Sustainable Construction Process:

Using Construction Virtual Prototyping Technology for

Visualization and Simulation of CO_2 Emissions

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The Degree of Master of Philosophy (MPhil)

The Hong Kong Polytechnic University

2014

The Hong Kong Polytechnic University

Department of Building and Real Estate

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A thesis submitted in partial fulfilment of the requirements for the

Degree of Master of Philosophy

June 2013

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ABSTRACT

The construction industry has been criticized as one of the major greenhouse gas (GHG) emitters and a relatively unregulated sector in the management of carbon emissions and other environmental impacts. As the pressure on climate change related risks is mounting, a major cut in carbon emissions and other diesel emissions, like carbon monoxide (CO), particulate matter (PM), and sulfur dioxide (SO_2), from construction operations is becoming a top priority if construction firms are to meet increasingly stringent emission controls. However, efforts for reducing these emissions still remain minimal, for the reasons that (1) a lack of awareness and concerns to estimate and manage emissions from on-site equipment usage, and (2) a lack of innovative techniques and monitoring methods to properly and quickly communicate the emissions with construction progress. Therefore, in order to minimize construction emissions, this study describes a 4D framework to estimate and simulate construction equipment emissions.

This study adopts the construction virtual prototyping (CVP) technologies and mixed reality (MR) to establish an emission prediction and simulation tool. The estimated emissions of the construction operations for each activity is calculated, tabulated and plotted to visually demonstrate the emission rates side by side with the integrated 4D models of the construction project. The virtual prototype (VP)-based model allows project teams to visualize the predicted emissions at different times in the construction processes, identify the emission peaks, and allow the project team to take proactive measures against potential emissions. The application of mixed reality (MR) in the management of construction emission also provides an interactive experience of the on-site emission control. Finally, a real-life public housing construction project in Hong Kong is adopted to demonstrate the application of the emission prediction visualization tool. Through the simulation process, it is hoped that this tool can encourage the construction industry practitioners to become environmentally conscious and pro-active in carbon mitigation measurements.

LIST OF RESEARCH PUBLLICATION ON THE WORK REPORTED IN THIS THESIS

Referred Journal Articles and Conference Papers

Johnny KW WONG, Heng LI, **Haoran WANG**, Ting HUANG, Eric LUO and Vera LI, (2013) Towards low-carbon construction processes: the visualization of predicted emission via virtual prototyping technology, *Automation in Construction*, 33: 72-78.

Johnny Kwok Wai WONG, Heng LI, **Haoran WANG**, Ting HUANG, Eric LUO and Vera LI, An integrated 5D tool for construction process emissions quantification and accident identification, *Advanced Robotic Systems*, under review.

Johnny KW Wong, Heng Li, **Haoran Wang** et al. (2012). An Application of Virtual Prototyping Technology to Low-carbon Construction Processes, Australasian Conference on Innovative Technologies in Construction- “From BIM to Beyond”, Wuhan, China, 6-7 Dec., 2012.

ACKNOWLEDGEMENTS

At the beginning of the acknowledgements, I would like to express deepest gratitude to my Chief Supervisor, Prof. Heng Li and Co-Supervisor Prof. Zhilin Li, for their leadership and continuous support throughout my MPhil study period. Without their help, I would not have a chance to complete this thesis. My gratitude is also extended to Dr. Johnny Wong, Dr. Tim Huang, Dr. H. Q. Fan, Dr. Eric Luo, and Dr. Neo Chan in providing me the tremendous opportunity and support of participating in both academic and industrial project.

I would like to express my sincere thanks to my great colleagues and classmates in Department of Building and Real Estate, Miss Shanshan Bu, Mrs. Cindy Chen, Miss Keqing Zheng, Miss Qiong Sun, Miss Emily Liu, Mr. Chen Jiang, Mr. Dongping Cao, Mr. Wei Lang, Mr. Zezhou Wu, Dr. Yi Peng and Dr. Zhigang Jin. Also, I'm thankful to several friends in the other departments of Hong Kong Polytechnic University, Mr. Xingyu Duan, and Mr. Shurui Nie, Mr. Bing Li, Mr. Zeihui Yong, Mr. Xiangmin Li, Mr. Junlong Zhang, Dr. Hao Xu.

Finally, I would like to express my deepest gratitude to my parents and family members for their endless love and constant encouragement.

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2D	Two-dimensional
3D	Three-dimensional
4D	Four-dimensional
AEC	Architecture engineering, and construction
AR	augmented reality
BIM	Building Information Modeling
CARB	California Air Resources Board
CEFT	Carbon Footprint Estimation Tool
CO_2	Carbon dioxide
CVPL	Construction Virtual Prototyping Laboratory
DES	Discrete-Event Simulation
DPM	Digital Process for Manufacturing
EPA	Environmental Protection Agency
GHG	Greenhouse Gas
GPS	Globe Position System
IPCC	Intergovernmental Panel on Climate Change
LCA	Life-cycle assessment
MR	Mixed Reality
PEMS	Portable Emissions Measurement Systems
PEEM	Plant emission estimation model
PM	Project Manager
PPR	‘Product’, ‘Process’ and ‘Resources’
VP	Virtual prototyping
VPS	Virtual prototyping simulation
VR	virtual reality

CHAPTER 1 INTRODUCTION

1.1 Overview

The international energy-related carbon dioxide (CO_2) emissions – the main contributor to global warming and climate change – in the atmosphere is heading towards an alarming level in 2011 (Abanda et al., 2010) (see Figure 1.1). There were 31.6 giga-tonnes of CO_2, an increase of 1.0 giga-tonnes, or 3.2% compared with 2010, emitted and released into the atmosphere (International Energy Agency, 2012). The high emission level has aroused risk consciousness and environmental concerns in governments, industries and the broader communities around the globe, and reminded of the extra efforts required to minimize carbon emissions and remove climate change hazards. Using a policy from Hong Kong SAR Government as an example, CO_2 emissions have been taken into account in recent legislative developments, and targeted to reduce by around 50-60% by 2020 relative to 2005 emissions baseline. Another national policy, also promoted by South Korea government, attempts to reduce Greenhouse Gas (GHG) emissions in building and construction sector by 26.9% by 2020 considering that buildings accounts for the main part of energy consumption and GHG emissions.

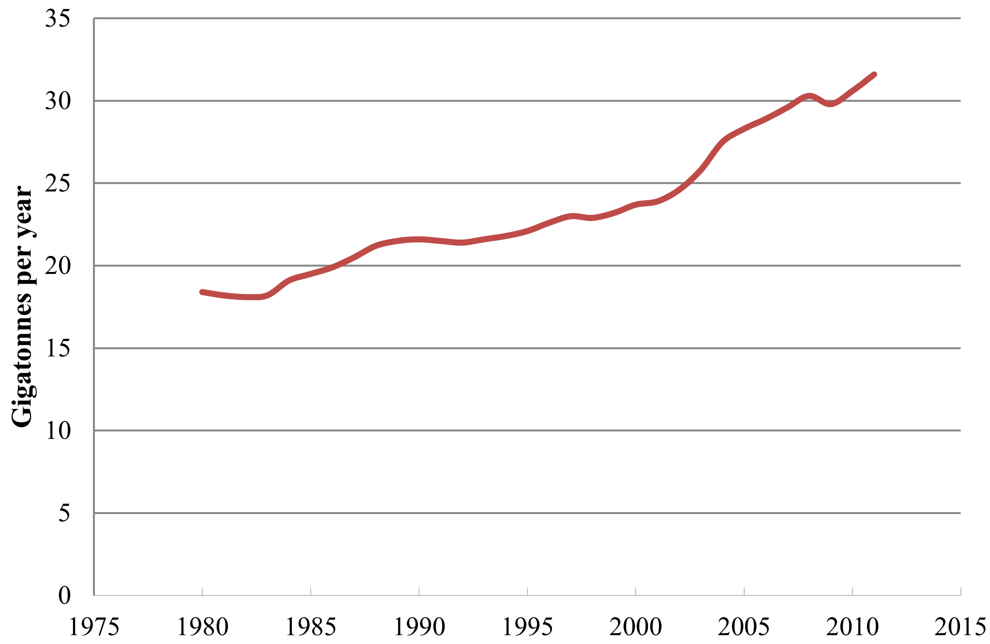

Figure 1.1 Global Energy-related CO_2 Emissions from 1980 to 2011 (Sources: US Energy Information Administration)

The building and construction sector is considered to have an essential role to play in carbon reduction and mitigation, due to its fuel-intensive nature and its large share of energy consumption and GHG emissions (AGC, 2009; Stadel et al., 2011). According to statistics from Intergovernmental Panel on Climate Change (IPCC), 40% of the major energy and 36% of the energy-related CO_2 emissions is attributed to building and construction sector in the industrialized countries. And among all US industries, the construction industry ranks as the third largest industrial emitter of CO_2 (USEPA, 2008).

Although the period of on-site construction process is quite shorter than the operation and maintenance period (Hong et al., 2013) and the amount of construction process CO_2 emissions from each project is small compared with other stages, the added quantity of emissions is larger for the reason that the number of ongoing construction projects is larger both in the developed or developing countries in recent years (Avetisyan et al., 2012). While much of the current debate on industry-related carbon emission has focused on energy consumption by buildings in operation, less attention has been placed on the emissions from the construction process despite it being an obvious and emerging challenge (EPA, 2009).

In fact, among all environmental impact due to construction (including waste generation, energy consumption and resource depletion etc.), emissions from construction equipment and plant account for more than 50% (Guggemos and Horvath, 2006; Ahn et al., 2009). Statistics from the US also confirm that construction activities produce 40% of carbon emissions of non-transportation mobile sources (EPA, 2009). Fuel consumption estimates for construction plant in the US are almost double the levels suggested by official reports (Sharrard et al., 2007). All these suggest that controlling the emissions from construction activities is a pressing challenge.

Initiatives and action plans have been recently introduced to aggressively target the construction sector in developed countries to cut the carbon footprint of construction sites (Newton and Tucker, 2011; Peña-Mora, et al., 2009). For example, in the UK and US, the Government has called on contractors to help cut carbon emissions (Cabinet Office, 2010; EPA, 2009), but there is still no clearly defined carbon-abatement scheme for the construction sectors in many parts of the world emissions during the construction processes of these massive infrastructure development (Transport and Housing Bureau, 2011). This implies that better planning and control strategies for emissions reductions during the construction phases are needed, and a better visualization of the environmental impact of construction activities is important to minimize the impacts to the natural environment in Hong Kong.

1.2 Problem Statement

Over the last years, the necessity of minimizing the construction process carbon footprint by changing and controlling construction plant operations has been highlighted in academic (such as Lewis et al., 2009) and industry level (Cabinet Office, 2010). Diesel fuel and electricity are regarded as the main energy sources responsible for the greatest total emissions from construction processes (Sharrard et al., 2007). With the upsurge in fuel costs, efficient consumption and management of fuel during construction process would reduce emissions as well as fuel costs. It is also likely in the future that construction firms will have to report emissions and their strategies to reduce the carbon emissions (Hajibabai et al., 2011). This situation brings opportunities and challenges for construction firms to find solutions and manage emissions without detracting from project productivity and final costs (Heydarian and Golparvar-Fard, 2011). Furthermore, Environmental Protection Agency (EPA) has undertaken an industry survey on emission reduction strategies among construction firms in US and the survey results indicated that nearly 53% of the respondents never use any form of emission reduction strategies (Figure 1.2).

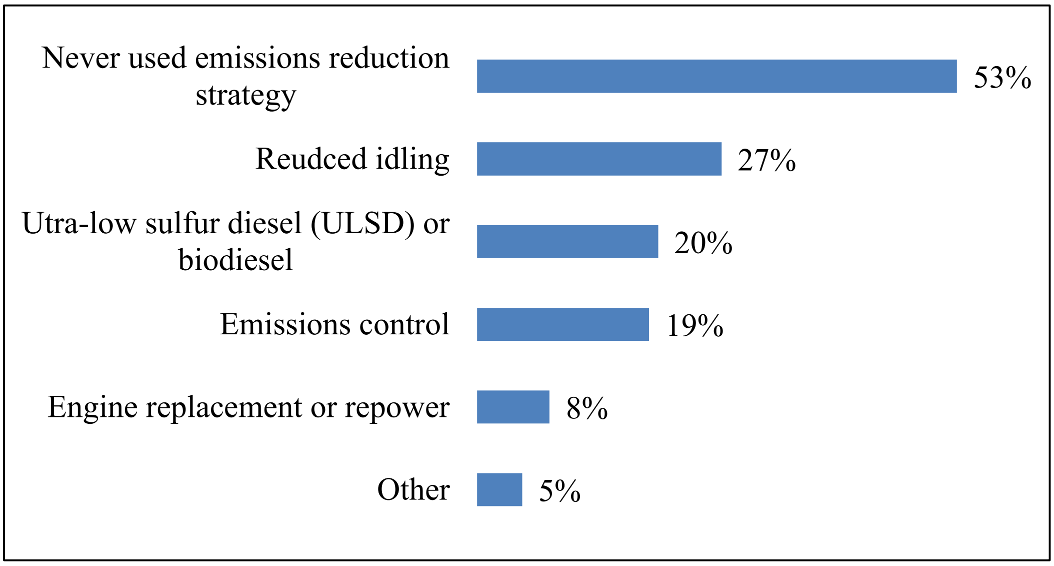

Figure 1.2 Survey results of construction firms that employ emissions reduction strategies. (Source: USEPA, 2008)

Although emission models exist (such as URBEMIS) for estimating the amount of carbon or GHGs emitted from construction plant, many current approaches are criticized for not supporting the environmental management of a specific construction project on its own (Ahn et al., 2009; Peña-Mora et al., 2009; Lee et al., 2009) and do not account for variations in construction operations between projects (Lewis, 2009). While commercially available tools, such as DesignBuilder, IES etc., provide a platform for building operating energy analysis, emissions from construction activities has not been given sufficient attention until recently, as it was believed that construction activity emissions were less significant than the energy consumption in operating the building over its life (Tah et al., 2010).

