-making tool as intended.

Chapter 5: Example

The simple structure shown in Figure 5-1 below is used to demonstrate the use of the cost models. The building consists of four columns, one in each corner, a roof, and four non-load bearing walls.

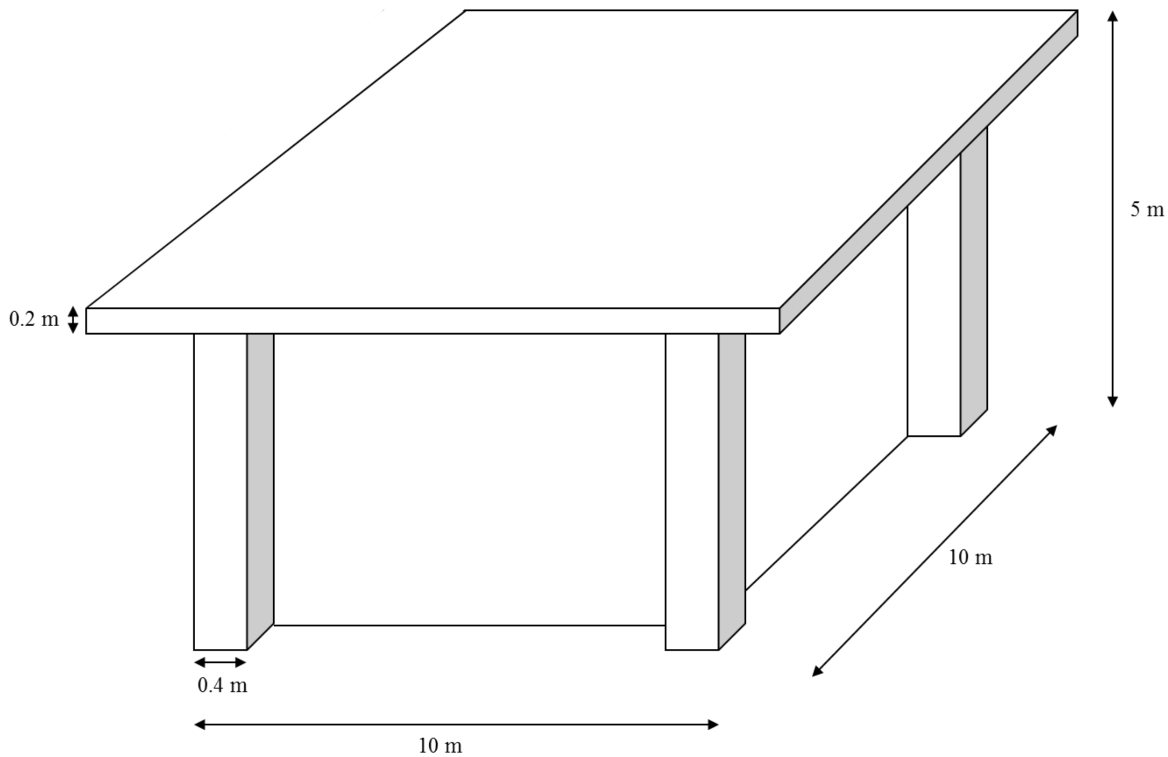


Figure 5-1: The example building

The analyses are conducted by considering the above building to be constructed using three different materials, namely, concrete, steel, and wood. Detailed description of these different material options has been provided in Table 5-1 below. It should be noted here that these analyses have been run with the same non-load bearing wall components in all three cases. Moreover, the column dimensions, the roof thickness and overall building layout are also similar for these three analysis options and are as per Figure 5-1.

Table 5-1: Structural components and material options for example building

Structural components	**Material**		
	Concrete	Steel	Wood
Columns	Cast-in-place reinforced concrete columns	Standard steel columns	Timber columns
Slabs	Cast-in-place reinforced concrete slab	Corrugated steel roof	Cross-laminated timber roof
Walls	Non-load-bearing walls with metal stud framing	Non-load-bearing walls with metal stud framing	Non-load-bearing walls with metal stud framing

This example is implemented in an object-oriented software architecture labeled “Rts”. Figure 5-2 below shows the user interface of Rts along with the visual representation of the example building.

