An integrated 5D tool for quantification of construction process emissions and accident identification

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Abstract -

The environmental and safety performance of construction sites are increasingly regarded as critical factors that need to be monitored for the successful completion of construction projects. Research has also repeatedly highlighted the need to minimise the carbon footprint of the construction process and enhance the capacity of the project team and on-site workers in detecting and avoiding potential construction site hazards. However, a multi-dimensional visualisation technology that would allow project teams to simulate potential carbon emissions from construction plant and equipment and to detect potentially 'dangerous' locations on a construction site is currently lacking. This paper illustrates an integrated 5D model that uses virtual prototyping technologies to quantify carbon emissions, simulate the pattern of emissions from the overall construction process and identify potential 'black spots' of site hazards at the planning stage. The proposed 5D BIM based pro-active construction management system (PCMS) can help to detect potential sources of danger to on-site workers and provides pro-active warnings to prevent fatal accidents caused by falling or being struck by moving objects. A public housing project developed by the Hong Kong Housing Authority is used as a case study to demonstrate the integration of the emission prediction visualisation and accident detection tool into the BIM. The proposed tool demonstrates the utilisation of BIM technology to promote pro-active carbon mitigation and safety performance strategies.

Keywords -

Carbon emissions; construction process; virtual prototyping; construction accidents

1 Introduction

Environmental and safety performance, together with 'cost', 'time' and 'quality', are currently considered to be five key indicators of construction project performance [1]. In recent decades, the construction industry has also been seen to play an increasingly important role in mitigating greenhouse gas emissions due to the 'fuel-intensive nature and large share of carbon emissions of the industry' [2]. However, construction sites are also regarded as the most risky and accident-prone workplaces. A poor site safety performance can result in legal liability for the contractors and clients as well as project financial loss and contract delay. In Hong Kong, for example, two major causes of injury on construction sites are striking against or being struck by moving objects, and being struck by moving vehicles [3 and 4]. The capacity to detect and avoid potential hazards will help to improve the safety performance of construction sites.

The current construction boom in Hong Kong presents challenges with regards to the potential for increased carbon emissions and on-site accidents [5]. Accordingly, there is a growing need to reduce the carbon emissions and enhance the safety of the working environment in the sector. A better visualisation of the carbon emissions from construction activities and potential on-site accident 'black spots' would help improve the environmental and safety performance of the industry. This paper reports the development and application of a virtual prototyping (VP) based 5D tool (i.e. three-dimensional model, emissions data and site real-time location data) for estimating the possible emissions from construction projects and detecting potential on-site accident black-spots. A public housing project in Hong Kong is used to demonstrate the application of the tool

2 The integrated emissions and hazard detection tool

Over the past decade, numerous studies have examined the use of IT technologies in quantifying the emissions from construction processes and detecting potential on-site hazards. Most of the current research on the prediction and visualisation of construction site emissions has been led by universities and research centres in the US [6-17]. Despite these efforts, most of the existing emissions visualisation and quantification models are still in the early stages of development and are limited to regional applications. Much of the existing research also focuses on specific construction trades or activities, such as concreting, earthwork and lifting. Moreover, limited research has focused on developing tools that provide a more holistic estimation of emissions from all of the construction activities in a project [2]. Hajibabai et al. [10] have highlighted the need for a more comprehensive tool to analyse and visualise the carbon emissions from construction sites.

With regards to site safety detection, advanced positioning systems such as the radio frequency identification device (RFID), global positioning system (GPS), ultra wide-band (UWB) and wireless local area network (WLAN) allow real-time monitoring of the location of construction workers, equipment and materials [18]. The purpose of these positioning technologies for safety management is to prevent workers from entering hazardous areas such as floor openings, floor edges and equipment operation areas [18-24]. However, because of their varying levels of accuracy, the different positioning systems have the potential to generate false alarms.

The visualisation tool presented in this paper is implemented in four steps [2]: i) collect the general project and equipment data; ii) develop the plant operation plans; iii) identify the predicted emission quantities and setup the emission estimation model (PEEM); and iv) construct a four-dimensional virtual prototype and import the emissions data. First, a series of activities, each of which have a defined duration, are linked with the construction plant, components and resources [2]. Information, including the operating hours of the equipment and plant based on the site equipment operation plan, is then acquired to predict the emissions from the construction process [2]. Details of the VP emissions visualisation model can be found in [2]. By linking the 3D models (Revit-based software) and the construction project schedules (MS Project files) using Autodesk NavisWorks, the tool is able to model the 4D construction schedule and allows real-time and whole-project simulation. The 5D BIM tool also includes a pro-active construction management system (PCMS), which can assist construction site workers in detecting potential sources of danger and provide pro-active warnings on potential hazards. The PCMS comprises two sub-systems: a real-time location system (RTLS) and a virtual construction simulation system (VCS). Figure 1 depicts the typical three-tier web-based application structure (presentation layer + business layer + data layer) of the PCMS.