As the rapid advancement in the field of computational software and hardware, the current trend of architecture engineering, and construction (AEC) industries is to moving towards digitalized information management (e.g. Building Information Modeling, BIM). More visualization platforms are developed for effective and efficient use of such information in the AEC industries, for example Li et al. (2012) describe an application of virtual prototyping simulation (VPS) to bridge construction and the visualization platform help planners optimize the construction plan. To address the issue of emission estimation, the visualization platform can assist in providing a better visualization of the environmental impact of construction activities.

With the limitations and requirement of the current research, this paper describes the use of virtual prototyping (VP) technology and mixed reality (MR) for the carbon emission visualization and prediction of the construction project, which aims to develop preliminary emission visualization overtime with a simulation tool (i.e. the construction process) via the Construction Virtual Prototyping (CVP) technology developed by the Construction Virtual Prototyping Laboratory (CVPL) of the Hong Kong Polytechnic University (Li et al., 2008), and with the concept of mixed reality (MR). A multi-dimensional visualization (i.e. a time linked 3D model and predicted emission data) will be developed to allow project teams to simulate potential emissions from construction plant and equipment. This aims to understand how the visualization tool would help support site operation decision making with respect to carbon emission control, for example, to identify the important sources of emissions and their peak times; and to consider plant operational efficiency (i.e. reducing idling time). This proposed system will be one of the first visualization models applying 4D-virtual prototyping technology to represent the predicted CO_2 emissions generated from the construction processes on-site.

1.3 Scope of the Research

The construction and building sector involves various members (e.g. owners, architects, engineers, and contractors), and a variety of construction segments (e.g. the construction of buildings, infrastructure, roads, bridges). Construction projects, regardless of the stakeholders and construction segments, contain different kinds of processes (e.g. manufacture, construct, maintain, refurbish, and demolish), during which CO_2 emissions principally result from consumption of diesel fuel and electricity to operate construction equipment or provide power to building services. Thus, the purpose of scope in this study is to provide a specific and narrow boundary of the emission estimation in construction sector. As mention previously, the proposed VP-based system is aimed to understand how the visualization tool would help support site operation decision making with respect to carbon emission control. It should be also noted that the model and methodology developed and used in this research are at its initial stage, and intended to be simple and straightforward for contractors and practitioners. Thus, the visualization tool developed in this study will limit to construction activities performed on-site in building construction stage (see Figure 1.3). This research does not include life-cycle energy consumption or emissions from materials manufacture, equipment production, materials, equipment and workers transportation to site, or any other tasks happening outside of the construction site. In addition, other environmental impact, like waste, noise, heavy metals, or water pollution, is also excluded in this study.

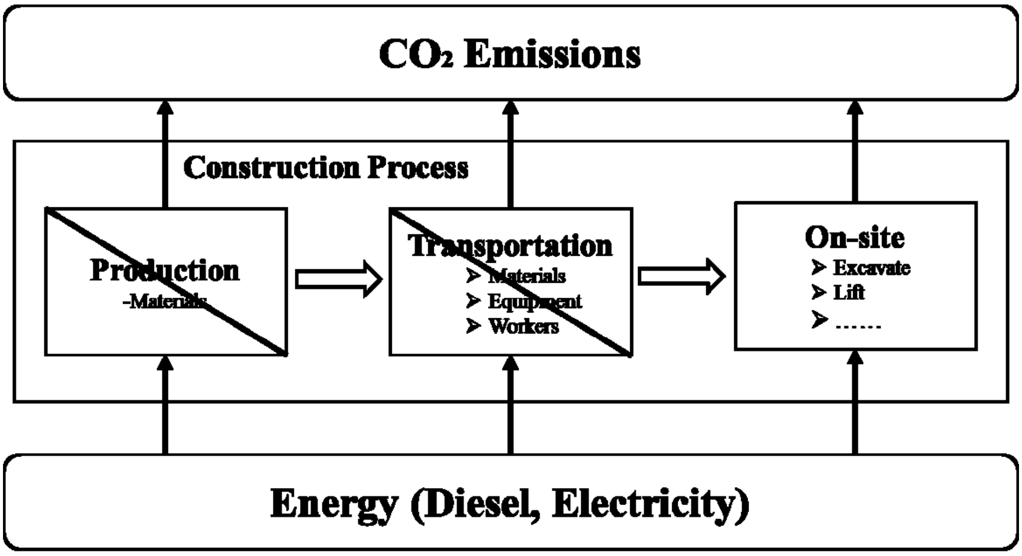

Figure 1.3 Scope of CO_2 emissions visualization delimited in the research

1.4 Research Goal and Objectives

While the green and environmental control in the construction industry is becoming more stringent, it is likely in the future that construction firms will have to report emissions and their strategy to cut back the carbon emissions during the construction phase (Hajibabaiet al., 2011). This provides opportunities and challenges for contractors and construction companies to find solutions and manage emissions in line with green requirements or standards.

Thus, the main goal of this research is to develop preliminary emission visualization overtime with a simulation tool (i.e. the construction process) via the Construction Virtual Prototyping (CVP) technology. The results of this research will allow construction companies or contractors to forecast the potential CO_2 emission level from their activities, and find ways to reduce excess emissions. To attain the final goal, this research pursues the following particular objectives:

(1) Understand how the simulation tool would help support site operation decision making with respect to carbon emission control.
(2) Develop a 'plant emission estimation model' (PEEM) based on the equipment operation schedule and detailed information of construction plants.
(3) Implement a multi-dimensional visualization tool, which combines a time linked 3D model and predicted emission data via the Construction Virtual Prototyping (CVP) technology and concept of mixed reality (MR), in a real case study.

Through the simulation of carbon emissions, it is hoped that the tool can enable the construction planners to take preventive or corrective action for emission minimization in the planning stage, to estimate the environmental performance of the construction project, and eventually to produce more environmentally sustainable development. Also, this tool aims to encourage the construction industry practitioners to become more environmentally conscious and pro-active in carbon mitigation.

1.5 Research Methodology

This thesis mainly concerns with the visualization of construction emission predication using the virtual prototype (VP)-based model, which are illustrated in Figure 1.4 with the use of a flow char diagram. Two aspects, therefore, need to be focused on: how to predict the carbon footprint of on-site construction activities and the potential of the VP-based model for the visualization of construction process carbon footprint. For the predication of construction emission, the on-site observation method and data management method are employed for the development of emission estimation model; and the visualization method (i.e. CVP technology) and case study are adopted to represent the construction emission predication.

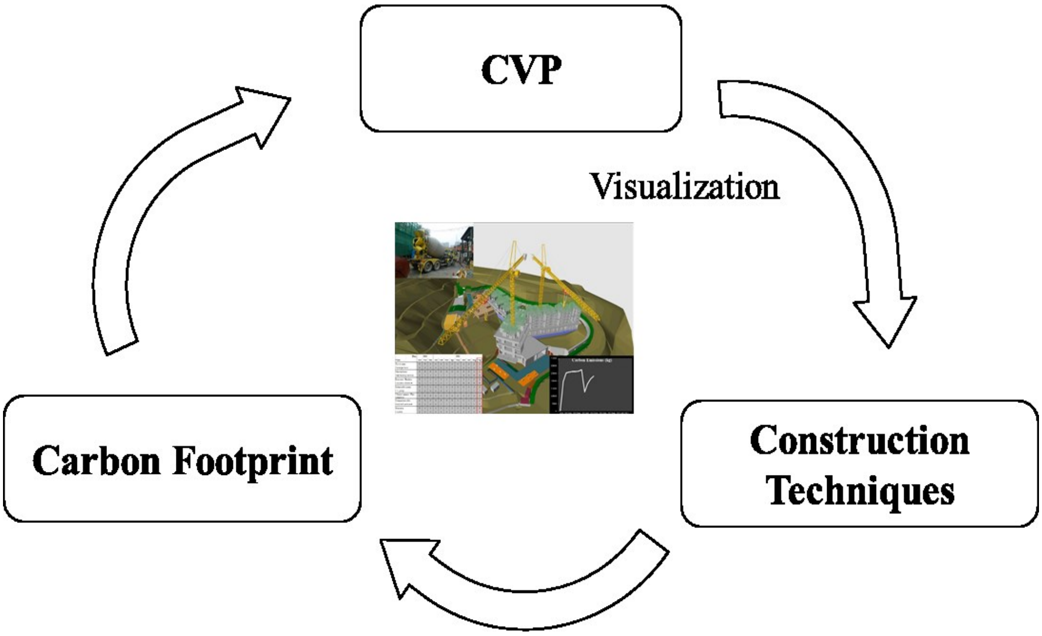

Figure 1.4 Flowchart of the methodology in the thesis

In addition, a critical review of construction related CO_2 emission is also a significant method to identify the research gaps, address the research scope and enhance the understanding of sustainable construction. The more specific research methodology will be presented and discussed in Chapter 3.

1.6 Thesis Organization

In order to verify the idea of research, the content of thesis is divided into five parts. Chapter 1 introduces the initial background of this study, including global warming problem, energy-related CO_2 emissions, and current emission related research efforts in construction industry. It also outlines the scope of this research, sets up the research goal and objectives, and briefly describes the research methodology. Chapter 2 provides a critical review of the literature on sustainable construction, current research fields in environmental performance of construction process, visualization technology in building environmental evaluation and an introduction of Construction Virtual Prototyping (CVP) and mixed reality (MR) technology. Chapter 3 presents the research methodology adopted in this research, followed by implementing a real-life case study and analysis in Chapter 4. Chapter 5 consists of a conclusion of the research, contributions and limitation of the study, and recommendations for future study.

CHAPTER 2 LITERATURE REVIEW AND BACKGROUND

2.1 Introduction

This chapter presents a literature review related with the field of CO_2 emissions in the construction site, mixed reality (MR) and construction virtual prototyping (CVP) technology. A background of sustainable construction and CO_2 emissions is first introduced. The current environment performance tool for construction related CO_2 emissions is then reviewed from three different aspects: life-cycle assessment tool, fuel based quantification of construction emissions, and BIM approach of CO_2 emissions calculation. This chapter will also review the visualization method of emissions from construction site. Besides, the research gap is identified in current CO_2 visualization during construction process and the application of MR and CVP technology for CO_2 emissions predication is specifically introduced.

2.2 Sustainable Construction and CO_2 Emissions

Prior to commencing with the exploration of sustainable construction, a literature review is conducted to provide an exact definition of sustainable construction, and identify the relationship between sustainable construction and CO_2 emissions. Related works describe that sustainable construction, also regarded as green construction, can be defined as the practice of construction that is carried out with the basic purpose of sustainable development, namely balancing the social, economic and environmental issues both for present and next generation(Sage, A.P., 1998; Parkin, S., 2000; S. Asad and M. M. A. Khalfan, 2007; Don Edward Mah, 2011).As Kibert (2008) asserts on this point, "*sustainable construction is a subset of sustainable development and addresses the role of the built environment in contributing to the overarching vision of sustainability.*" In general, the ultimate goal of sustainable construction is thus that create environmentally-friendly, resource-efficient and healthily-built new community and facilities throughout the lifecycle of building (S. Asad and M. M. A. Khalfan, 2007; Kibert, 2008). As an example, ten key factors are specifically identified for the commitment to sustainable construction by the UK Government in *'Building a better quality of life – a strategy for more sustainable construction'* (DETR, 2000). These factors are: controlling the consumption in design stage; implementing lean construction principles; minimizing energy consumption in construction and operation stage; monitoring pollution through whole lifecycle; preserving and enhancing the local biodiversity; conserving water and non-renewable resources; respecting people and local environment; and setting targets, monitoring and reporting, aimed at the benchmark performance.

In addition to the definition and various factors of sustainable construction, it appears that a number of recent studies have been extended to evaluate environmental impacts during the building construction phase, especially estimate the energy consumption and CO_2 emissions (Kim et al., 2012a; Kim et al., 2012b; Melanta et al., 2012; Hong et al., 2013). Furthermore, among the construction-related environment impacts (e.g. energy consumption, waste generation, air pollution, etc.), energy consumption and CO_2 emissions from construction equipment, in particular the fuel-based hazardous emissions during the construction processes, account for the largest part (more than 50%) of the total environmental impacts (Guggemos and Horvath, 2006). Existing studies have addressed several fields of the environmental performances of building construction such as fuel-based emissions measurement, life-cycle energy and emissions assessment, visualization techniques of emissions, and cap and trade policies. The following section will discuss several research fields in the environmental performance of construction processes.