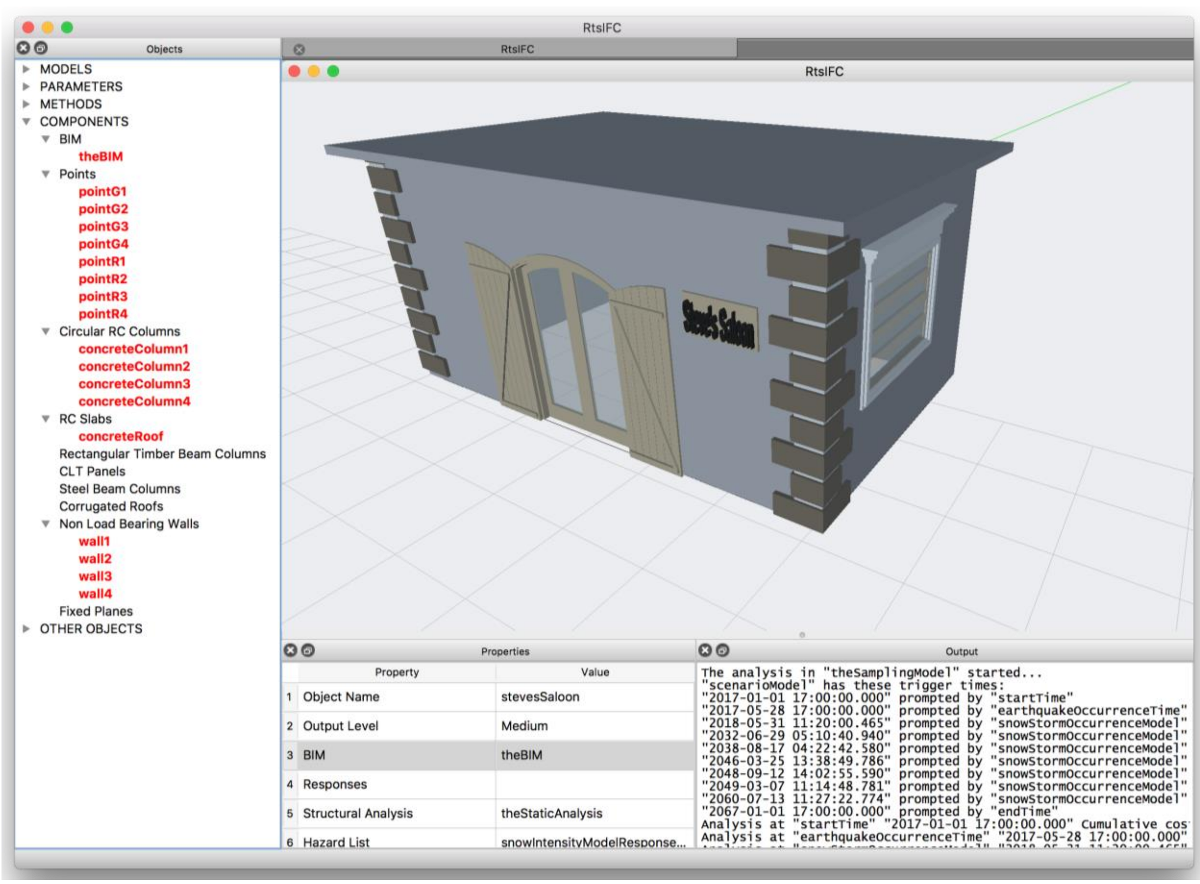


Figure 5-2: The user interface of Rts showing the example building

Figure 5-3 below shows the result obtained after the analyses. The total lifecycle cost has been obtained by analyzing the building at all key times, such as construction, demolition, and extreme hazard events in between.

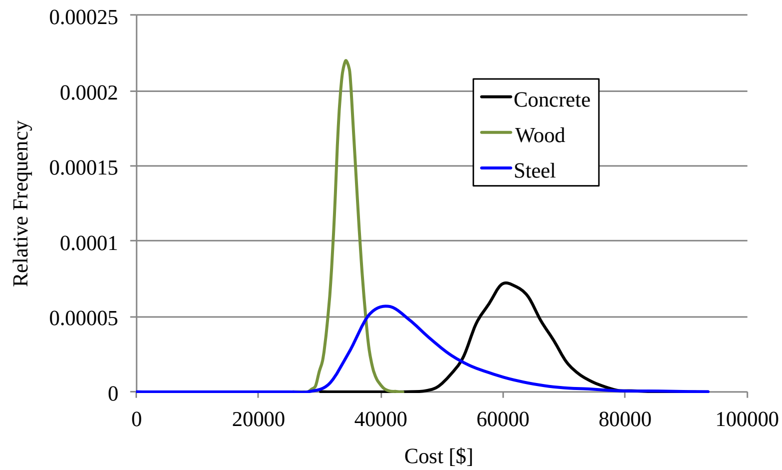


Figure 5-3: Relative frequency diagrams for total lifecycle cost

The relative frequency diagram shown above are comparable to probability density curves and suggest that wood is the best option from lifecycle perspective. Wood has the lowest cost probabilities over the lifetime of the building.

However, these results do not show the complete picture. The software program, Rts, used for implementation of these models is not fully functional yet. The structural response model in Rts was not working when this example was run. This means Rts was not able to determine the damage state of the building due to hazard. Consequently, same damage state was assumed for all three cases for this example.

Chapter 6: Conclusion and Future Work

The long-term vision for this thesis is to design buildings based on a holistic analysis of its lifecycle costs. The proposed numerical models are solely data-driven and do not suffer from prejudices based on choice of materials or design configurations. Moreover, quantifying expected environmental and health impact of a building at the design stage helps in decision making process. In this work, the emphasis was on developing models for environmental and health impact of various lifecycle phases of a building. Additional models are needed to address functionality, human experience, and direct costs of these phases. Better models with reliable data will make the software framework, Rts, a comprehensive and bias-free building design tool.

6.1 Future Research Directions

During this study, several research areas or topics have been identified for further advancements. The proposed cost models are not complete and can be improved by including missing contributions if any and/or by obtaining more reliable data. Some of the major research topics and tasks identified are discussed below:

- In chapter 2, fuel-to-cost conversion factors (F_{fuel}) forms an integral part of each environmental impact model and the current data available for such factors is underwhelming. The data used for the models has been obtained from a single study and hence, significantly undermines the model reliability. Furthermore, the said study deals with environmental impact of certain fuels usage in transportation and hence, is not directly related to buildings. Given the general disinclination towards assigning pure cost values to environmental damage, the lack of more relevant studies is not surprising. Future research is suggested towards either developing models where such fuel-to-cost conversion factors are not required or obtaining reliable data for the current models.

- In chapter 2, the environmental impact cost models are primarily based on converting energy usage to damage cost. The fuel-to-cost conversion factor used in these models includes the impact of Green House Gasses (GHG) produced during the energy usage on the environment. But, during some activities such gasses are also produced without the energy usage. For example, leakage of natural gas during extraction and transportation or particulate emissions during construction activities. More comprehensive models are needed to include such missing contributions.
- In chapter 2, the cost model for extraction and manufacturing phase uses embodied energy data from a single source. The major reason behind this choice was the disagreement among data from different sources. As an alternative, average of such data sources may be used in the model.
- Further research is suggested to develop and implement a model for maintenance, replacement, and demolition decisions. This model should be developed considering effect of several factors on the stakeholder's decision for such actions. Primary purpose of this model should be to ascertain the need for maintenance or demolition actions at a certain point in lifecycle of a building. It should be able to call the maintenance and demolition cost models respectively in the event such action is taken.
- In Chapter 3, the methodology proposed for the construction cost models is tedious, error prone, and component specific. This means preparing such models takes time and different models need to be developed for different components. It is a potential area for further research where a more generic model can be developed, which can be used for multiple

components. One way is to use an API to directly link a BIM software to a costing system to generate automatic cost estimates with zero user inputs.

- In chapter 4, the model proposed for calculating human impact cost of hazards is simplified. It only calculates such cost for the people who are inside the building while ignoring effects on people outside the building. Moreover, effects due to non-structural damage are not included. Further research is suggested to develop a more complete model for human impact cost.

As already discussed, one of the main limitations of this framework is the lack of reliable data. The models are only as good as the data they are based on. However, if this framework is successful in achieving even the most basic aspects of the long-term vision, it will itself generate a push towards future researches for obtaining better data.

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Appendixes

Appendix A Energy Usage as per Fuel-type in Manufacturing and Mining Industry

The objective of this appendix is to explain the procedure used to derive the energy usage per fuel type data described in Table 2-5. Canada is one of the largest mining communities globally (Jeswiet et al. 2015) and consequently, mining has a significant impact on the environment. Statistics Canada (STC) and Natural Resources Canada collects energy use data, usually through surveys. This data is then used by Canadian Industrial Energy End-use Data and Analysis Centre (CIEEDAC) to estimate energy usage trends in Canadian mining industry (Nyboer and Griffin 2016). Energy fuel consumption data for manufacturing industries used in this thesis has been obtained from Statistics Canada (Statistics Canada 2015).

