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Assessing Environmental Performance in the Construction Industry

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ABSTRACT

Environmental Management System (EMS) has recently been advocated for most economic sectors. Construction, one of the pollution generators creating destruction to the environment, is by no means exempted from EMS. However, in implementing EMS, the greatest obstacle found is the lack of objective performance evaluation criteria. To overcome this, Environmental Performance Assessment (EPA) is introduced to assess environmental performance, which however is not popularly adopted in the construction industry. This paper attempts to develop a series of input (*EOIs*) and output (*EPIs*) indicators for EPA and measure their relations by using robust fitting and spectral methods based on survey and interview results undertaken in Hong Kong and Australia. The results show that the proposed *EOIs* correlate strongly with *EPIs*. Therefore, EPA can help improving and predicting environmental performance of an organization.

KEYWORDS

Environmental management system
Environmental performance assessment
Operational levels
Hong Kong
Australia

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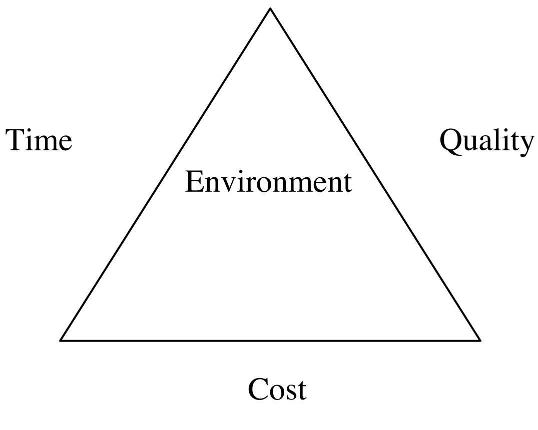
INTRODUCTION

Construction creates and provides facilities for human activities and social development; on the other hand, its impacts on the environment are very serious (Bossink and Brouwers, 1996). Therefore, the fourth dimensions, the "environment", other than cost, time and quality was highly motivated in the construction project management (Shen and Tam, 2002), as illustrated in Figure 1. The environmental performance of construction companies, which is defined as the company's achievements in managing any interaction between construction activities and the environment, plays an important role in environmental protection (Morledge and Jackson, 2001, Polster *et al.*, 1996, Rikhardsson, 1999). Environmental Management System (EMS) can provide a framework to achieve and to demonstrate a desired level of environmental performance (Tse, 2001, Wu, 2003). In implementing EMS, Environmental Performance Assessment (EPA) is an essential tool for continuous improvement. Thus it is necessary to implement EPA for construction firms (Kuhre, 1998, Shen and Tam, 2002).

Figure 1: Four dimensions of construction project management (Shen and Tam, 2002)



In Hong Kong and Australia, construction is one of the pillar industries in the national economy and also one of the pollution generation industries that lacks a systematic way in controlling pollution. Construction organizations' poor response to EMS is attributed to their poor environmental consciousness; low profit margins; and the immaturity of the construction market. As a result, there are few records of construction firms implementing EPA. Therefore, the environmental situation does not show any obvious improvement. Hence it is worthwhile to identify and try to remove the difficulties in the implementation.

Research Objectives

This paper aims to evaluate the effectiveness of EPA by correlating the input factors at an operational level (*EOIs*) and the output factors of the environmental performance outcome (*EPIs*) for construction in Hong Kong and Australia. The objectives are to:

- Highlight the importance of EPA in evaluating environmental performance;
- Identify a series of input (*EOIs*) and output (*EPIs*) assessment indicators;
- Examine the relationships between *EOIs* and *EPIs* in the context of construction by using robust fitting and spectral methods; and
- Provide recommendation for the construction industry.