2.3 Carbon Emissions Estimation Tool for Construction Processes

2.3.1 Life-cycle Assessment (LCA) Tool

In the building and construction sector, the life-cycle assessment (LCA) has been widely employed as an effective tool to analyze and evaluate the environmental influence of buildings, such as embodied energy and carbon emissions of a building's materials, elements and facilities maintenance, throughout the lifecycle of the building which contains construction, occupation, and deconstruction phases. Due to the data constraints and various demands in each project, three typical LCA assessment methods have been developed for construction sector (Kim et al., 2012; Ahn, 2012), including: process analysis involves all related-factors for a holistic assessment of environmental burden; input-output (I-O) analysis is used to simply address relationship between industries; and the hybrid approach combines the advantages of both methods.

It also has been suggested that life-cycle assessment (LCA) can largely reduce the overall emissions by providing an assessment of whole life-cycle energy consumption, identifying the range and types of carbon emissions in building construction projects, comparing the greenhouse gas emission of alternative construction plans and adjusting plans to select more energy-efficient and less carbon footprint plans for the materials, on-site installation, operation, and demolition. These previous LCA environmental assessment studies have mainly focused on the operation and maintenance stage of buildings (Park and Hong 2011; Hong et al. 2013), and tend to ignore or partially address the on-site construction processes with the exception of Guggemos and Horvath (2005, 2006), Sharrard et al. (2007, 2008), Li et al. (2010), Bilec et al. (2006, 2010), Cass and Mukherjee (2011).

Sharrard et al. (2007) attempted to accurately and specifically calculate and evaluate the environmental performance of construction process by input-output-based LCA approach, due to the complexity and fragmentation of construction industry. On-site energy use and electricity generation are the main two aspects for the quantitative and qualitative analysis. The results show that the amount of particulate matter (PM) is 30% larger than average and the level of other air pollutant emissions, like oxides of nitrogen, is double than the government reports. Another research conducted by Guggemos and Horvath (2006) found that equipment usage related energy consumption and air emissions account for at least 50% of the total emissions. Furthermore, Sharrard et al. (2008)

developed an input-output-based hybrid LCA assessment model, based on Carnegie Mellon University's Economic LCA model tool (EIO-LCA), and eight construction projects are investigated, using the new LCA framework, to demonstrate and verify the model's efficiency and applicability. Comparing these case study results to other past LCA frameworks, it indicates that construction sectors are the main contributor to the environment impacts of construction projects, and transportation and utility sectors contribute to a larger part to the certain impact than service sectors.

Bilec et al. (2006) performed a hybrid LCA framework, integrating the advantages of both process and input-output approach, in a precast concrete parking garage's construction and found that on-site equipment, transportation, and support functions are the three main impact sources for the environment. This study, however, overlooked the main factors of construction industry: schedule and cost, and provided few strategies for the decision makers. In order to holistically evaluate the construction process, Bilec et al. (2010) modeled the construction process with a usage of augmented process-based hybrid LCA tool. The model created by Bilec et al. (2010) includes various construction activities, like transportation of workers to site, construction service sectors, manufacturing of equipment used for certain activity, and fugitive dust generation during the construction phase. In the office building case study, services are the main contributor to the total emissions. The results also indicate that construction process is as significant as other life-cycle stages for the evaluation of the environmental impact. Given that the assessment of construction process can help decision makers identify environmental impact, like CO_2 emission peaks, and modify the construction plan in the planning stages, Li et al. (2011) created an integrated LCA model to evaluate two main factors involved in a typical construction process: construction plants and ancillary materials. The research not only provides a decision-support tool for sustainable action tool for construction planners, but also develops a worker-health based model, a disability adjusted life year (DALY), for analyzing the human health damage caused by construction dust. A case study of earthwork shows that proposed model enables the contractors effectively to estimate the environment performance of certain construction activity, and eventually to produce more environmentally sustainable development.

Hong et al. (2013) developed an assessment model based on process-based LCA and input-output LCA to quantify the environmental impact of buildings during construction stage from three different aspects: material manufacturing, transportation, and on-site installation and construction. The results find out that the on-site equipment usage phase produces the second largest amount of energy consumption 4.03% and Global Warming Potential 3.08%.

All these efforts, discussed above, provide the construction industry with a better understanding of environmental performance of construction process, and help contractors to engage in the best practices of sustainable development. These studies, however, are criticized for not supporting the environmental management of a specific construction on its own (Ahn et al., 2009; Pena-Mora et al., 2009; Lee et al., 2009) and do not account for variations in construction operations between projects (Lewis, 2009). In addition, for a more specific aspect, the data from these studies is not collected based on actual on-site energy use and emissions. Therefore, the following section provides an up-to-date review of the various approaches and models for construction emissions quantification based on actual energy use in the construction site.

2.3.2 Operational Emissions Quantification Tool

As an important source of CO_2 emissions, the construction sector has sought to not only assess the environmental impact, as discussed in previous section, by a life-cycle tool assessment during the construction phase, but also reduce the actual on-site emissions by using various strategies and methods. For CO_2 emissions reduction strategies, the EPA has released a report in 2009, and suggested that equipment fuel efficiency and operational procedures, on which contractors have great influence, are the two penitential areas for improvements (EPA, 2009). Four primary fields are identified for the contractors to improve the fuel efficiency of construction equipment, including reducing equipment idling (Lewis et al., 2012), maintaining the equipment (Edwards and Holt, 2009), selecting proper equipment (Shapira and Goldenberg, 2007; Hasan et al., 2013), controlling operational efficiency (Ahn and Lee, 2012) and using alternative fuel (biodiesel) (Pang et al., 2009).

A study is conducted by researchers in Yonsie University to estimate the GHG emission from on-site plants for various road construction activities using final design documents of 24 cases (Kim et al., 2012). This research employs a process analysis method to quantify the fuel consumption, which is directly related to the GHG emissions, of equipment for the on-site construction activity.

There are three steps in calculation of GHG emissions: estimating the working hours, quantifying the consumed energy, and calculating the GHG emissions by CO_2 equivalents. Results show that earthwork is the largest contributor, accounting for 90%, to the total emissions, among other activities. This research also discovers that proper selection of plants and the specific site conditions are the two basic emission reduction methods through the use of focus group interview and questionnaire-based survey. However, the amount of fuel consumption in the construction stage is hard to determine based on design documents (Hong et al., 2013).

Efforts from the North Carolina State University (NCSU) are mainly focused on the fuel consumption and air pollutant emissions of construction equipment in the construction site. There are two primary non-road vehicle emission inventory models: EPA NONROAD and California Air Resources Board (CARB) OFFROAD. Due to a lack of ability for real-world emission data collection in both two models, Lewis et al. (2009) compared various sources diesel engine data, identified the need to collect and analyze the emissions data for real-world construction activities and proposed a future research area for pollutant emissions from in-use construction equipment. Rasdorf et al. (2010), therefore, outlined standard procedures for acquiring the field data. The amount of air pollutant emissions per construction activity is measured second-by-second by a portable emissions monitoring system (PEMS). For example, PEMS for accurate data collection method and field study procedures (Frey et al., 2007; Rasdorf et al., 2010) were used for eight different types of construction vehicles (Frey et al., 2010). The results show that fuel-based emission rates are less variable than time-based emission rates. In addition, Frey et al. (2008, 2010) established a data quality control regulation. The awareness of emissions from non-road diesel construction equipment can be promoted by the identification of emissions peaks and potential construction activity with heavy pollution. On the other hand, these previous efforts, however, lack potential emissions reduction strategy for the decision makers.

Furthermore, several studies in NCSU have paid attention to the quantification of construction activity emissions at a project level. For a better understanding of the relationship between individual activity and emission production, Rasdorf et al. (2012) linked the fuel use and related emissions to the construction schedule, and the aforementioned energy consumption and emission data was from a commercial building case by Marshall et al. (2012). The aforementioned data in the Marhall et al.'s research is mainly from two different aspects: EPA's NONROAD is used to generate emission estimates, and RS Means CostWorks tool can help develop quantity take-off and related cost estimate. The results indicated that site work was the main contributor to the overall project emissions, and caused a significant emission peak in the early stage of a project (Marshall et al., 2012; Rasdorf et al., 2012). In order to illustrate the impact of engine idling in the reduction of fuel use and CO_2 emissions, Lewis et al. (2012) used PEMS for gathering emissions directly from the in-use equipment, and estimated the idling impact with operation efficiency, which refers to the hour-based productivity of certain equipment. This productivity integrated CO_2 emissions assessment tool can help stakeholders to pay attention to those high idling time plants and reduce excessive idle time. In addition to emissions estimates from the fuel consumption, Hasan et al. (2013) present a carbon footprint simulation process to assess the environmental performance of tower crane utilization on high-rise construction project.

2.3.3 BIM Approach for Quantification of CO_2 Emissions

Over the past few decades, building information modeling (BIM) was emerging as an innovative means for the architecture, engineer, and construction (AEC) industry. It allows for a better collection of information and work processes from different disciplines and multiple project phases. Although BIM is a recent technology, several studies have been conducted to identify the potential of BIM for the CO_2 emissions quantification in building construction phase (Mah et al., 2011; Stadel et al., 2011; Bynum et al., 2013; Li et al., 2013). Mah et al. (2011a) and Mah (2011b) suggested the use of BIM techniques to quantify the CO_2 emissions of each activity, providing a useful tool for decision makers in enhancing the sustainable practices in construction.

Li et al. (2013) described the use of BIM to simulate the construction processes, and measure the CO_2 emissions in a dynamic way. The advancement of BIM technology will assist in providing reliable and accurate quantification of CO_2 emissions, shortening the time of information collection, and generating detailed animations. In this sense, there is considerable potential to improve the understanding of the application of BIM as a tool in the fields of enhancing sustainability in ACE industry.

2.4 Building Environmental Assessment by Visualization

For the past decade, a variety of simulation or visualization approaches have been employed to represent the construction emissions, for the reason that the visual representation of data enables stakeholders to derive the overall information from data more direct and more effective (Russell et al., 2009). A critical review of current literature concerning CO_2 emissions visualization and simulation technology indicates that these previous research efforts can be divided into two directions: optimal emission estimation models, and control/monitor carbon emission. Table 2.1 shows the CO_2 emissions' estimation and control in previous studies.

Table 2.1 Previous studies in CO_2 emission prediction/control

Phase	IT Application	Authors											
		1	2	3	4	5	6	7, 8	9	10	11	12, 13	14
Operation Phase: Actual Control	Geographic Information System (GIS)				√	√	√	√		√			
	Globe Position System (GPS)	√	√					√				√	
	Differential GPS (DGPS)				√								
	Geodetic				√								
	Computer-aided Design (CAD)						√	√					√ √
	GPS/DR (Dead Reckoning)				√							√	
	Portable Emissions Measurement Systems (PEMS)	√		√									
	Vehicle Performance and Emissions Monitoring System				√							√	
	Building Information System							√		√			√ √
	Real-Time Action Recognition Model									√			
	4D Augmented Reality Model									√			

Notes: 1=Pena-Mora et al. (2009); 2 = Paul et al. (2010); 3 = Frey et al. (2010); 4= Ochieng et al. (2003); 5 = Hajibabai et al. (2009); 6 = Hajibabai et al. (2011); 7 = Shiftehfar et al. (2010); 8 = Shiftehfar and Golparvar-Fard (2009); 9 = Heydarian and Golparvar-Fard (2011); 10 = Artenian et al. (2010); 11 = Zhao et al. (2003); 12 = Mah et al. (2011a); 13 = Mah (2011b); 14 = Abanda et al. ;

In order to accurately predict the total emission from construction operations, efforts have been reported in the literature on optimal emission estimation models: Discrete-Event Simulation (DES) (Frey et al., 2010), Collaborative Tunneling Simulation (Ochieng et al., 2003) and Extended Kalman Filter algorithm (EKF) (Zhao et al., 2003). The major challenge of this research direction is the level of effort required to develop a reliable DES model for construction operations. In relation to the operability of actual emission collection, another challenge is validation at the output level. As with a specific application field, the Collaborative Tunneling Simulation System (Ochieng et al., 2003) was developed to estimate the energy consumption and carbon footprints of tunnel construction in the preplanning phase. As a result, the environmental performance of the tunnel construction is roughly two times bigger, compared with that of building construction. In addition, the Extended Kalman Filter algorithm (Zhao et al., 2003) integrated Globe Position System (GPS) data into a low cost DR system. And the EKF algorithm consists of three fundamental elements: the dynamic model, measurement equations and the formulation. The simulation results indicated that the DR sensors can provide improved heading and velocity information when calibrated by the Kalman filter results based on available GPS data.

Other efforts have focused on the detection, visualization, communication, analysis and control of actual carbon emission in the operation phase of the construction by employing various information technologies. PEMS (Frey et al., 2010), Vehicle Performance and Emissions Monitoring System (Zhao et al., 2003), and GPS (Artenian et al., 2010; Mah, 2011; Zhao et al., 2003; Ochieng et al., 2003) have been used in the data collection of carbon emission, including the location of construction equipment, the actual record of emissions, and vehicle information. For the visualization aspect, many efforts have been devoted to an application of Geographical Information System (GIS)(Zhao et al., 2003; Mah et al., 2011; Mah 2011; Abanda et al., 2010) for visualizing CO_2 emissions resulting from construction activities, CAD (Shiftehfar and Golparvar-Fard, 2009; Heydarian and Golparvar-Fard, 2011; Mah, 2011; Abanda et al., 2010), and BIM (Shiftehfar and Golparvar-Fard, 2009; Heydarian and Golparvar-Fard, 2011) for developing 3D models. Artenian et al. (2010) also present a GIS based decision support tool to identify the nearest concrete bath plant, and detected the optimal route that generates the least CO_2 emissions for material transportation. This model will assist various decision makers of construction procurement and concrete providers to make more environmentally sound decisions.