It is important to note here that the mining energy usage data used here for estimating average fuel split does not include energy consumption during oil, gas, and coal extraction. The environmental impact contributions from oil, gas and coal extraction have already been incorporated into fuel-to-cost conversion factors discussed in section 2.2. Similarly, the manufacturing energy usage data used here includes data related to building materials and construction only. Mining energy consumption data for different fuel types is being provided in Table A-1. Oil, gas, and coal extraction data has not been included.

Table A-1: Energy consumption per fuel type in mining industry (Nyboer and Griffin 2016)

Fuel-type	Mining energy consumption per fuel (PJ)
Diesel	39
Coal coke	12
Natural gas	33
Electricity	55
Heavy oil	12
LPG	4

The data provided has been used to construct the pie chart detailing the energy usage in Canadian mining industry based on different fuel types (Figure A-1).

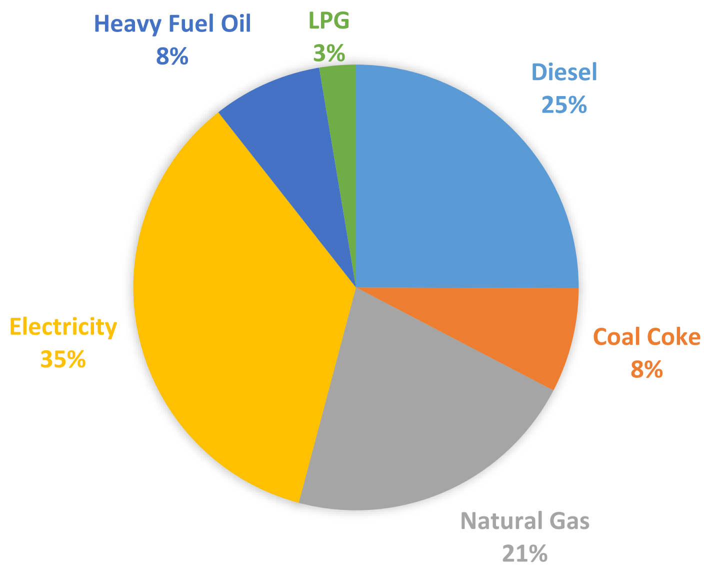

Figure A-1: Energy consumption in mining as per fuel-type (Nyboer and Griffin 2016)

Similarly, energy fuel consumption data for manufacturing industries has been obtained from Statistics Canada (Statistics Canada 2015). Instead of including all manufacturing industries, only those manufacturing industries have been included those are related to building materials and construction. Table A-2 lists the major industries included in the manufacturing energy usage data. Manufacturing energy consumption data for different fuel types is being provided in Table A-3. The raw data available has been used to construct the pie chart detailing energy usage in Canadian manufacturing industry based on different fuel types.

Table A-2: Major industries included in the manufacturing energy usage data (Statistics Canada 2015)

Paint, coating and adhesive	Spring and wire product	Glass
Plastic product	Structural metals	Cement
Rubber product	Hardware	Lime
Iron and steel mills and ferro-alloy	Non-ferrous metal foundries	Non-ferrous metal smelting and refining
Steel product	Machine shops	Alumina and aluminum
Gypsum	Screw, nut and bolt	Iron foundries
Steel foundries	Fabricated metal	Furniture

Table A-3: Energy consumption per fuel-type in manufacturing industry (Statistics Canada 2015)

Fuel-type	**Mining energy consumption per fuel (PJ)**
Coal	39
Coke oven gas	19
Electricity	260
Diesel	6
Natural gas	174
Petroleum coke	22

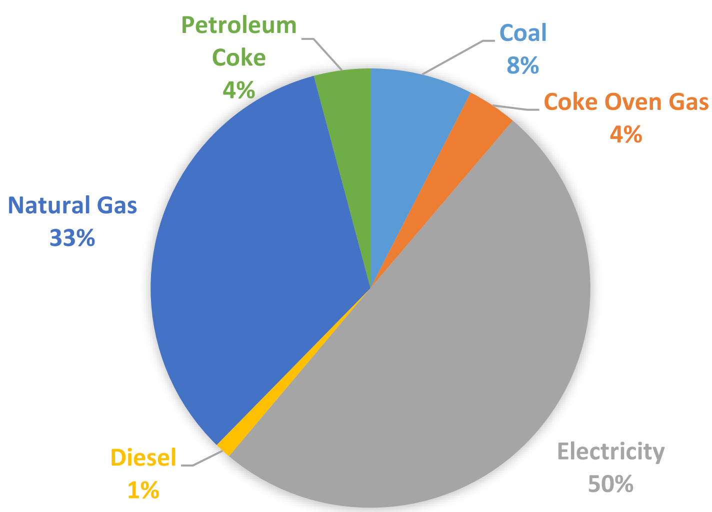

Figure A-2: Energy consumption in manufacturing as per fuel-type (Statistics Canada 2015)

Total cost for extraction and manufacturing phase has been obtained by combining the data represented by Figure A-1 and Figure A-2. However, these pie charts cannot simply be added up as the contributions from mining and manufacturing sectors towards the total may not be equal. Relative contribution of mining and manufacturing industries towards a combined "extraction and manufacturing" sector has been presented in Figure A-3. It has been obtained by comparing the total energy usage from Table A-1 and Table A-3.