Research Methodology

Based on the previous work (Bachas and Tomaras, 1994, Benneth and James, 1999a; 1999b, Canadian Institute of Chartered Accountants, 1994, Chen *et al.*, 2000, Clayton Group Services, 2001, Cole, 2000, Construction Industry Research and Information Association, 1999, Environmental Protection Agency, 2007, Henderson and McAdam, 2000, HK-BEAM Society, 2007, Hong Kong Government - Environmental Protection Department, 2006, Hong Kong Housing

Authority, 2002, Hong Kong Productivity Council, 2006, International Organization for Standardization, 2006, Jasch, 2000, Kuhre, 1998, Lawson *et al.*, 2001, Meyer, 2001, Poon, 1997, Ren, 2000, Shen and Tam, 2002, Tam *et al.*, 2002a, Tam *et al.*, 2002b, Thoresen, 1999, Tibor, 1996, Tilford *et al.*, 2000, White and Zinkl, 1999), input and output indicators (*EOIs* and *EPIs* respectively) are identified in Section 4, the relationships among them are assessed. A sample of forty-nine construction managed by five large-sized construction firms in Hong Kong and a sample of fifty-seven construction projects managed by six large-sized construction firms in Australia are studied. One hundred and six project managers are interviewed and all *EOIs* and *EPIs* were clearly explained to them for clarity. All the interviewed project managers are engaged in all levels of on-site activities and had site experience of at least fifteen years. As the interviewees are experienced project managers and they are involved in the overall project management, they can provide the best knowledge on the projects regarding related environmental management issues.

The comparative results for the one hundred and six construction projects are measured based on the information given by project managers which were asked to choose an appropriate degree of importance for each indicator (*EOIs* and *EPIs*). A rating scale of 1 (least important) to 7 (most important) is used according to the operational measures and the environmental performance adopted in the projects.

Robust fitting method and spectral methods are used to correlate *EOIs* and *EPIs* in this study. It is supported by the MATLAB programming package including all plots and mathematical equations.

DEVELOPING PERFORMANCE INDICATORS

Environmental Performance Assessment (EPA) is a critical tool of EMS in checking, reviewing, monitoring and evaluating environmental performance of organizations. It is an ongoing process of collection and assessment of data and information to evaluate performance, and trends over time (Jasch, 2000, Tam *et al.*, 2002a). A primary role of EPA is to provide a comprehensive assessment of the environmental performance of a construction project. Environmental indicators focus on the use of tangible measures to evaluate performance. They offer significant and standardized data on environmental performance, not only as assessment but also in comparison with different site conditions (Benneth and James, 1999a, Jasch, 2000). By monitoring the indicators, regular evaluation and target control can be exercised since they can highlight any adverse trends in the process of environmental control (Tam *et al.*, 2002b). Since operational performance is an important and indispensable element in evaluating environmental performance, this paper focuses on evaluation factors of EPA at the operational level because site environmental assessment is essential for parties within a construction organization (Clayton Group Services, 2001, Crawley and Aho, 1999, Ren, 2000). Therefore, Environmental Operational Indicators (*EOIs*) are used to measure the input performance of an organization. From that, Environmental Performance Indicators (*EPIs*) are used to measure the output performance of an organization based on their input. The following highlights the (*EOIs*) and Environmental Performance Indicators (*EPIs*) used in this study.

Environmental Operational Indicators (*EOIs*)

Organizational operations are defined as being physical facilities and equipment, during production processes (Jasch, 2000). *EOIs* are used to assess the major inputs including resources, energy and other aspects of facilities and equipment, which relate to: *i*) design, operation, and maintenance; *ii*) material, energy, product, service, waste, and emission; and *iii*) supply of materials, energy and services to, and the delivery of product, associated with the organization's physical facilities and equipment.

In this study, some parameters for *EOIs* are suggested to improve environmental performance; for example, environmental site planning can provide an early preparation for the overall environmental performance (Jasch, 2000, Kuhre, 1998); energy consumption should be included in the evaluation criteria of *EOIs* (Benneth and James, 1999a, Clayton Group Services, 2001, International Organization for Standardization, 2006, Jasch, 2000, Kuhre, 1998, Meyer, 2001, Tibor, 1996); effective maintenance of equipment helps improving operation efficiency and operational environmental performance (Benneth and James, 1999a; 1999b, HK-BEAM Society, 2007). There is no doubt that air, noise, sewage and waste are the four major environmental problems and should be given considerable attention to improve environmental performance (Hong Kong Government - Environmental Protection Department, 2006); input of services used to prevent and to minimize the generation of these four subjects should be considered (Bachas and Tomaras, 1994, Benneth and James, 1999a; 1999b, Clayton Group Services, 2001, Jasch, 2000, Kuhre, 1998). In addition, waste indicators should also be included as they are highly visible phenomena and their targets can be set and easily understood (Benneth and James, 1999a; 1999b). Based on the above, eight indicators (*EOIs*) inputting operational measures are derived as follows.