On the other hand, a number of researchers use a framework to comprehensively monitor emissions. For example, Arsalan and Mani (2011) focused on the gained amount of reduction in carbon footprint and proposed a vision-based tracking and integrated productivity and carbon footprint assessment framework. But the most challenging task is measuring accurate operation productivity. To solve this problem, the equipment's location and action were semantically analyzed through an integrated 3D reconstruction and recognition algorithm using the D^4AR, 4-dimensional augmented reality environment (Colparvar-Fard et al., 2010; Colparvar-Fard et al., 2009). All parties involved in the project could visually determine the amount of carbon emissions in their projects and improve each activity by adjusting productivity and reducing idle time. In addition, CO_2 emissions of various house construction stages were also quantified and utilized in a 3D building information model (Mah et al., 2011; Mah, 2011). The use of BIM and the integration of an intelligent database permit end-users to calculate CO_2 emissions for different styles of houses with different types of construction methodology, which allows rapid emission computations for different kinds of house sizes, designs, and materials. Furthermore, Frey et al. (2010) summarizes the results of field research that used PEMS to collect fuel use and emission data from construction equipment to assess the environment impacts of construction activities.

As discussed above, for the control of CO_2 emissions resulting from construction operation, existing work has paid attention to either a simulation way to evaluate the environmental impact in the pre-planning phase, or a visualization method to quantify emissions during the lifetime of construction process. However, few of these efforts have considered the complexity of the construction site, like, the surroundings, terrain, and et al., and the operation phase is also an ideal model, such as earthmoving (Hajjar et al., 1997), excavating. Another important issue, which cannot be ignored, is that all research discussed above is conducted in North America. And, the environment is totally different Hong Kong. For example, GPS can be successfully adopted to record the position of equipment in North America construction site, but it might be inaccurate due to skyscrapers in high density city, like Hong Kong.

2.5 Mixed Reality (MR) Technology and the

Construction Virtual Prototyping (CVP) Technology

2.5.1 Mixed Reality Technology

Mixed reality (MR), extending the concept of augmented reality (AR), is defined as a special subclass of virtual reality (VR) for enhancing the real world with virtual objects (Milgram and Kishino, 1994; Tamura et al., 2001). It aims at providing users with physical and digital objects to interact in real time for a comprehensive experience of the world. The MR technology has been widely used in the fields, like architecture and urban planning, manufacturing, and education and training. Due to the complexity of construction sites, the construction industries have also show great interest in adopting MR technology (Wang et al., 2009). The MR technology can assist the decision makers to extract features from scenes of construction site to identify the relationship between the real-world coordination system and the virtual environment.

2.5.2 Construction Virtual Prototyping Technology

Virtual prototyping (VP) is a computer-aided design process involving the construction of digital product models ("virtual prototypes") and realistic graphical simulations that address various issues of physical layout, operational concept, dynamics analysis and functional specifications (Baldwin et al., 2009; Huang et al., 2007). The construction virtual prototyping (CVP) technologies developed by Li et al. (2008) has conducted many research and projects into the application of VP into real-life construction projects in Hong Kong and mainland China.

The objective of the CVP technology is to enable the constructors or contractors to 'try before build' or 'construct the building many times' in the computer before the construction project commences. The rapid prototyping of projects allows the project team to examine the feasibility of construction and provides for an effective means for communicating temporal and spatial information on project participants (Li et al., 2008). The four-dimensional (4D) model is generated from the combination of three-dimensional images and the process (i.e. time), which allow the project team to visualize the construction plan and view the simulated time-lapse representation of corresponding construction sequences (Huang et al., 2007). The current application of the CVP has been focused on the development of a detailed or improved construction program during the construction program, which aims to identify collisions or potential danger of the construction project in the virtual experiment (see in Figure 2.1), and to support knowledge generation and transformation at the planning step of construction project development.

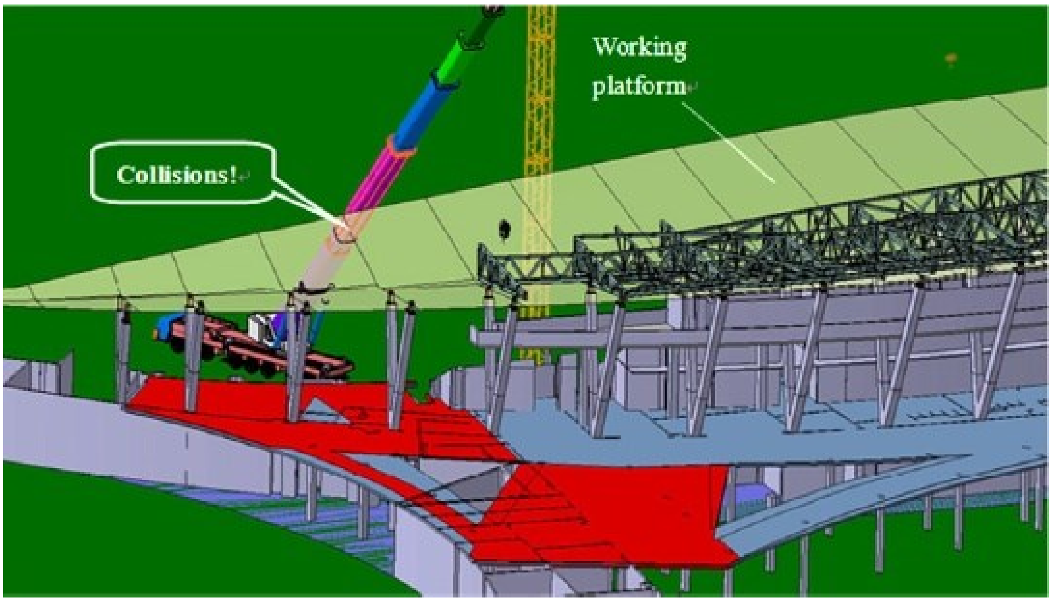

Figure 2.1 An example of safety evaluation in the construction virtual prototyping platform (Guo et al., 2013)

The VP model developed by the CVP Laboratory is mainly based on 'Product', 'Process' and 'Resources' (PPR) models from the Dassault Systemes Corp. The 'Product' model represents the building which is intended to be developed, while the 'Resources' model relates to the construction equipment and temporary work to be used for moving or supporting building components. The 'Process' model represents the procedure of how 'Product' is constructed using the 'Resources'. Both *CATIA* and *DELMIA* are two core software in the PPR framework (Huang et al., 2007). To develop the project-specific CVP, the construction equipment must be defined. The construction equipment and plant in CVP is established by using the Device Building workbench. Through the application of *CATIA*, the 3D-CAD models of building, temporary works and construction equipment will be generated from the design.

On the other hand, *DELMIA Digital Process for Manufacturing (DPM)*, an assembly process planning and verification solution will be adopted to provide the capability to link and view product data from any major CAD system, examine construction sequences and processes, and connect each process step to the construction process (Huang et al., 2007). *DELMIA* provides a virtual environment for the project team to define and simulate construction processes and evaluate different construction methods to identify possible problems, safety and time waste (Guo et al., 2010). Recently, *Autodesk Revit-based software* and *NavisWorks* are also adopted by the CVP Laboratory for the development of 3D and 4D simulation models. Detailed discussion of the implementation of CVP and the application of the technology is available in Li et al. (2008).

In general, the VP technology enhances the monitoring of the construction activities by running through the whole construction process in a simulation system. If a problem is found, the project planner will propose remedial actions and then re-run the simulation process to verify if the proposed remedial actions are workable (Li et al., 2008). The 'trial and error' process will continue until the 'ideal' construction process is achieved. The CVP technology helps identify the construction risks and problems prior the commencement of the project. The application of CVP in many real-life projects has suggested that VP technology to be a useful tool and effective visual communication and collaboration platform for project stakeholders in various stages of the construction projects (Guo, et al., 2010).

While the CVP is proved to be a useful and effective visual communication and collaboration platform for clients and project team in the design, construction and management of construction projects, its application towards the environmental management, in particular on the emission predication and visualization is still unexplored. Based upon CVP Laboratory research, the VP technology is presented as an important tool to providing a visual communication and collaboration information for carbon emission prediction and minimization for the construction projects.

2.6 Chapter Summary

This chapter provided a review on research context of sustainable construction process. It first discussed the definition of the sustainable construction, and identified the need to manage the emissions from construction process. Then, three current research fields for evaluate the environmental performance of construction process were briefly introduced and the research gaps were identified. The current application of visualization and simulation technology for sustainable construction was also provided for enhancing the understanding of visualization in construction industry. Finally, a succinct review of MR and CVP technology in the VR field was also presented, with an aim to provide a brief discussion of the research topic.

CHAPTER 3 RESEARCH METHODOLOGY

3.1 Introduction

This chapter presents an application of virtual prototyping technology for the carbon emission visualization and prediction of the construction project, which aims to develop preliminary emissions visualization overtime with a simulation tool. Prior to embarking on the introduction of methodology, the chapter begins with a brief review of previous studies that combined visualization technology with emissions quantification in construction project. This chapter also provides a comprehensive introduction of the methodology and general steps of this research. The chapter then discusses the data collection method for an effective estimation and simulation of construction equipment emissions. This chapter ends with a brief summary.

3.2 Previous Studies

In the past few decades, research into computer or visualization models to quantify the emissions from construction processes have been growing. Currently, most of the research initiating construction activity emission visualization are led by a number of prominent institutes in Northern America, such as University of

Alberta (Hasan et al., 2013), University of Illinois (Ahn et al., 2009; Hajibabi et al., 2011; Pena-Mora et al., 2010; Shiftefar et al., 2010) and North Carolina State University (Lewis et al., 2009; Frey et al., 2010). For example, the visualization technology has been adapted to optimization of concrete truck mixer routes so as to minimize emission, making use of GIS technology (Peña-Mora et al., 2009; Artenian et al., 2010; Hajibabai et al., 2011), and to monitor productivity and carbon footprint (Heydarian and Golparvar-Fard, 2011).

On the other hand, a selection approach incorporating CO_2 emissions analysis and simulation with production performance allows lift engineer to assess the effectiveness of tower crane on high-rise construction project (Hasan et al., 2013). Operational efficiency has also been considered to quantify the amount of emissions from construction equipment operation (Ahn and Lee, 2013). Despite these efforts, many existing emissions visualization and quantification model are still in the early stages and limited to regional application. Many existing works are also focused on a specific field of activities, such as lifting (Hasan et al., 2013), earthmoving (Ahn et al., 2009; Rekapallia and Martinez, 2010; Kaboli and Carmichael, 2012), concrete transportation (Artenian et al., 2010). Limited tools have been developed towards a more holistic estimation of emissions embracing all major activities in the construction process. Furthermore, it's also a great challenge for construction planners and contractors to quantify project-level emission, due to the time-consuming and segmented processes (Melanta et al., 2012). For these reasons, the need for developing new theories or different model for automatic greenhouse gases emission data analysis and visualization has been highlighted (Hajibabi et al., 2011).

3.3 Overview of the Development of VP-based Emission Prediction Framework

Before discussing the methodological issues, it is essential to emphasize the objective of this study for improving the understanding of the research designs. The main goal of this research is to develop preliminary emission visualization overtime with a simulation tool (i.e. the construction process) via the CVP technology. The first research problem involves the understanding of how visualization tool would help improve the sustainable construction with respect to carbon emission control. The second research problem relates to provide the estimates of the construction emissions based on the equipment operation schedule and detailed information of construction plants. Finally, a multi-dimensional visualization platform is developed for the decision makers, which combines a time linked 3D model and predicted emission data via the CVP technology and concept of MR, in a real case study.

While many existing discussion on industry-related emissions has focused on energy consumption during the post-construction and occupancy stages of the building, including energy consumptions directly related to heating, cooling and powering a building, emissions generated from the construction and development processes is relatively less discussed and reviewed. This study, thus, will generate a pilot 4D virtual prototype to estimate and simulate construction equipment emissions at the pre-planning phase. The equipment and plant on construction sites in this study will focus on the on-site, fuel-intensive heavy plant and equipment, such as bulldozers, cranes, concrete pumps, excavators etc., which are expected to produce significant amounts of carbon emissions during operation and idling stage. The emission prediction model helps evaluate and explore possible solutions and improvements to the reduction of carbon emission on site from the plant operation through the assessing the feasibility of the proposed construction methods and sequences.