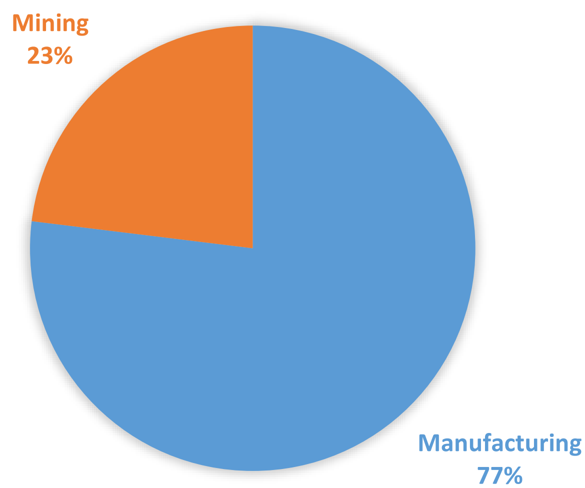

Figure A-3: Relative energy consumption in manufacturing and mining

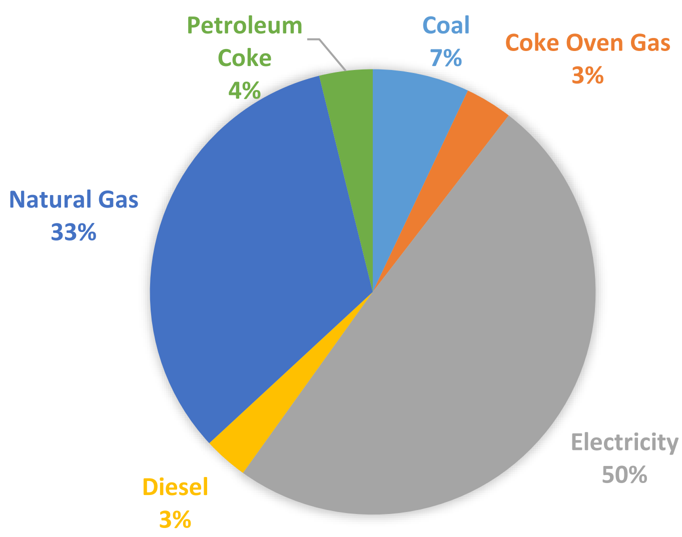

Figure A-4: Average energy usage in extraction & manufacturing phase

Thus, mining sector contributes only 23% while manufacturing sector contributes 77% towards a combined extraction and manufacturing sector. These factors have been used while adding up the contributions from Figure A-1 and Figure A-2 to obtained Figure A-4. Environmental impact data (F_{fuel}) for petroleum coal and coke oven gas is not available therefore, their contributions have been ignored in Table 2-5.

Appendix B Cost Data for Circular RC Column using RS Means

The RS Means database provides unit cost data for various items required in construction and related activities. Choices regarding what items to be used depend on several factors. For example, selection of formwork depends on size and shape of the RC column, which in turn is driven by architectural considerations. Table B-1 lists the RS Means items that are required for this example along with the parameters that determine which items need to be chosen.

Table B-1: Item selection

Checklist item	RS mean item	Parameters	Consideration for selection	Choice made by
Formwork	Round fiber tube, 1 use, 16” diameter (Item no. 031113251700)	Shape and size of the column	Architectural	Owner or architect
		Single or multiple use	Economic	Contractor
Reinforcing	A615 Grade 60 columns, #3 to #7 (Item no. 032110600200)	Column strength	Structural	Engineer
Concrete	Ready mix, 4000 psi (Item no. 033105350300)	Mix	Economical	Contractor
		Compressive strength	Structural	Engineer
Placing	Columns, round 16” thick, pumped (Item no. 033105700400 and 600)	Method	Economic	Contractor
Curing	Curing blankets, 1” to 2” thick, buy, max. (Item no. 033913500450)	Method	Time constraint, economic	Contractor

Unit costs for the items selected in Table B-1 were looked up in RS Means, and corresponding quantities were calculated to obtain the total cost of each checklist component. The total construction cost for this RC column comes out to be US $ 338 (Table B-2). It is important to note here that cost of materials, labor, and equipment that the installing contractor pays are included in this cost estimation. However, any markups for profit or labor burden are not included. Moreover, the cost estimate values are represented as national average cost in US dollars as per 2012 market conditions.

Table B-2: Cost estimation of RC column example

Items	Item description	Unit	Unit cost	Quantity	Total cost
Formwork	Forms in place, columns round fiber tube, recycled paper, 1 use, 16” diameter	L.F.	13.84	10	138.40
Reinforcement	Reinforcing in place, 50-60 ton lots, A615 grade-60, columns, #3 to #7	Ton	2030	0.0514	104.34
Concrete	Ready mix includes local aggregate, sand, portland cement, and water 4000 psi	Cubic Yard (C.Y.)	103	0.517	53.25
Placing	Includes labor and equipment to place, strike off and consolidate columns, square or round 16” thick, pumped	C.Y.	41.32	0.517	21.36
Curing	Water curing curing blankets, 1” to 2” thick, buy, max.	S.F.	0.51	42.08	21.46
Total base cost (2012 US $)					**338.81**

RS Means can provide cost estimate including overhead and profit that the installing contractor will charge the customer. This includes the cost of materials plus 10% profit, the cost of labor plus labor burden, and 10% profit and the cost of equipment plus 10% profit. General contractor’s overhead and profit though is not included even in RS Means. This cost overhead and profit part are not being included in our estimate as such costs may vary from place to place and contractor to contractor.

As the data provided in RS Means represents “national average” cost, this data needs to be modified to the project location using the city cost indexes (CCI). Now if we must convert our estimate to represent a project located in Vancouver, we can obtain the city index for Vancouver as 123.9 from RS Means. It would provide the cost estimate for our example to be 419.79 Canadian dollars. This cost is still as per 2012 estimates, and latest RS Means data is needed for an estimate as per 2016 market.

B.1 Cost Equations for estimating Construction Cost of RC Column

Above example demonstrated that construction cost estimation requires different “construction items” to be identified and their unit prices to be looked up from price data tables like RS Means. This whole process is tough to automate because even a single construction action can correspond to a significant number of possible “item” choices. That is why almost all the construction cost estimation tools/software require the user to input the necessary items before an estimate can be obtained as output. In our case, the luxury to ask the user to input each item is not available. Hence a different approach is being used.

There are many items in RS Means that are almost similar in all other regards, and the price varies only due to a single variable. The cost data of such items has been collected and consolidated into equations. These equations were later used to estimate the construction cost. In the considered RC column example, the cost of formwork depends on the shape and size of the column while the cost of ready mix concrete depends on the strength of concrete. The RS Means data for formwork was plotted in a graph and the best fit line equation was obtained (Figure B-1).

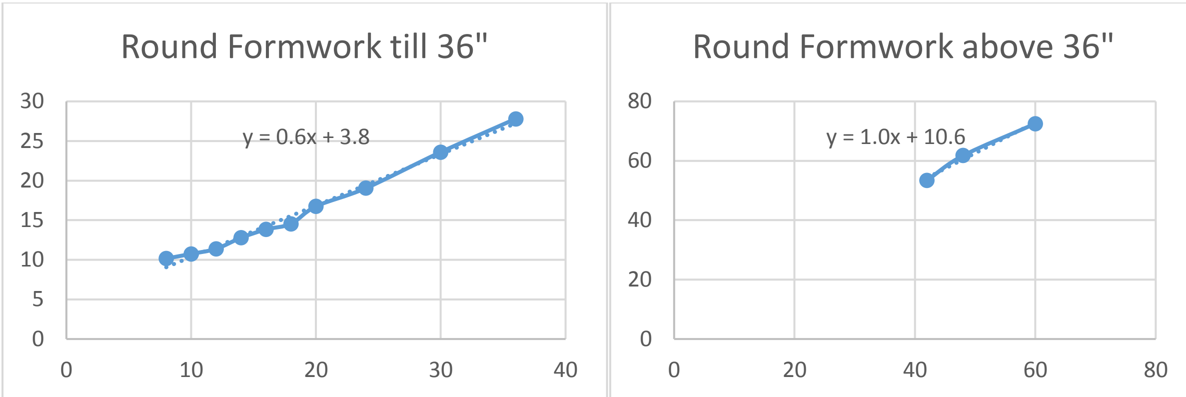

Figure B-1: Plotting RS means data

Thus, cost of formwork for a round concrete column can be calculated in 2012 US Dollars by using equations

$$c_{fw} = (0.6d + 3.8) \cdot h \quad \forall d \le 36" \tag{B-1}$$

$$c_{fw} = (1.0d + 10.6) \cdot h \quad \forall d > 36" \tag{B-2}$$

where c_{fw} = cost of formwork in 2012 US dollars; d = diameter of the circular RC column in inches, and h = height of the RC column in feet. Studying these cost equations for formwork, it has been noted that cost of formwork for a circular RC column is a function of column diameter and height. Similar cost equations were obtained for the remaining items, which have been duly included below.