The real-time location system (RTLS) can be divided into two parts: the real-time location network and the real-time location engine. The 'network' is constructed using small hardware devices which serve as tags, which are designed to be mounted onto helmets and moving objects, and anchors, which are designed to be fixed in static locations to serve as reference points. The anchors locate the tags. The system uses the time of flight (TOF) based location schema. The tags also help to alert construction workers by vibrating and/or emitting a specific sound when they are exposed to a particular danger. An important task in location-based construction safety risk monitoring is to define the relevant dangers (e.g., static dangers and dynamic dangers) in the models and to calculate the relative distances between workers. The real-time location engine is designed with three functions: managing the location network, calculating the tag locations and sending alert signals to the tags. A network may be composed of dozens of tags and anchors. When the ranging results are received, the location engine uses an effective algorithm to calculate the tag positions and sends the positions to the application server for the virtual construction simulation and safety management.

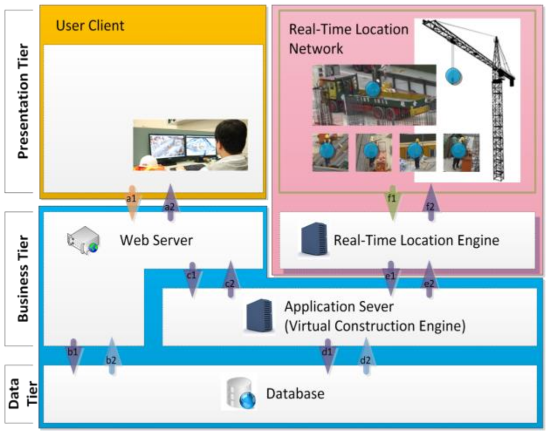

Figure 1. System architecture of the PCMS

The virtual construction simulation system (VCS) comprises the application server (i.e., the virtual construction engine), the client end, the web server and the database server. The application server handles the business logic of the PCMS by monitoring three possible sources of danger, namely, a person falling from a height, striking against or being struck by moving objects, and being struck by moving vehicles. The system monitors the relative distances between the workers (represented by the positions of the tags installed on the helmets) and potential sources of danger (represented by the tags installed on the moving objects and danger zones that are dynamically defined in the 3D model of the construction site). If the detected distance between a worker and a nearby source of danger is equal to or less than an allowable value, a warning signal will be triggered and sent to the real time location engine, which will then relay the signal to trigger the warning device on the tag installed on the worker's helmet. Other functions of the application server include synchronising the user ends to simulate the construction processes and storing and retrieving tag positions to enable the construction processes to be replayed. The user client is a web-based application for visualising construction processes, tracking people and equipment and replaying construction processes. The user client also implements administration features such as managing the danger zones, configuring the anchor positions, managing the relations between tags and tag carriers and managing the virtual construction models

3 Application of the 5D model

A public housing project in Hong Kong is used to demonstrate the applicability of the VP-based emissions prediction and the PCMS. The housing project involves the construction of a 34-storey residential building and a public car-parking area. To calculate the potential CO2 emissions from the project, a number of discussions and meetings were held with the main contractors and material suppliers to ascertain the equipment to be used during the construction process and the likely fuel consumption rates of all items of equipment. The total number of hours used and the total amount of equipment required were then determined after the details of all of the items of equipment, including the type, engineer tier and nature of activities involved, were collected. The emissions data were then imported into the simulation model using Autodesk NavisWorks. In the simulation, different construction activities are presented in a 4D virtual reality environment. The simulation displays the amount of total emissions and the emission variations. The amounts of CO_2 emitted by various types of equipment are presented in graphic format in the lower right corner (Figure 2).

The simulation can visually represent the operation of any items of construction equipment or plant at a particular stage. The construction team members and contractors can identify any activities that have high predicted emission rates and find a solution, such as reducing the idling time of the equipment [2]. The simulation can also enable project team members to communicate and identify strategies to minimise unnecessary emissions and set up an appropriate environmental management plan. The simulation predicted that the housing project would generate a total of 700,000 kg of CO2 emissions from all items of plant and equipment. To reduce the environmental impact of emissions, the Hong Kong Housing Authority wishes to reduce the total emissions of the project by fifteen percent (i.e. 105,000 kg). The project team reassessed the construction programme and the equipment schedule, and identified any unnecessary tower crane and excavator operations to reduce energy consumption.