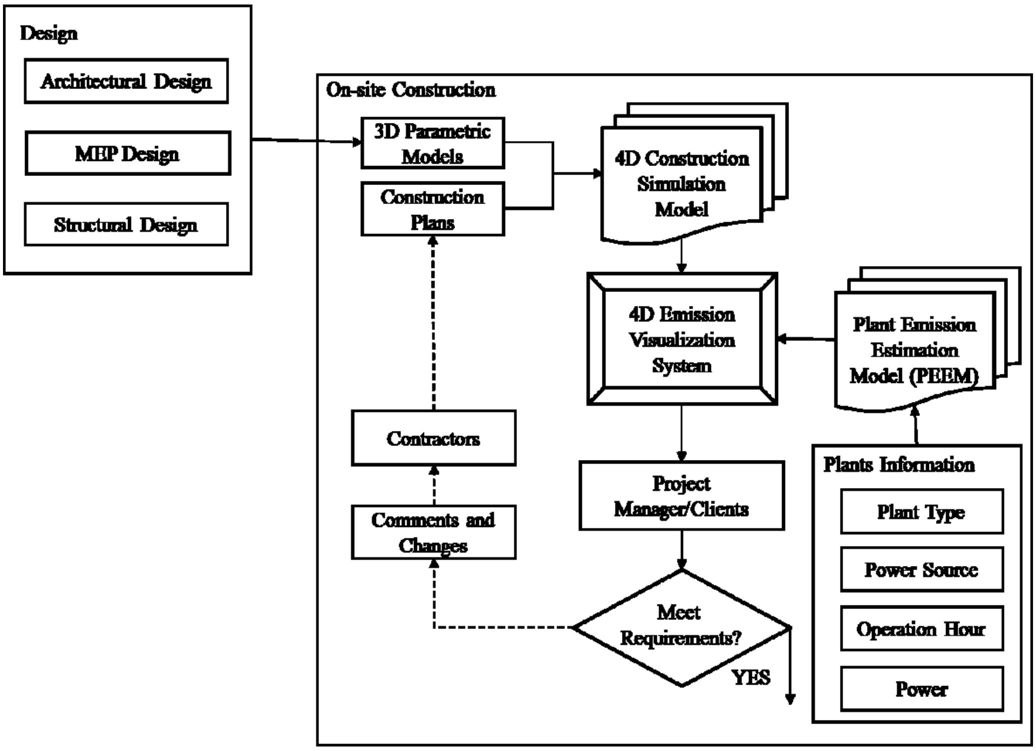

Figure 3.1 VP-based emission prediction framework

The methodology for this study, as illustrated in Figure 3.1, starts at the initial phase by gathering enough data concerned with the construction project including graphical elements (e.g., architectural, structural, and MEP designs, etc.) and non-graphical elements (e.g., the construction plan, construction equipment list, and general information of construction project, etc.). Since the on-site construction process is determined by the collected information, it is vital significant for the estimation and simulation of emissions. The following data collection section will fully detail the information. As shown in Figure 3.1, the prediction framework consists of two main parts: 4D construction simulation model and plant emission estimation model (PEEM). The 4D construction simulation model is simply 3D models plus time, which represents the sequence of installation of the construction components. Based on the equipment operation schedule for the building construction, the PEEM is used to calculate the amount of emission at the project level. Then, the 4D emissions visualization system involves an application of VP technology for providing a platform combining the 4D construction simulation model and PEEM. With the help of this emission visualization platform, the project manager (PM)/ clients can visualize the construction processes and the resources/plant employed for each of the construction processes, evaluate the environmental performance of the on-site installation, and develop appropriate environmental management plan for the project.

3.3.1 Data Collection

This research aims to utilize virtual prototyping technology to develop a multi-dimensional emission prediction and visualization tool for construction process through a series of logical steps, for example collection of field data related to emissions, 3D BIM Models, and so on. The visualization model of emissions developed for this project consists of two set of data.

The first set of data involves in the development of the Building Information Models (BIM). These models were built by *Revit Architecture, Revit Structure, Revit MEP* software, and optional *AutcoCAD Civil 3D* of Autodesk. The latest 2009 version of Revit system was being used for the development of the construction simulation. The construction site plan, construction drawings and details (in 'dwg' file format) were converted into a visualization and simulation environment (in a 'dgn' format). The computer rendering perspective images are required to be produced using information from the model. By linking the 3D models (i.e. Revit-based software as mentioned above) and the construction project schedules (i.e. *MS Project* files) through the*Autodesk NavisWorks*, it is able to model the 4D construction schedules and enables a real-time and whole-project simulation.

The second set of data includes the information about the equipment and plant used for the project, which is critical to quantifying and forecasting the project emissions. Type and quality of the plant and equipment adopted will considerably determine the total project emissions. The emission model development commences with coordinating the project contractor and sub-contractors in order to identify the plant and equipment to be adopted on site, calculate the daily operation of equipment (i.e. daily equipment usage), and predict how long the equipment worked on site (i.e. the total number of days of equipment operation). The numbers of trips or operations will be determined by the total amount of materials to be placed onto the site or soils/rocks to be removed from the ground etc.

3.3.2 Plant Emission Estimation Model

Before describing the emission estimation model employed in this study, it is essential to present a brief introduction of existing off-road equipment emissions inventory models mainly developed by states and private agencies in US (see in Table 3.1). These models, compared with LCA-based approach, can provide a more accurate and reliable estimation of emissions from the operation of on-site equipment by utilizing emission rates for different type of equipment (Ahn, 2012). However, the majorities of these models provide individual source emissions (e.g. passenger vehicle) and rarely support comprehensive emissions estimation (Melanta et al., 2012). As shown in Table 3.1, a summary of existing emission estimation model, mainly used for determining the construction-related emissions, is provided for listing the type of model, air pollutants and source organization. The utility of each model are also presented in the table. For example, the carbon footprint estimation tool (CEFT) developed by University of Maryland provides project-level emission quantities of transportation construction projects.

Table 3.1 Example of existing models for CO_2 emission estimation in the fields of construction management (Melanta et al., 2012)

Model Name	Air Pollutant	Source Organization	Scope
NONROAD 2008	CO, CO_2, NO_X, SO_X, HC, PM	EPA	Non-road vehicles and diesel equipment
URBEMIS	CO, CO_2, NO_X, PM, ROG	SQAQMD	Air pollutants from construction of urban projects.
SMAQMD 2009	CO, CO_2, NO_2, PM2.5, PM10	Sacramento Metropolitan Air Quality Management District	Air pollutant of road construction project.
OFFROAD 2007	CO, CO_2, NO_X, SO_X, HC, PM	California ARB	Agricultural, construction, garden equipment, and recreation vehicles
CEFT	CO_2e, PO_G, SO_X, VO_C	University of Maryland	Transportation infrastructure, equipment and materials production, and deforestation and soil movement.

Note: List modified from Melanta et al. (2012)

To estimate the emissions of a project, information such as the operation hours of the equipment and plant based on site equipment operation plan must be acquired from the project team (i.e. contractor and the sub-contractors). To address this issue, the 'plant emission estimation model' (PEEM) will be developed from the equipment operation schedule for the building construction. The amount of emission in each activity is calculated with the emission rate of each plant with the details from the plan operation plans/schedules. The predicted emissions level will be act as a control target level for operation phase (Peña-Mora et al., 2009).

PEEM is designed to be an available tool for the estimation of vehicular emissions produced within construction process from the operation schedule of the equipment usage. In order to develop the PEEM, three types of data will be needed to collect first for each construction activity from the contractor and sub-contractors (Lewis, 2009): *general* (i.e. project details), *work activity* (i.e. construction schedule; description of the task, duty cycles being performed by plant, etc), and *modal description* (i.e. a listing and description of the equipment activity modes), to assess the field conditions at the construction site where the plant is deployed and to record the nature of the plant activity. Other information related to the specific plant item, including identification, engine power and tier, and details of the owner/supplier will also be collected. With the construction activity plans, the plant usage schedule, quantities of potential emissions of the construction plant and equipment can be calculated. Adopting the approach by Peña-Mora et al. (2009), the CO_2 fuel-based emissions will be calculated based on the emission rate of each plant, extracted from emission inventories such as OFFROAD, NONROAD (EPA, 2008) and EMFAC. The emissions for each duty cycle of a plant item will be calculated by multiplying the duty cycle time by the corresponding emission factor (Ahn et al., 2009).

3.3.3 4D Construction Simulation Model

To develop a virtual prototype, construction drawings will be acquired and developed in 3D format, and other information including construction schedule and methods, plant operation hours based on field activity plans will be quantified using simulation technologies (i.e.*Autodesk Revit Architecture*). To build static 3D resource models including those for construction plant and temporary works, the construction methods can be expressed in the virtual platform.

To convert to a 4D model, the data of the schedule and the 3D models were exported to a simulation by the *Autodesk NavisWorks*. The dynamic process simulation consists of a series of activities including labor and plant, each of which has a defined duration and is linked with components to be constructed and resources. Figure 3.2 briefly illustrates the process of developing the 4D simulation. These 3D and 4D models can assist in not only providing the realistic visual expression and a consistent visual platform, but also serving as a common communication language of as-planned information for all parties in a project (Song et al., 2005).

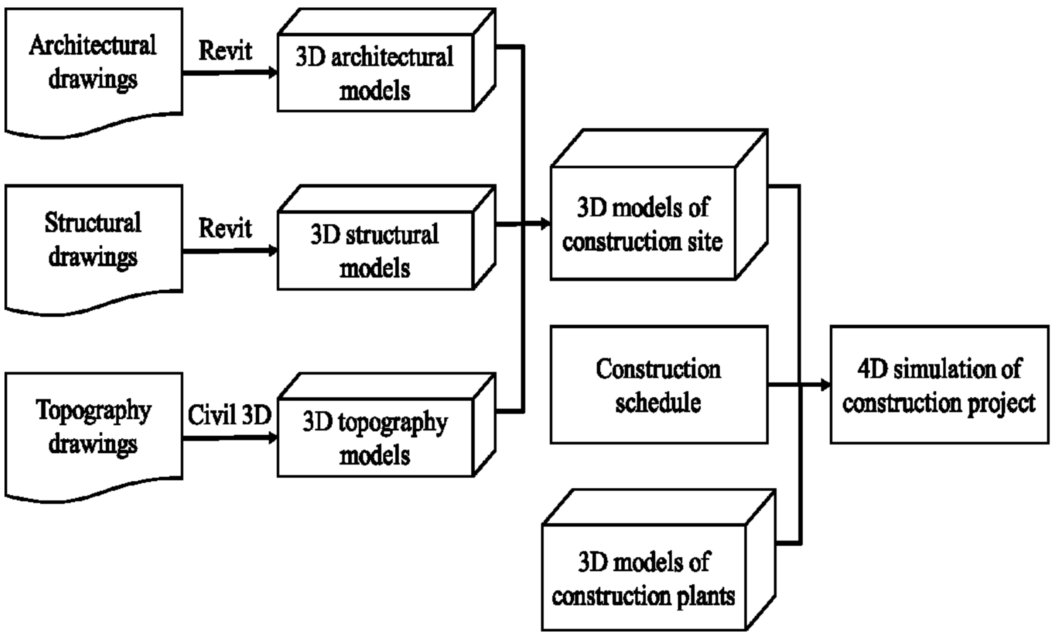

Figure 3.2 4D visualization and simulation of construction process

The estimated emissions of the construction operations for each activity will be calculated, tabulated and plotted to visually demonstrate the emission rates side by side with the simulation model of the construction project. The estimated fuel consumption for each plant item will be calculated using information such as plant type, fuel consumption rates, fuel costs, and operating hours. The model allows project team to visualize the predicted emissions at different times in the construction processes, identify activities that have high rates of generated emissions, decide optimal construction methods and sequences, and mitigate the potential emissions.

3.4 Chapter Summary

This chapter described the methodology and methods that were adopted in this thesis. The chapter began with a review of previous studies in construction activity emission visualization targeting to have a better understanding of the methodology used in the following section. Then, a comprehensive introduction of the theoretical frameworks and detailed steps for the implementation of the research design were provided for developing preliminary emission visualization overtime with a simulation tool. Furthermore, this chapter discussed the strategies for data collection method involving two set of data: BIMs, and equipment and plant related information. The details of two main models in the theoretical frameworks were also demonstrated. The PEEM was used for the estimation of equipment emissions that occur within construction process from the operation schedule of the equipment usage. On the other hand, the 4D construction simulation model was developed based on 3D models, construction schedule and methods, plant operation hours. The following chapter will implement the case study to verify the practicability of VP-based emission prediction framework.

CHAPTER 4 CASE STUDY IMPLEMENTATION AND ANALYSIS

4.1 Introduction

The chapter is organized to test the applicability and effectiveness of the methodology which was proposed in Chapter 3. An on-going Public Rental Housing Development Project in Hong Kong is employed to illustrate the application of VP-based emissions prediction framework and identify the potential problems during the test process. At the beginning of this chapter, it describes the general information of the project, like master program, and site plan. Then, the case study is implemented step by step, which involves on-site data collection, emission rate quantification, and VP-based emission visualization platform development. Furthermore, the results of this test are discussed and analyzed. In fact, this chapter also has the potential to improve the understanding of sustainable construction by virtual prototyping technology. The chapter concludes with a short summary.

4.2 Description of the Case Study Site

With the current boom in construction sector in Hong Kong, it has led to a continued growth in carbon emissions associated with an increasing construction activities, in particular the fuel-based hazardous emissions during the construction processes of these massive infrastructure development. The project used to demonstrate the concept and applicability of the VP-based emissions prediction model was the Public Rental Housing Development Project, of which the construction period is from October 2011 to March 2014 (29 months), at Tung Tau Cottage Area East (TTCAE) in Hong Kong. The main contractor of this project is the Able Engineer Construction Ltd. The construction schedule of this project is show in Figure 4.1 (part a to part d).