Cost of ready mix concrete using RS Means data for a circular RC column can be described using equations

$$c_{cc} = (0.01 f_c + 81.3) \cdot \frac{\pi d^2}{576} \cdot \frac{h}{27} \quad \forall f_c \le 5000\,psi \tag{B-3}$$

$$c_{cc} = (0.04 f_c - 97.1) \cdot \frac{\pi d^2}{576} \cdot \frac{h}{27} \quad \forall f_c > 5000\,psi \tag{B-4}$$

where c_{cc} = cost of ready mix concrete in 2012 US Dollars; f_c = compressive strength (in psi) of concrete used; d = diameter of the circular RC Column in inches and h = height of the RC Column in feet.

Cost of physically placing concrete in the formwork using concrete pump to cast the Circular RC Column can be calculated using equations

$$c_{pc} = (61.8 - 1.1d) \cdot \frac{\pi d^2}{576} \cdot \frac{h}{27} \quad \forall d \leq 36" \tag{B-5}$$

$$c_{cc} = 21.1 \cdot \frac{\pi d^2}{576} \cdot \frac{h}{27} \quad \forall d > 36" \tag{B-6}$$

where c_{pc} = cost of placing concrete in 2012 US Dollars; d = diameter of the circular RC Column in inches, and h = height of the RC Column in feet.

Similarly, cost of curing concrete, by using thick jute blankets, which are then kept wet by spraying water, can be calculated using equation

$$c_{cur} = 0.5 \cdot \frac{\pi d}{12} \cdot h \tag{B-7}$$

where c_{cur} = cost of curing concrete in 2012 US Dollars; d = diameter of the circular RC Column in inches, and h = height of the RC Column in feet.

Finally, cost of reinforcement steel to be used in circular RC column can be calculated using equation

$$c_{rein} = 0.3 \cdot \frac{\pi d^2}{4} \cdot h \cdot \frac{\rho}{100} + 15\% \tag{B-8}$$

where c_{rein} = cost of reinforcement steel in 2012 US Dollars; d = diameter of the circular RC Column in inches; h = height of the RC Column in feet, and ρ = reinforcement steel ratio in percentage. "15%" has been added to account for the tie up steel wires used to tie the reinforcement steel frame.

To understand the accuracy of our equations we can use them for our previous example and compare the results (Table B-3).

Table B-3: Comparison of cost estimate results using cost equations

Items	Item description	Cost using RS means	Cost using equations
Formwork	Forms in place, columns round fiber tube, recycled paper, 1 use, 16" diameter	138.40	142.52
Reinforcement	Reinforcing in place, 50-60 ton lots, A615 grade-60, columns, #3 to #7	104.34	105.34
Concrete	Ready mix Includes local aggregate, sand, Portland cement, and water 4000 psi	53.25	53.41
Placing	Includes labor and equipment to place, strike off and consolidate columns, square or round 16" thick, pumped	21.36	22.61
Curing	Water curing Curing Blankets, 1" to 2" thick, buy, max.	21.46	21.35
Total base cost (2012 US $)		**338.81**	**345.23**

It can be seen from the comparison that the equations give a good enough representation of the RS Means cost data. However, more importantly, these cost equations demonstrate the relationship between cost and various physical parameters of an RC Column. It was found that total cost of a circular RC column can be estimated using height and diameter of the column, the strength of concrete used, and reinforcement ratio.

By varying these four parameters and calculating the resultant cost of the column using RS Means, a data table was set up. This data is used to establish a relationship between independent variables (height, diameter, concrete strength, and steel reinforcement) and dependent variable (column cost) by using linear regression analysis.

B.2 Linear Regression Model

The general linear regression model has the form

$$y = \theta_1 \cdot x_1 + \theta_2 \cdot x_2 + ... + \theta_k \cdot x_k + \varepsilon \quad \text{(B-9)}$$

where y = the response that the model predicts, called the dependent variable; θ_i = the model parameters, called regression coefficients; x_i = the physical measurable independent variables called regressors and ε = a random variable that represents the remaining model error.

For it to be called linear regression model, it must be linear in regression coefficients while the independent variables can take complex forms too. Usually, these models tend to have an intercept, i.e. value of y when all x_i are set equal to zero, but in this case as a column with zero diameter, height or strength cannot exist, no intercept term will be included in the model.

B.3 Model Parameters for RC Column Component

Data was obtained by varying those above four independent variables and calculating the cost of RC column by using RS Means. Only four possible values for column height have been considered. The first three values (8, 10, 16 feet) are normal column height values in typical buildings. The last value of 20 feet was taken to represent some unorthodox designs used nowadays. The diameter of the column was taken to vary between the lower limit of 8 inches to the extreme limit of 60 inches. These values for the diameter range were taken as these are the more common diameter dimensions for columns as per the RS Means data. Just like diameter values, the concrete strength values were also chosen based on RS Means data and vary between 2000 psi and 12000 psi. It should be noted that cost data for only ready mix concrete has been included for this example. In most of the codes, the minimum permissible reinforcement ratio for RC structures is assumed to be 1 percent. So, 0.01 was taken as the lower limit for our reinforcement ratio values. The maximum permissible reinforcement ratio varies from code to code. Some codes assume it to be around 5 to 6 percent while others keep it around 8 percent. For this calculation, we assumed the upper limit for reinforcement ratio to be 0.08. Although, steel of different strength and composition is available and used in construction, for this example, data regarding only A615 grade steel is being used.