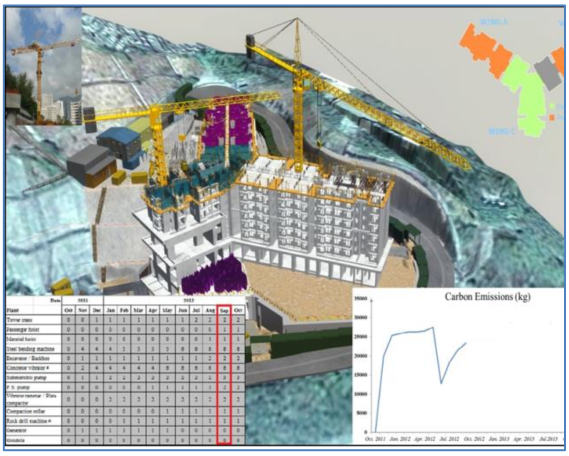

Figure 2. A visualisation of the estimated CO_2 emissions of the plant/equipment used in typical floor concreting work and the formwork installation stage

To detect any potential hazard black spots in the housing project, the location-based virtual construction was developed by integrating the virtual construction technology with the RTLS. This enabled the virtual models to be immediately connected with realistic construction situations, in particular through integrating the static virtual models and dynamic dangers. Two toolkits, Unity and SmartFoxServer, were used to develop the location-based virtual construction for this project. Unity helps generate 3D video games, architectural visualisations and real-time 3D animations, and was used to build features, including visualising the construction process and defining the static and dynamic dangers, for the user client. SmartFoxServer, which is a massive multiplayer game server, was used to help construct the application server. A server object extension will be developed based on the SmartFoxServer to drive and synchronise all of the user clients with the real construction situations. After testing several location technologies, the project team finally selected CSS (Chirp Spread Spectrum) as the ranging technology. The CSS uses TOF to estimate the physical distance between two devices, although it has higher precision than other TOF methods, e.g. greater receiving signal strength.

A collaborative localisation schema was adopted to construct the real time location system (RTLS), which does not require synchronisation between the infrastructure nodes, and is believed to be suitable for construction site environments. The location tags perform ranging with the location anchors, hence the distances are known. The coordinates of a location tag can be estimated based on these distances and the known anchor coordinates. Based on the application requirements, the system is designed such that the positions of the location tags are calculated by the location engine. Approximately 100 tags were installed on-site for around four months to evaluate the technical feasibility and usefulness of the PCMS. The construction site was separated into eight zones approximately 30m x 30m in size for the PCMS. Ranging results were sent to the location engine through the CSS wireless network. An example of an image captured by the PCMS system during the trial run for this project is shown in Figure 3. The red spot represents the location of the site operators while the blue spots represent the locations of the hook of the tower crane. The simulation results indicated that the project had no obvious site hazard black-spots.

In summary, the CO_2 emission prediction tool presented in this paper can help contractors to identify the sources of emissions and to quantify the amount of emissions generated. The tool also promotes a pro-active environmentally conscious construction approach and the best practices for sustainable development. The tool can assist builders/contractors to forecast activities with excessive emissions and identify suitable mitigation strategies, such as replacing old plant and equipment with energy-saving models and reducing idling time. The PCMS also provides a platform for the construction project team to reassess their site safety plan. The tool provides pro-active warnings to site workers and helps them to detect surrounding sources of danger, such as height hazards and materials being moved by the tower crane.

Figure 3. Location of the site operators (red spot) and the hook of the tower crane (blue spots) captured by the PCMS system

4 Conclusion and Future Research

This paper outlines the development and application of a 5D visualisation tool to support project teams in estimating and visualising the CO_2 emissions from construction activities and predicting potential hazard black spots. Nonetheless, the 5D model is still in its preliminary stage and the tool needs to be applied to different construction projects of varying scale and nature. A comprehensive carbon footprint assessment tool is also required to predict the total embodied energy (including the carbon emitted from embodied energy and the building assembly process) of the project. An integrated life-cycle analysis (LCA) with BIM will be developed to monitor the embodied carbon [for example, 25 and 26]. A BIM based tool that can provide support for managing construction and demolition waste is currently lacking. The PCMS presented in this paper is also at the trial run stage, and the tool requires further testing and validation before it can be widely adopted on-site. These limitations will be tackled in future studies.

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