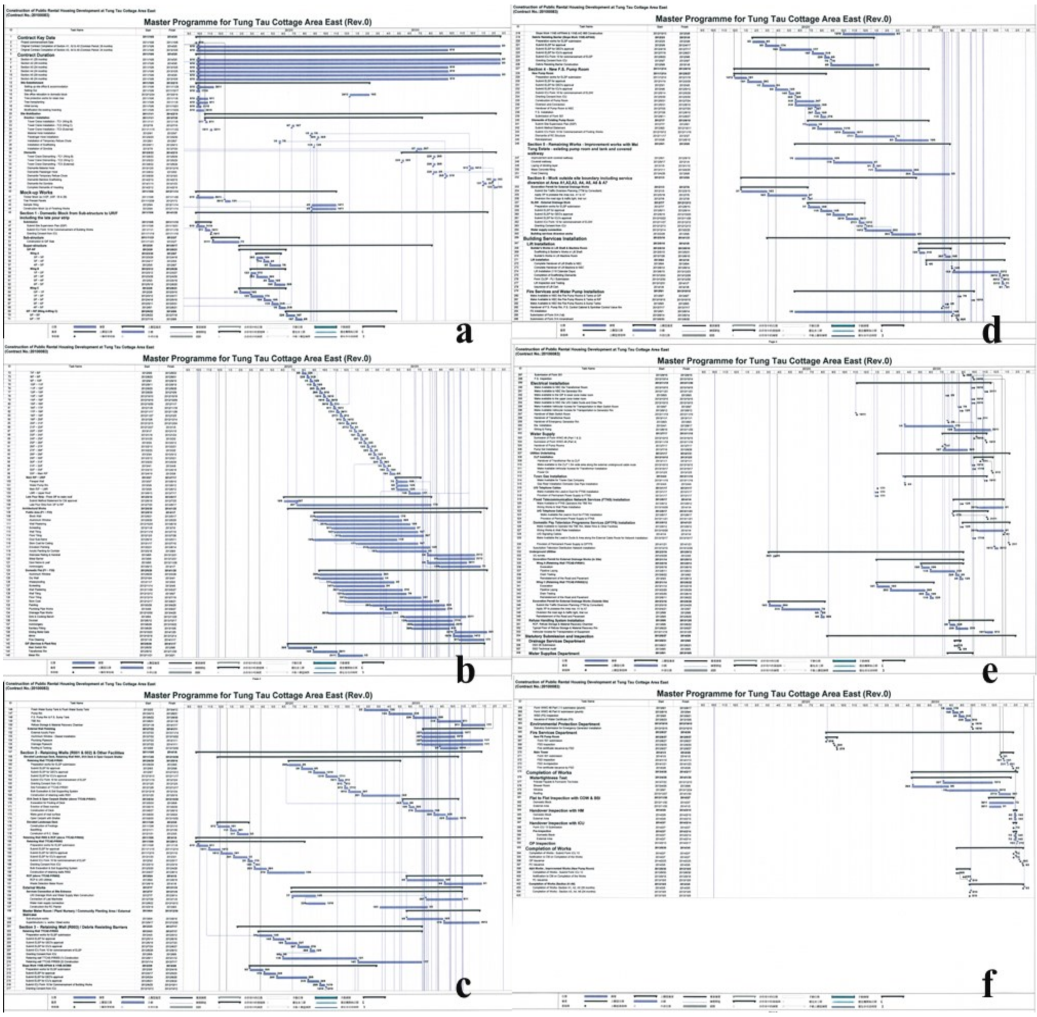

Figure 4.1 Master programme for Tung Tau Cottage Area East

This public rental house project consists of one 34-storey domestic block, providing 990 flats, an open car-parking for privates cars, light goods vehicles and motorcycles with shelters; an Estate Management Office and associated external works. As shown in Figure 4.2, the construction site comprises three major platforms (Wing A, B and C) in different levels and extensive man-made slopes, with an area of about 1.2 hectare (ha). In this high rise construction project, the conventional building construction process can be divided into five different stages: temporary work for construction site, earthwork, foundation work, framework, rooftop work, and operation work.

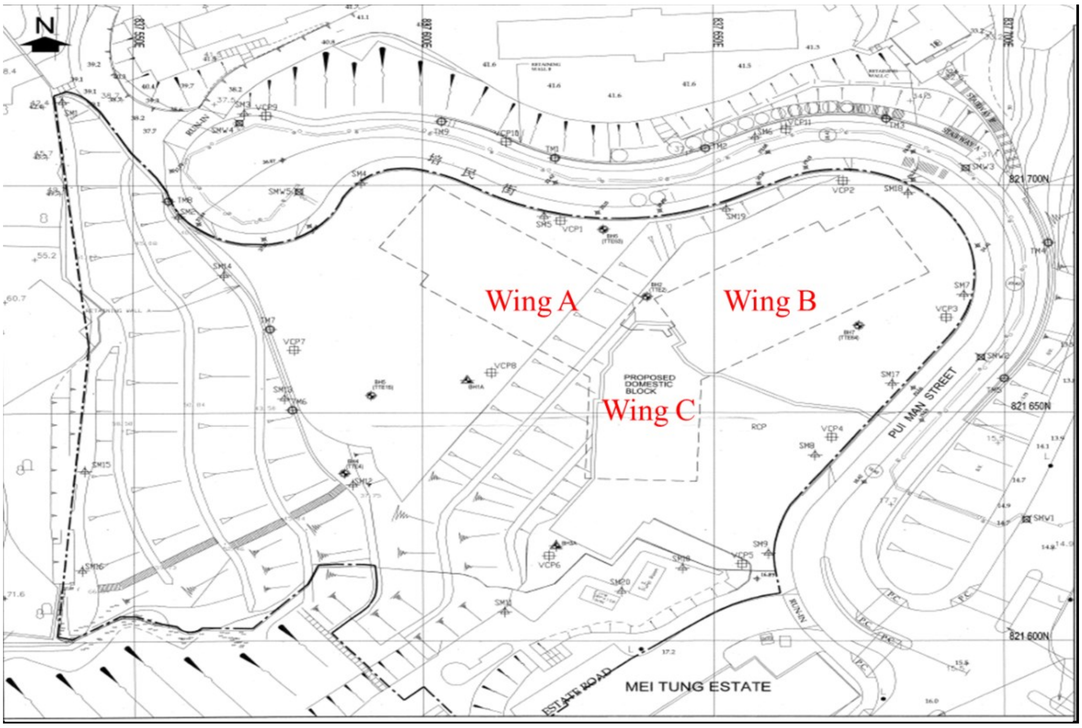

Figure 4.2 The general outline of Tung Tau Cottage Area East construction site

4.3 *Development of VP-based Emission Prediction Platform*

Prior to detailing the development of VP-based emission platform, the current application of the 4D model has been focused on the development of a detailed or improved construction program during the construction program, which aims to evaluate the constructability (Chan et al., 2012) and safety (Guo et al., 2013) of the construction project in the virtual experiment, and to support knowledge generation and transformation at the planning step of construction project development. In general, the VP technology enhances the monitoring of the construction activities by running through the whole construction process in a simulation system.

While the CVP has been proved to be an effective and practical visual communication and collaboration platform for clients and project team in the design, construction and management of construction projects, its application towards the environmental and 'green' management, especially on the on-site equipment related emission prediction and visualization is still unexplored. In this section, the implementation of the VP-based emissions prediction model is examined and applied through a real-life high rise housing project in Hong Kong, which comprises three steps (Figure 4.3).

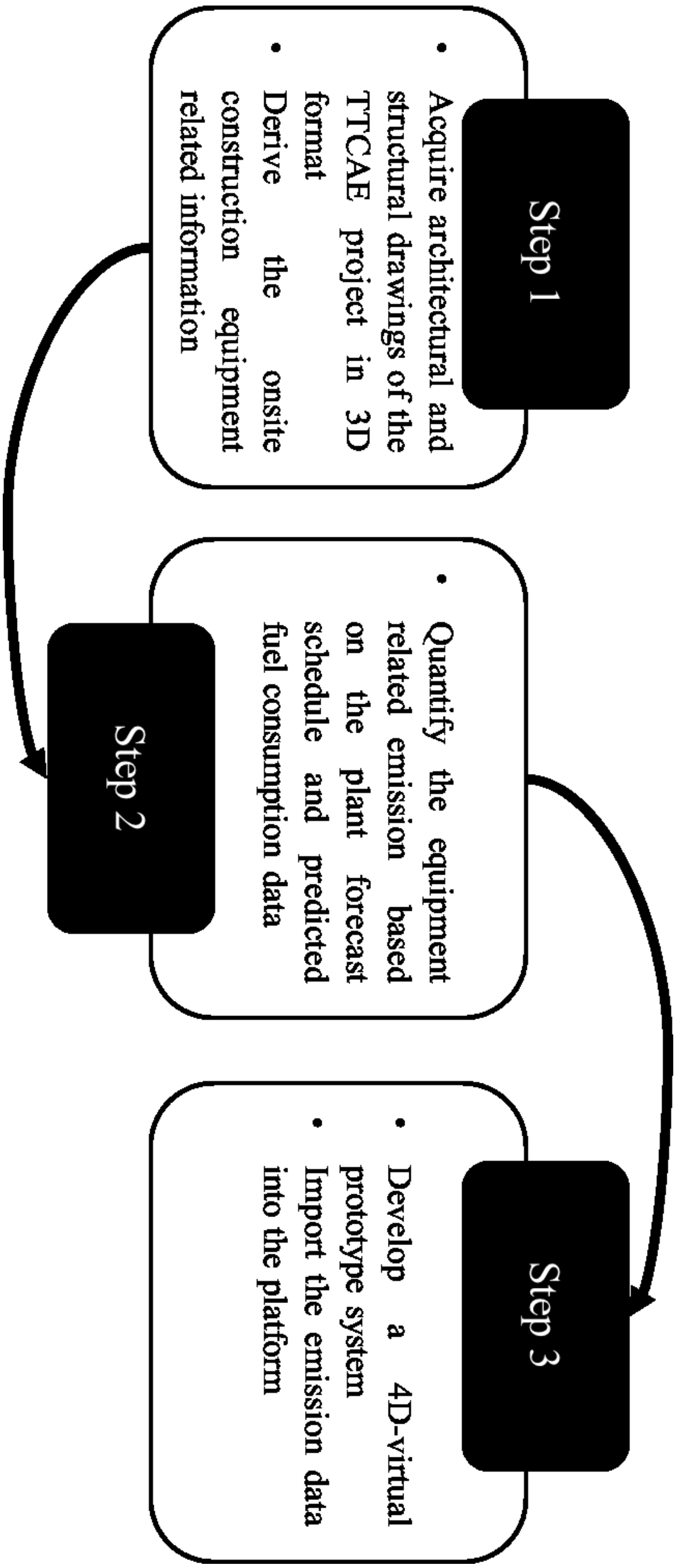

Figure 4.3 Overview of the case study workflow

4.3.1 Step 1 – Collection of General Project and Equipment Data

1) 3D visualization related models

This perspective described in this study seeks the implementation of a multi-dimensional emission prediction and visualization tool for construction process by virtual prototyping technology. To achieve this aim, and to develop the visualization tool, the construction site plan, 2D construction drawings and details (in 'dwg' file format) were collected and converted into a 3D virtual visualization environment (in a 'dgn' format). Three different types of digital models can be identified from the development of 3D visualization platform (Li et al., 2009). The first type is BIMs (Building Information Models), the second type is activity-based model, which is a non-physical model related with productivity rate, and the third is equipment-based model. For example, the 3D site layout of this project, as shown in Figure 4.4, is built from 2D site-layout planning. The BIMs include the virtual terrain contours, built based on 2D survey points through *Civil 3D*, and the site office, rebar storage area, access road and equipment, built from 2D drawings through *Revit*. These models can provide static realistic images for planners to check the design errors and collisions. Furthermore, the construction sequence of 3D site-layout model is generated by linking all these models together. With the help of simulating real-life working process, it can easily and clearly understand how visualization tool would help support site operation planning and decision making among client, consultant and contractor.

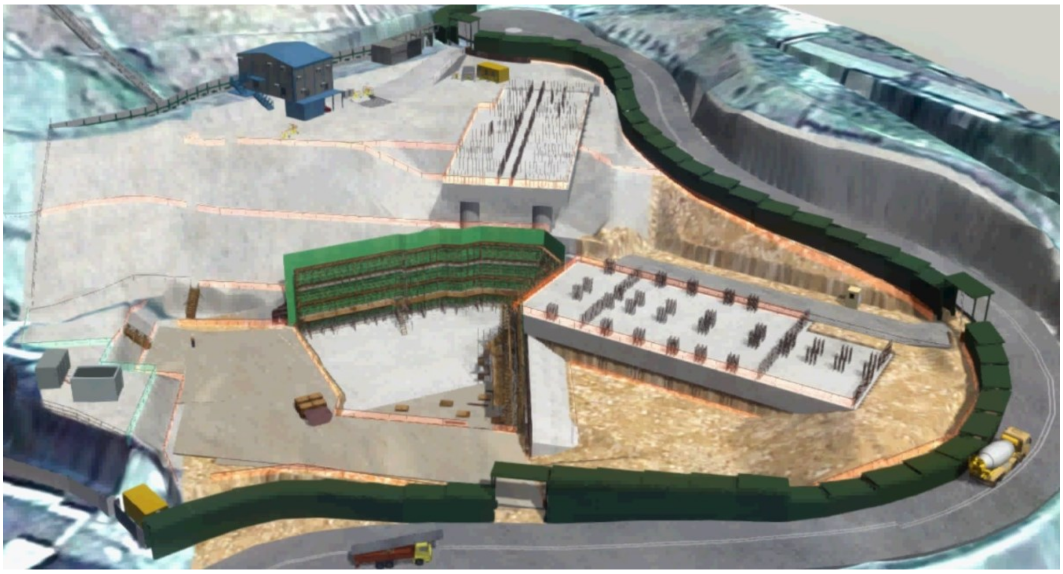

Figure 4.4 Site layout of TTCAE project in 3D environment

2) Equipment emission related information

The scope of this study, present at the beginning of this thesis, limited to construction activities performed on-site in building construction stage. On-site construction activities involve a wide use of various construction equipment, for example, tower/mobile crane for material hoist; excavators, rollers, and scrapers for earthwork; and steel bend machine for rebar installation. Thus, information such as the operation hours of the equipment and plant based on site equipment operation plan (Figure 4.5) must be acquired from the project team (i.e. contractor and the sub-contractors). As shown in Figure 4.5, the project team provides the list of construction plant utilized throughout the whole construction period. There are 13 different kinds of on-site construction equipment and the number of each equipment per month is also listed in the plant forecast schedule.