As we have used 13 diameter values, 4 height values, 11 concrete strength values and 8 reinforcement ratio values, our total data entries should have been 13 x 4 x 11 x 8 = 4576 entries. However, most of these entries would not have made any sense, for example, a 20 feet tall RC column with 8-inch diameter, built with 2000 psi concrete and minimum reinforcement does not make any sense practically. Consequently, an effort has been made to remove to all such impractical data. Following basic guidelines were used to remove such data:

- Columns with larger height but smaller diameter were removed
- Columns with very height concrete strength but very low reinforcement steel were removed
- Columns with low concrete strength but high reinforcement ratio were also removed
- Columns with larger diameter but low concrete strength were not included
- Long columns with low concrete strength were also not included

After all the exclusions, only about 1324 valid scenarios were left out of originally 4576 possible cases. Cost data for these valid cases was calculated using RS Means and a data table was constructed. A part of the data has been provided in Appendix C as a sample.

Appendix C Sample Data Table

As discussed in section B.3, 1324 valid scenarios for circular RC column were left out of originally 4576 possible cases and a data table was constructed using RS Means cost data. As the complete data table is hard to include, a part of the data is being included here.

Table C-1: Sample regression data table

Cost of RC column in 2012 US Dollars	Height of RC column in feet	Diameter of RC column in inches	Concrete strength in psi	Reinforcement ratio
1298.03	16.00	20.00	4500.00	0.04
4360.69	10.00	42.00	5000.00	0.06
2276.34	10.00	36.00	5000.00	0.04
2546.74	16.00	42.00	4000.00	0.01
328.44	10.00	14.00	3500.00	0.02
412.00	8.00	14.00	5000.00	0.05
1708.75	16.00	30.00	3500.00	0.02
787.87	8.00	18.00	5000.00	0.07
641.08	8.00	16.00	5000.00	0.07
460.87	8.00	14.00	5000.00	0.06
2238.71	10.00	30.00	6000.00	0.06
476.25	10.00	18.00	4000.00	0.02
193.22	8.00	10.00	4000.00	0.03
265.16	10.00	14.00	2500.00	0.01
1724.44	16.00	20.00	6000.00	0.06
1249.66	16.00	18.00	4500.00	0.05
895.91	10.00	18.00	6000.00	0.06
4928.00	10.00	48.00	10000.00	0.04
4409.37	10.00	42.00	10000.00	0.05
2624.49	20.00	20.00	5000.00	0.08
1414.14	16.00	18.00	5000.00	0.06
1865.15	10.00	36.00	4500.00	0.03
1091.42	16.00	20.00	3500.00	0.03
698.29	10.00	14.00	5000.00	0.08
828.40	10.00	20.00	6000.00	0.04
850.38	8.00	30.00	3000.00	0.02
950.04	8.00	20.00	5000.00	0.07
4675.78	10.00	42.00	12000.00	0.05
1439.58	10.00	36.00	3000.00	0.02
3158.28	20.00	24.00	8000.00	0.06
2326.35	16.00	36.00	4000.00	0.02

Appendix D Potential Issues related to Regression Analysis and their Solution

The results of the raw data trial given in section 3.2 have been used as a reference to comment on the potential issues related to regression analysis and possible mitigation methods.

D.1 Collinearity

It refers to the case in which two or more independent variables in the regression model are highly correlated, making it difficult or impossible to isolate their individual impact on the dependent (response) variable (Baguley 2012). As we can see from the correlation matrix of the model parameters obtained from the raw data trial result (Figure D-1), the partial correlation coefficient of concrete strength and reinforcement ratio is higher as compared to others indicating higher collinearity.

```
Correlation matrix of the model parameters:
|           1    -0.381531    -0.208219    -0.145678 |
|   -0.381531            1    -0.492138     0.117129 |
|   -0.208219    -0.492138            1      -0.6946 |
|   -0.145678     0.117129      -0.6946            1 |
```

Figure D-1: Correlation matrix of raw data trial

However, as the principle aim of this model is response (cost) prediction, and obtaining individual impact of independent variables on predicted cost is of little importance, collinearity is not going to be a problem and has been ignored.

D.2 Heteroskedasticity and Correlation of Errors

Heteroskedasticity means that the variance of the model error varies with response or any independent variable. Moreover, correlation of errors indicates that there are additional independent variables that are not included but influence the observations (Baguley 2012). Model prediction plots and residual plots have been considered as overall checks for both heteroskedasticity and error correlation here.

The model prediction plots show the overall quality of the model. The better the points align with the straight line, the better the model is. Thus, raw data model is not a good model (Figure D-2).

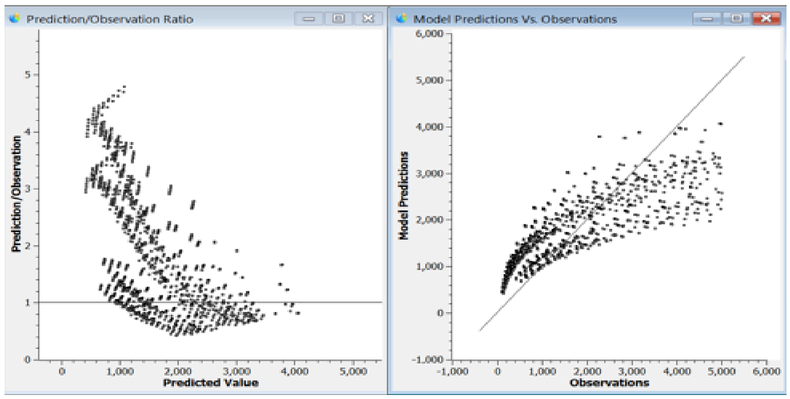

Figure D-2: Model prediction plots for raw data trial

Plots of the residuals i.e. the observed errors are also crucial in checking a regression model. Plot of residuals versus the independent variables is an effective way of checking heteroskedasticity. If we observe the residual plots for our raw data trial, we can see that error is much smaller for lower values of regressor x2 (column diameter, see Figure D-3) as compared to mid to higher values. Thus, the model is better for smaller values of diameter as compared to larger diameters. This shows heteroskedasticity, which has been addressed in subsequent trials

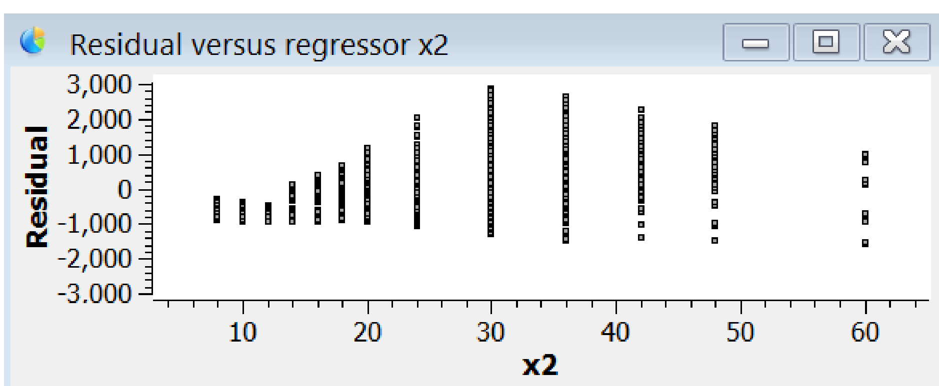

Figure D-3: Residual plot for raw data trial

D.3 Non-Normality

Another fundamental assumption of the errors in linear regression is that they are "normally" distributed. This can be checked from the normality plot provided by Rts (Figure D-4). Usually, a severe violation of this assumption invalidates the model. Thus, the deviation from the straight line should not be too much for a model to be acceptable.