Construction of Public Rental Housing Development at Tung Tau Cottage Area East
Contract No. 20100083
Able Engineering Company Ltd — Monthly

PLANT FORECAST SCHEDULE — Nos. Anticipated No. (average) | Actual No. (average)

Date	2011			2012											
Plant	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Air compressor	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tower crane	0	0	1	1	1	1	1	1	1	2	2	2	2	2	2
Passenger hoist	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
Material hoist	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
Steel bending machine	0	4	4	4	5	5	5	5	6	6	6	6	6	6	6
Excavator / Backhoe	0	1	1	1	1	1	1	1	1	1	2	2	2	2	2
Concretor vibrator #	0	2	4	4	4	4	4	6	6	6	6	6	6	6	6
Submersible pump	0	1	1	2	2	2	2	2	2	2	2	3	3	3	3
F.S. pump	0	0	0	0	0	0	0	0	1	1	1	2	2	2	2
Vibrator rammer / Plate compactor	0	0	0	2	2	2	0	0	0	2	2	2	2	2	2
Compaction roller	0	0	0	0	0	0	0	0	0	2	2	2	2	2	2
Rock drill machine #	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
Generator	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0
Gondola	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Date	2013												2014		
Plant	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Air compressor	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tower crane	2	3	3	3	3	3	3	2	1	1	1	1	1	1	1
Passenger hoist	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0
Material hoist	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
Steel bending machine	6	6	6	6	6	6	6	6	6	6	4	4	4	2	2
Excavator / Backhoe	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Concretor vibrator #	6	6	6	6	6	6	6	6	4	4	4	4	2	2	2
Submersible pump	3	3	3	3	3	3	3	3	2	2	2	2	1	1	1
F.S. pump	2	2	2	3	3	3	3	3	3	3	3	3	2	1	0
Vibrator rammer / Plate compactor	2	2	3	3	3	3	3	3	3	3	3	3	3	2	2
Compaction roller	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Rock drill machine #	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Generator	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gondola	0	0	0	32	32	32	32	32	32	32	40	40	40	32	32

Figure 4.5 On site equipment operation plan collected from project team

Researchers from CVP conduct actual on-site observations in order to understand the environment, to collect predicted fuel or electricity consumption data from the contractor and sub-contractors, to acquire details about estimated fuel consumption rates of equipment from the suppliers, and also to ensure the equipment planned in the schedule will being used in the actual construction activities. Figure 4.6 shows an example of the on-site observations concerned with tower crane. It provides the detailed information of tower crane: type, manufacture, owner, client, year of produce and the series number.

Figure 4.6 An example of tower crane information: a) service manual of tower crane; b) detailed information of tower crane; c) tower crane in the construction site

Table 4.1 The equipment and plant used for Tung Tau Public Housing Project (Collected from Main Contractor)

Summary of Equipment						
Type of equipment/ plant	Manufacturer	Series	Year	Power source	Power [a]	Total operation hour
Tower crane	Sichuan Construction Machinery	C7050B	2009	Electric	110kw	3480
Passenger hoist	Ketong	SC200/200	2008	Electric	30kw	960
Material hoist	Minglong	SS100, SS100/100	2008	Electric	15kw	1280
Steel bending machine	Fengyida	GW50	2008	Electric	3kw	9200
Excavator / Backhoe	SOMITOMO	SH125X	2002	Diesel	87hp	3000
Concrete vibrator	Kezhuwang	ZXR	2008	Diesel	5hp	17040
Submersible pump	EAST PEARL PUMPS	JYWQ	2009	Electric	3kw	2600
F.S. pump	KOSHIN	FS-2024S		Electric	0.2kw	3250
Vibrator rammer / Plate compactor	Xingchen	HCR80K	2009	Diesel	5.0hp	5200
Compaction roller	WACKER	RD-7H	2003	Diesel	7.5hp 5.5kw	1840
Rock drill machine	Coal Industrial Equipment	Y28	2008	Electric	15kw	780
Generator	WANTONG	WT6500SD	2009	Diesel	5.5kw	1120
Gondola	Jin Fei Tian Hong	ZLP630	2009	Electric	3kw	24480

Remark: a -Diesel (hp), Electric (kw)

After the details of all equipment involved in the project is collected and categorized by type, engineer tier, nature of activities involved, total number of hours used, and the total number of equipment required were determined (Table 4.1). Engineer tier requirement affects the emission output of the equipment, and in general the equipment classified under higher tier numbers requires higher emission restriction control. Data on the operation hour of each equipment was collected from forecast schedule provided by the subcontractors and manual observation of several months of this on-going task. For example, the duration of tower crane lifting activity is determined by the construction schedule and is about 3480 hours.

4.3.2 Step 2 – Quantification of Emission Rate of TTCAE Project

Based on the estimation model described in the previous section, the predicted emission quantities were calculated for various equipment types employed in different construction activities. As stated in the chapter of research methodology, the PEEM was developed from the equipment operation schedule for the building construction. The amount of emission in each activity was calculated with the emission rate of each plant with the details from the plan operation plans/schedules. As illustrated in Table 4.2, adopting the method from Pena-Mora et al. (2009), the CO_2 energy-based emissions could be calculated based on the emission rate of each plant, extracted from emission inventories such as OFFROAD, NONROAD (EPA, 2008) and EMFAC.

Table 4.2 Emission rate of each plant

Equipment	Power	CO_2 kg/hr
Tower crane	110kw	92.4
Passenger hoist	30kw	25.2
Material hoist	15kw	12.6
Steel bending machine	3kw	2.52
Concrete vibrator	64.9kw	54.516
F.S. pump	3kw	2.52
Generator	5.5kw	4.62
Gondola	3kw	2.52
Submersible pump	3kw	2.52
Rock drill machine	15kw	12.6
Excavator / Backhoe	87hp	56
Compaction roller	7.5hp	11.1
Vibrator rammer / Plate compactor	5hp	3.36

Since the details of all equipment involved in the project was provided in the previous section (see Table 4.1), quantities of potential emissions of the construction plant and equipment can be calculated based on the amount of energy (i.e. fuel or electricity). For a better understanding of the emission calculation process, the tower crane was employed as an example to illustrate the monthly emission quantity of typical task during the frame construction stage. The load factor of each piece of equipment is not considered in this research, due to the duration of construction schedule. Following is the equation used to calculate the emissions of tower crane, and the power source is electricity.

$$CO_2 \text{ (kg)} = \text{Equipment number} \times \text{Engine power (kw)} \times \text{Operating hours} \times \text{Emission factor (kg/ kw-hr)}$$

Remark: The emission factor is 0.84 kg/kw-h, as obtained from Hong Kong Electric Holdings Ltd.

The following is the numeric example:

$31046.4\ CO_2 \text{ (kg)} = 2 \times 110 \text{ (kw)} \times 168 \text{ (hr)} \times 0.84 \text{ (kg/ kw-hr)}$

4.3.3 Step 3 - Development of a 4D-virtual Prototype Based Emission Visualization Platform

Through the virtual prototyping of construction processes, a series of activities with each of which have a defined duration, will be linked with construction plant, components and resources. Figure 4.7 shows four different stages of the construction activities of this project in virtual reality environments, which is presented in a 4D model (i.e. 3D plus time). The predict CO_2 emission data for the whole construction project in a tabular format are imported into the 4D model. The simulation displays the process of construction activities and the movement of the construction plant/ equipment together with a table over the corner of the screen to summarize the details of the equipment involved in this particular construction activities at that moment and the emissions information (i.e. amount of emissions). The variations of the emissions in the project will display while the planner evaluates and visualizes the construction process. The amounts of CO_2 emissions would be presented in graphic format (Figure 4.7(a) to (d)). In general, there are two noticeable emission peaks identified in the simulation for this project: the first emission peak appears when the construction of the typical residential floor in the fourth level and the piling work in the site area commences concurrently. The second emission peak to happen is during the construction of the upper floor and rooftop of the residential block, and the execution of the external work activities.

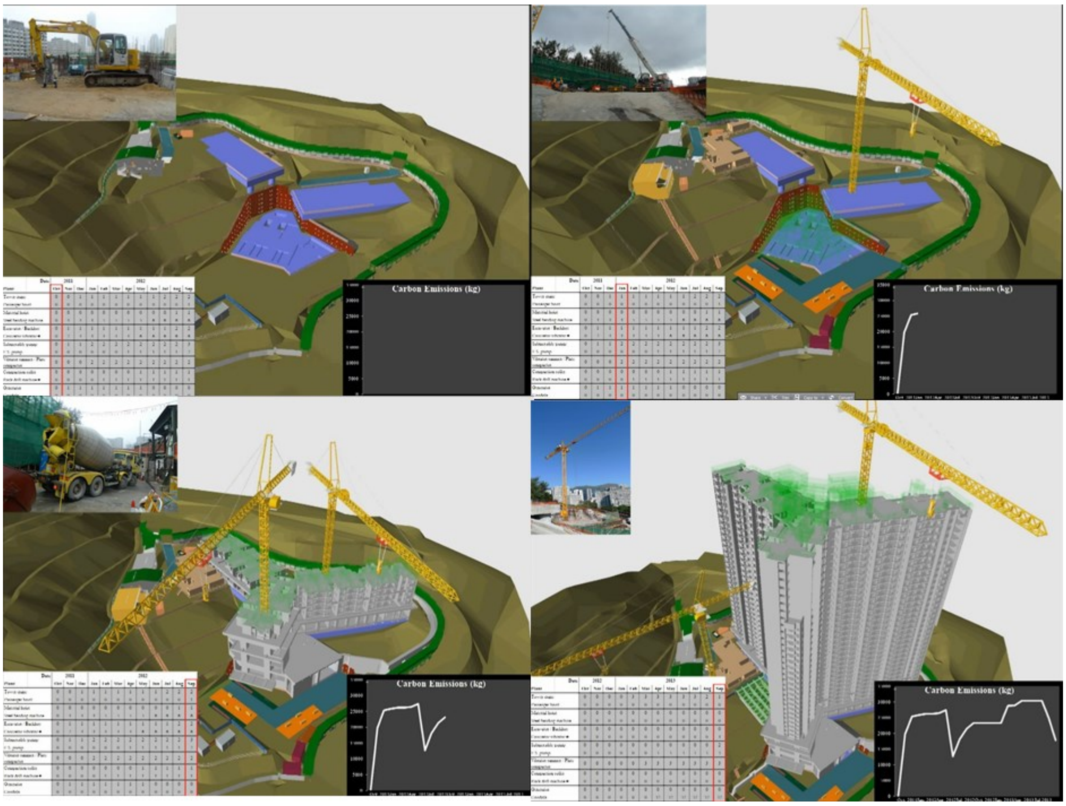

Figure 4.7 4D simulation models with CO_2 emission (estimated) rate of plant/equipment in different phases of the Public Housing Development Project: (a) foundation construction; (b) lower floor construction; (c) typical floor concreting work; and (d) rooftop construction.

The simulation can also be regarded as an AR system used to visually present the operation of the equipment or plant at a particular stage or construction activities. As an example, Figure 4.8 indicates the location and detailed activity of the excavator during the excavation and underpinning around the site area. The 3D virtual environment combined with 2D real image can interactively display the on-site construction activity. One of the principal problems is that the viewpoint can usually be defined from any direction in the virtual environments, whereas the perspective of 2D images data cannot be changed. Visualizing the operations of the equipment/plant at different times of the construction processes together with the associated emission rates allows the project team to identify activities that have high rates of generated emissions and to reduce idling time of construction equipment during the construction activities. The simulation acts as a communication tool for the client, the contractors and the sub-contractors to discuss how to reduce excess emissions, for example by replacing old equipment items before the start of construction activities, and to develop appropriate environmental management plan for the project.

Figure 4.8 Visualized excavator operation versus the real excavation process

4.4 Discussion of Results

The percentage of CO_2 emission, different plants generate during the construction activity, is shown in Figure 4.9. From Figure 4.9, we can find that tower crane, excavator / backhoe, and generator are the top three contributors to CO_2 emission, which accounted for about 39%, 26%, and 15%, respectively, of the total on-site CO_2 emission. In general, there are three key operations identified as the major sources of the emissions throughout the construction process: the first noticeable operation is crane lifting involved in erecting structural components, lifting precast façade, precast staircase elements and large panel formworks in current project. Excavation appears to be the second noticeable operation employed to dig holes, handle materials, lift and place pipes on the construction site. During the initial period, generators, ranking as the third operation, are used as main electricity sources for the project.