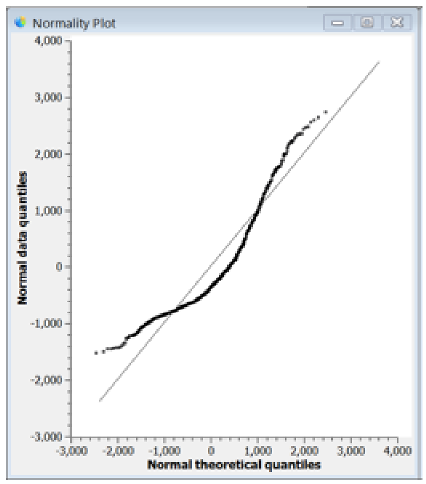

Figure D-4: Normality plot for raw data trial

D.4 Model Correction through Trials

It has been already stated that a regression model based on raw data is not working in this case. Data can be made to fit a linear regression model better by either transforming the dependent variable (response) or the independent variables or by making better independent variables by combination of some variables.

D.5 Trial-1: Transforming Response to Log-form

For this trial, the dependent variable (response) was transformed to its natural log form. No other change was made to the data. Once again, using Rts, the linear regression model was constructed. As seen from the results (Figure D-5), even though this model is much better than the raw data model, it is still not a good model. Pros and cons of this model are discussed below in Table D-1.

Table D-1: Pros & cons of Trial-1

Pros	Cons
Residuals are much smaller as compared to raw data model	Model prediction plots still not along the straight line, i.e. overall not a good model
Normality plot is better as compared to the raw data model	Diameter and Concrete strength still show some heteroskedasticity
	Coefficient of Variance for the Concrete Strength Variable is high

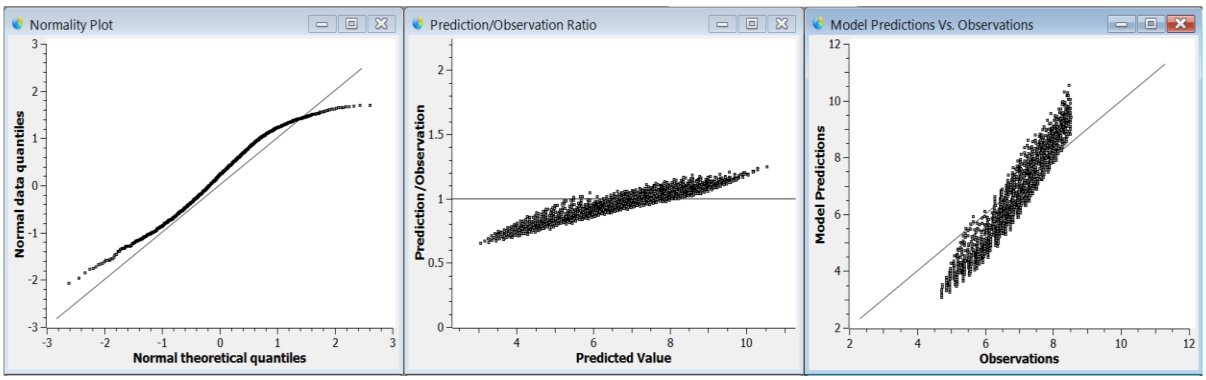

Figure D-5: Trial-1 results using Rts

D.6 Trial-2: Transforming Response to Cube-root-form

For this trial, the dependent variable (response) was replaced by its cube root form. No other change was made to the data. The linear regression model was constructed using Rts. Results have been shown in Figure D-6. This model is better than both the trial-1 model and the raw data model. Pros and cons of this model are discussed in Table D-2.

Table D-2: Pros & cons of Trial-2

Pros	Cons
Model prediction plots are along the straight line, i.e. overall a better model than Trail -1 model	Even though residuals are much smaller as compared to raw data model they are not as small as in trail-1
Normality plot is even better than the Trial-1 model	Diameter and Concrete strength still show some heteroskedasticity
	Coefficient of Variance for the Concrete Strength Variable is high
	Although Model Prediction plots are along the straight line, many outliers are present

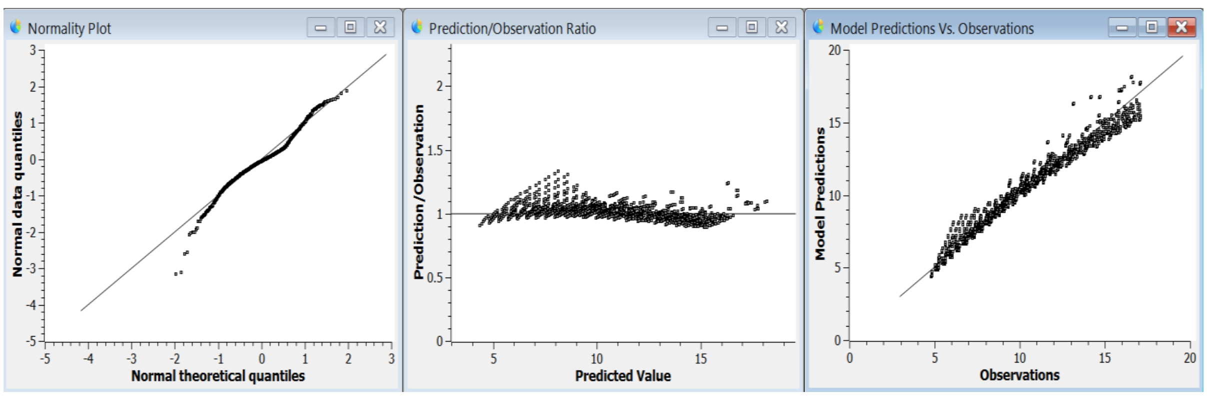

Figure D-6: Trial-2 results using Rts

D.7 Trail-3 & 4: Transforming Independent Variables

For this trial, the dependent variable (response) was kept in its cube root form. Moreover, instead of just reinforcement ratio, the product of reinforcement ratio and diameter (ρd) was used. The linear regression model was constructed using Rts. Results were as in Figure D-7. This model was an improvement on the first two trials. Pros and cons of this model are discussed in Table D-3.