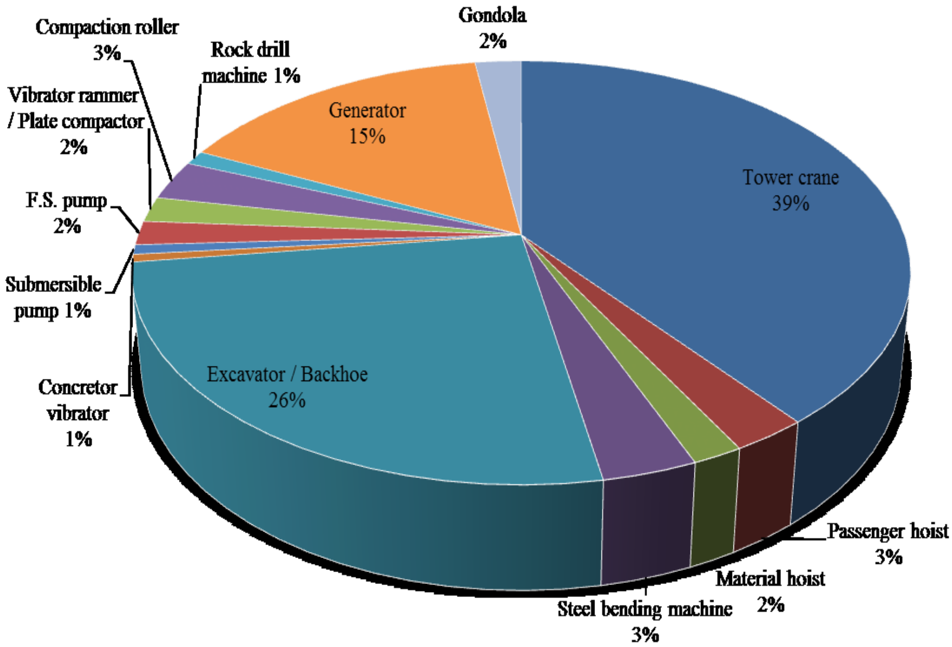

Figure 4.9 Percentage CO_2 emission from activity by plants

It is also significant to view and evaluate the relationship between construction planning schedule and estimation of carbon emissions. Current construction master program for Tung Tau Cottage Area East, provided by subcontractors, is divided into six major parts. A master program does not have the ability to illustrate the carbon emissions that occur during the construction. In combination with exiting construction master program, section 1, section 2 and section 6, as shown in Figure 4.10, are identified as three main phases along a sliding scale of impact in terms of carbon emissions.

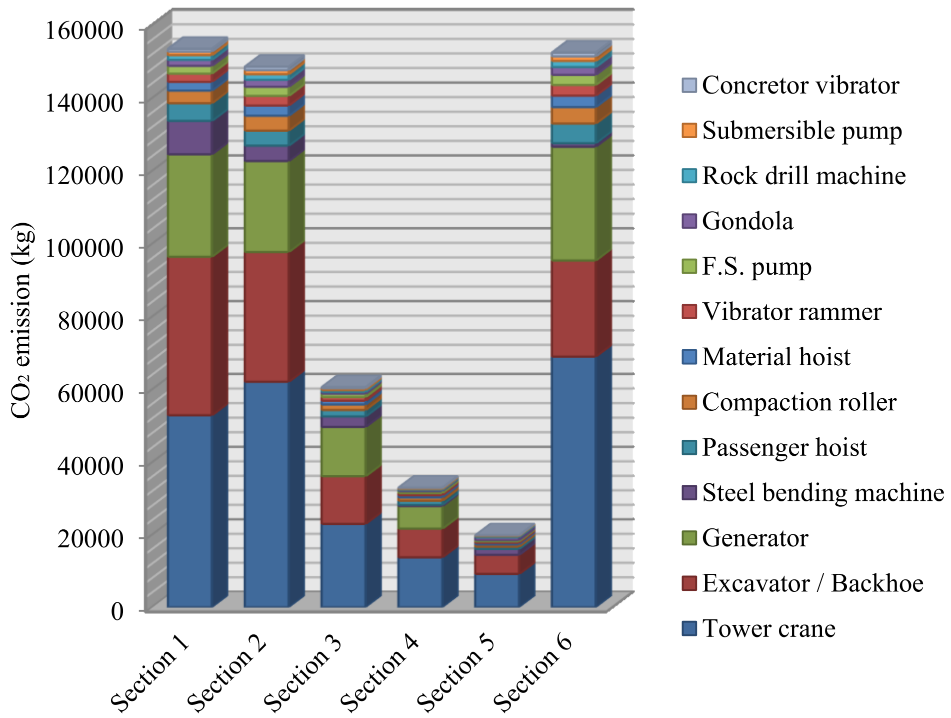

Figure 4.10 Comparative analysis of construction sections

The planning stage of the construction project has been regarded as a critical process in the early project phase that determines the successful implementation and delivery of project (Li et al., 2008). Project planners are required to develop main construction strategies, to establish path and schedules for construction and to arrange methods and resources for execution of construction works. In fact, this stage is also a critical period for emission control. The environment impact of construction activities could be controlled and immediately reduced by the careful planning of the contractors.

With the development of the virtual prototyping technology and its application on the construction planning, the contractor can visualize the construction processes and the resources/plant employed for each of the construction processes. However, its applications on emissions estimate and monitoring is not fully explored. In the past, the energy consumption by buildings in operation was considered as the major culprit of industry-related emissions, but the emissions produced during the construction procedures were largely negligible. There was lack of proper approach of quantifying the environmental impact of construction activities. Despite the recent advances in emissions visualization tools, the contractors and practitioners were still lack of effective and efficient means of estimating and quantifying hazardous emissions produced during the construction phase. This study presents an alternative application of construction virtual prototyping system which has the potential to predict and visualize the construction-related CO_2 emissions.

The approach presented in this study aims to provide the contractor a way to estimate and visualize the emissions of the project so as to identify the major sources of the emissions throughout the construction process and to reveal the emission peak in the particular phase of the project. This, in turn, assists the construction planners to identify the potential idling time of construction equipment during the construction activities and try to reschedule the construction process/program results in a decrease in emissions with any delay.

The simulation can be used as a tool to communicate amongst the project team members and discuss how to reduce excess emissions, for example by replacing old equipment items before the start of construction activities, and to develop appropriate environmental management plan for the project. In this case study, the total carbon emissions from the construction plant and equipment of this high-rise housing project is around 700,000 kg, based on the prediction from the tool. In view of this, the clients wishes to reduce to overall emissions for 10-15 percents (i.e. up to 105,000 kilogram of carbon emissions) and the project team revisited the construction program and tried to highlight the likely energy consumption reduction through the unnecessary operation of tower cranes and excavators in order to minimize construction equipment emissions and cut the fuel costs.

As maintained by Heydarian and Golparvar-Fard (2011), reducing the idle time and unnecessary consumption of construction plant and equipment on-site not only helps reduce the fuel use and construction-related emissions, but it also helps extend the life of engine, providing safer work environment for operators and workers on site. It also helps develop a more accurate plan and equipment operation analysis, and improve construction productivity, leading to a significant cost saving and time reduction (Zou and Kim, 2007). This enables the construction planners to take preventive or corrective action for emission minimization in the planning stage, to estimate the environmental performance of the construction project, and eventually to produce more environmentally sustainable development.

4.5 Chapter Summary

In this chapter, it described a step-by-step process for implementing the multi-dimensional visualization and simulation tool, which combines 4D construction model and predicted emission data via the Construction Virtual Prototyping (CVP) technology.

With the purpose of exploring the basic information of TTCAE project, the chapter first provided the construction schedule and outline of the site, which would determine the boundary of case implementation. Several main construction activities have also been identified from the mater program. Then, the real-life high rise housing project was adopted to illustrate the workflow of research. Step 1 was purposed to collect general project and equipment data. Step 2 was to calculate the predicted emission quantities on plant operation plans and the emission estimation model. Step 3 was about the development the 4D-virtual prototyping based emission visualization platform. In addition, an alternative application of construction virtual prototyping system has an important role to play in the prediction and visualization of the construction-related CO_2 emissions through the discussion and analysis of results.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This chapter is organized to summarize the research findings and results of this study. It will first examine the objectives of the research, followed by a brief summary of the major contributions to existing knowledge. The limitations of this research will also be provided, and recommendations will be present for future study.

5.2 Review of Research Aims

Referring back to the introductory chapter, it was stated that the need for an efficient means of controlling CO_2 emissions at minimum cost, and an effective mechanism has been highlighted within the academic, research and industrial communities. After a critical and systematic review of exiting research, it is found that a better planning and control strategy for emissions reduction is essential to the on-site construction activities, and a better visualization of the environmental impact during construction phase is important to minimize the negative effect on the natural environment in Hong Kong. On the other hand, innovative techniques and monitoring methods have been widely used in AEC industry, leading towards digitalized information management (e.g. Building Information Modeling, BIM)

To address these challenges and opportunities, this thesis proposes an alternative application of construction virtual prototyping technology which has the potential to enhance the sustainability of construction processes by predicting and visualizing the construction-related CO_2 emissions. The CVP technology, developed by Li et al. (2008), has been successfully adopted to test the constructability and improve the safety of certain construction project. In order to achieve the goal of application to sustainability, this thesis originates with three specific objectives: (1) understanding how the simulation tool would help enhance the sustainability of site operation with respect to carbon emission control; (2) developing an emission estimation model (PEEM) based on the equipment operation schedule and detailed information of construction plants; and finally, (3) implementing a multi-dimensional visualization tool in a real case study. The details of major research conclusion drawn from these objectives are present in following section.

For the first objective, a state-of-the-art literature review of sustainable construction was launched to understand the needs to control carbon emission during the construction process. Afterwards, it was found that three different tools, namely LCA method, operational emission quantification tool, and BIM based tool, have been developed for the improvement of the environmental performance in the construction industry. The current application of visualization and simulation technology for sustainable construction was also present for enhancing the understanding of visualization technology application in construction industry.

With respect to the second objective, this study established an integrated framework. This integrated prediction framework consists of two main parts: 4D construction simulation model and PEEM. The use of VP-based visualization platform integration of PEEM allows end users to estimate the vehicular emissions produced within construction process from the operation schedule of the equipment usage. This PEEM models can also provide managers and decision makers with a quantitative approach for CO_2 emissions during the design and construction stage.

For the third objective, this research offered a successful case for exploring the feasibility of exhibiting the application of the carbon emission visualization tool. The development of VP-based framework and supporting approaches presented in this study allows the contractor to estimate and visualize the emissions of the project to identify the major sources of the emissions throughout the construction phase. This tool also provides contractors a way to ensure that they are more responsible and assist clients to meet their own environmental objectives. And the result of case has also indicated that the emission peak in the particular phase of the project assists the construction planners to identify the potential idling time of construction equipment during the construction activities and try to reschedule the construction process/program results in a decrease in emissions without a notable adverse effect on cost.

5.3 Contributions to Existing Knowledge

This study has provided an alternative approach to visualize the environmental impact of construction activities so as to minimize the impacts to the natural environment in Hong Kong. The major contribution of this research is the establishment of conceptual models for holistic estimation of emissions embracing all major activities at project level. The development and application of VP-based emission estimation platform might not only provide the contractor a way to estimate and visualize the emissions of the project and take preventive or corrective action for emission reduction in the design stage, but might also help to enhance the understanding of how the innovative approach would support site operation decision making with respect to sustainable issues.

5.4 Limitations and Future Research Work

Although the research findings summarized in this study have been proven to generally achieve the aim stated in chapter 1, it should be noted that the model developed in the research is still at its initial stage and the model should be applied to more real-life construction projects of various types to verify the robustness of the model developed in this research. For example, the emission estimation model (PEEM) is a preliminary model which does not concern load factor and engine tie of equipment. Furthermore, the scope of this research is only restricted to investigate the CO_2 emissions produced by on-site construction activities in building construction stage. It would be more valuable to include the off-site transportation activities. Finally, the investigated real-life case is confined to the long construction period and the data mainly depends on the planning schedule.

Together with the emission prediction model developed in this study, the next stage of the research will develop a holistic emission estimate and monitoring mechanism for comprehensive construction site emission control. Also, the environment cost (i.e. fuel or electricity) and financial impacts of the emissions will be added to the emission predication model to allow the project planners to consider the implication of the fuel-related cost. The future work will provide a way to evaluate the sensitivity of emissions from construction operation to the role of construction planning and plant operation schedules.

On the other hand, a more comprehensive carbon footprint assessment tool is required if we want to accurately predict the total embodied energy (including carbon emitted from embodied energy and building assembly process) and to improve the carbon performance of the project. So far, however, there have been only few attempts to develop an integrated life-cycle analysis (LCA) with BIM to monitoring the embodied carbon of a construction project [e.g. Russell-Smith and Lepech (2011) and Wang et al. (2011)]. There is a lack of local case study that provide any reference for benchmarking and predicting embodied carbon emissions via BIM technology.

5.5 Chapter Summary

In this chapter, it presented an outline of the major achievements, conclusions and contributions derived from this thesis. At the beginning, it reviewed the achievements of the stated research objectives. Then, the main contributions of this study to existing knowledge were summarized. Finally, limitations of this study were highlighted and recommendations for future studies were given based on the major findings of this work.

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