Table D-3: Pros & cons of Trial-3

Pros	Cons
Model prediction plots are along the straight line, i.e. overall a better model than Trail -1 model	Although Model Prediction plots are along the straight line, many outliers are present
Normality plot is even better than the Trial-1 model	Diameter and Concrete strength still show some heteroskedasticity
Coefficient of Variance for all the variables is pretty low	
Residuals are much smaller as compared to raw data model and even small as compared to Trail-1	

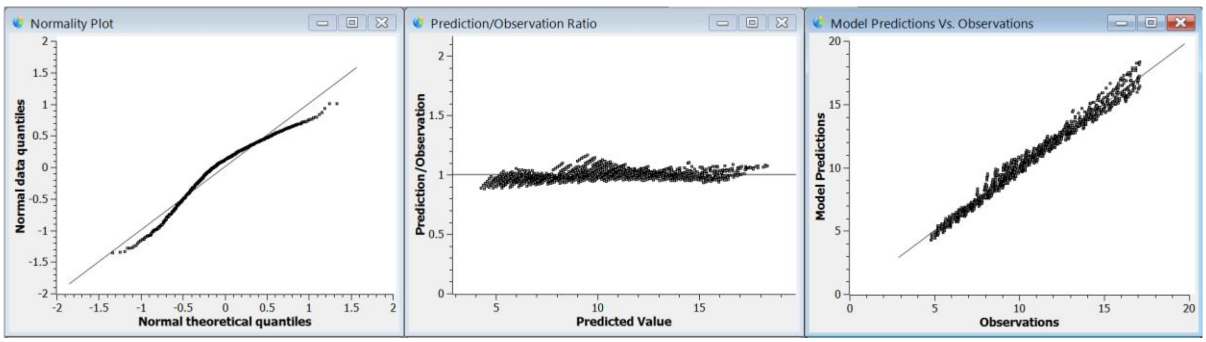

Figure D-7: Trial-3 results using Rts

After many trials, it was found that using natural log form of concrete strength and product of diameter and reinforcement ratio in place of reinforcement ratio alone, improves the model. The linear regression model was constructed using Rts (Figure D-8). The model prediction plots for this model are a better fit than all previous models. Pros and cons of this model are discussed below in Table D-4.

Table D-4: Pros & cons of Trial-4

Pros	Cons
Model prediction plots are along the straight line with very few outliers, i.e. overall a good model	x_2 $(diameter)$ and x_4 (ρd) still show some heteroskedasticity
Normality plot is also satisfactory	Model has become a little complex
Residuals are much smaller as compared to raw data model and even small as compared to Trail-1	
Coefficient of Variance for all the variables is pretty low	

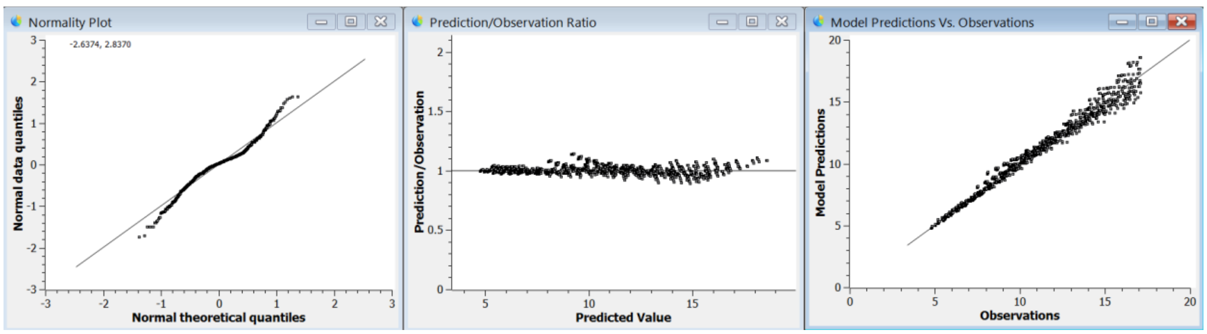

Figure D-8: Trial-4 results using Rts

D.8 Model Comparison and Selection

For the model validation purpose, five data entries were taken from the original data at random and were consequently not used in model creation. Moreover, the data from original RC column example was also used. These six data entries were used to test and compare the trial models. The results have been summarized in Table D-5. The numbers in parenthesis signify the percent change of model results from the observed values. These calculations provide mathematical proof to the discussions in the previous section where it was concluded that trial-3 and trial-4 models are much better than the trial-1 and trial-2. It has been observed here that trial-3 model is in fact, slightly better than trial-4 model, at least based on available data sample. Thus trial-3 model has been selected as the final model. This trial-3 model has been used as the final linear regression model.

Table D-5: Comparison of model trial results

Sr.	***h***	***d***	***f_c***	***ρ***	Observed	Trial-1	Trial-2	Trial-3	Trial-4
1	8	8	4000	0.01	113.14	70.61 (-37.59%)	147.94 (30.76%)	131.71 (16.41%)	150.70 (33.20%)
2	10	10	4500	0.05	304.43	375.19 (23.24%)	527.37 (73.23%)	341.01 (12.02%)	375.05 (23.20%)
3	10	16	6000	0.04	571.48	697.31 (22.02%)	774.44 (35.51%)	627.69 (9.84%)	619.41 (8.39%)
4	10	24	5000	0.07	1650.23	2611.73 (58.26%)	1806.02 (9.44%)	1666.95 (1.01%)	1834.97 (11.19%)
5	16	30	6000	0.08	4479.70	25285.69 (464.45%)	3722.68 (-16.90%)	4364.02 (-2.58%)	4564.32 (1.89%)
6	10	16	4000	0.0132	338.81	253.55 (-25.16%)	452.68 (33.61%)	388.45 (14.65%)	410.44 (21.14%)

D.9 Final Regression Model with Unit-less Regression Coefficients

In the current model, the regression coefficients have different units. It is more convenient to have unit-less regression coefficients. Regression coefficients have been made unit-less by making the regressors (independent variables) unit less, which in turn has been achieved by dividing them by a standard value. For example, the regressor x_2, which is the diameter of RC column, has been made unit-less by dividing the whole column of regressor x_2 in the data set by a standard diameter value. Similarly, the other regressors have also been made unit-less. If done right, this process should not have any effect on the outcome of the model. The values taken as the standard values for individual regressors are being listed in Table D-6.

Table D-6: Standard regressor values for obtaining unit-less coefficients

Regressor	Standard value
Height	3 metre
Diameter	0.4 metre
Concrete strength	27 MPa

Reinforcement ratio is already unit-less, so there is no need for a standard reinforcement ratio value.