<u>EOI-1: Environmental Site Planning</u>

Site planning is critical in determining and improving the performance of on-site activities which allows better arrangement of activities in respect of labour, plant and equipment, materials, time and cost (Jasch, 2000, Kuhre, 1998). Devising a plan that outlines the environmental management programme and the operational practices on construction sites can streamline operations, cut costs and improve environmental performance. *EOI–11: Initial site planning* is a sub-indicator.

<u>EOI-2: Energy Consumption</u>

Energy is required to support all operations, such as use of construction plants and temporary lighting system (Benneth and James, 1999a; 1999b, Jasch, 2000). It is necessary to understand the consumption of energy during construction activities (Henderson and McAdam, 2000, Tibor, 1996). *EOI–21: Monitor of energy usage* is a sub-indicator.

<u>EOI-3: Maintenance of Equipment</u>

Many aspects of facilities and equipment can influence the environmental performance of construction. For instance, regular maintenance of equipment can often dramatically reduce the generation of emission and help improve operating efficiency (Benneth and James, 1999a; 1999b, HK-BEAM Society, 2007). *EOI–31: Quality of maintenance* is a sub-indicator.

<u>EOI-4: Air Pollution Control</u>

Total suspended particulars have increased in our environment, which affect the respiratory system, reduce visibility, lead to dirty clothing and buildings, and increase the rate of corrosion. Construction activities generate a lot of dust and significantly contributing to air pollution. This situation needs to be controlled by *EOI–41: Water sprays for minimizing dust airborne particles,* and *EOI–42: Mitigation measures to the generation of polluted air* (Chen *et al.*, 2000).

<u>EOI-5: Noise Pollution Control</u>

The high-density development such as

Hong Kong makes noise as one of the critical construction concerns (Cole, 2000). Noise is an inevitable phenomenon resulting from construction work, in which piling is the nosiest activity. Therefore, to reduce its impacts, *EOI–51: The use of time management* and *EOI–52: Mitigation measures to noise levels* are necessary.

EOI-6: Water Pollution Control

Generation of polluted water and the ineffective use of water are common in construction activities (Hong Kong Productivity Council, 2006). It is necessary to encourage and educate the staff in *EOI–61: Monitor of water usage; EOI–62: Water reusing and recycling systems;* and *EOI–63: The use of wastewater treatment.*

EOI-7: Waste Pollution Control

The amount of waste is increasing at a fast rate (Hong Kong Government - Environmental Protection Department, 2006). According to the Environmental Protection Department (Hong Kong Government - Environmental Protection Department, 2006), the construction industry generated about 965,425 tonnes of C&D waste per year in 2006. Inconsistent with the continuous development of economics and infrastructure, people's awareness of waste reduction is always low on construction sites, which aggravates the situation. As a result, excessive loss of materials and improper waste management are common. *EOI–71: The use of purchasing management* (Hong Kong Housing Authority, 2002), *EOI–72: Waste reuse and recycling* (Lawson *et al.*, 2001, Poon, 1997), *EOI–73: Green construction technology* (Chen *et al.*, 2000) and *EOI–74: The use of chemical waste treatment* (Tilford *et al.*, 2000) are sub-indicators.

EOI-8: Ecological Control

Ecological impact is not common for building projects in Hong Kong and in Australia but can be significant for civil engineering projects. Ecological impact means any disturbance to the pre-existing conditions such as topsoil, trees and vegetation and living habitats (Construction Industry Research and Information Association, 1999). *EOI-81—Degree of efforts in reducing ecological impact*—is a sub-indicator. It can be determined by measuring the effort to cope with the potential ecological impacts.

Environmental Performance Indicators (*EPIs*)

EPIs need to be developed to reflect the output performance of a project. They are also used to evaluate the efficiency and effectiveness of environmental management systems (Canadian Institute of Chartered Accountants, 1994). On-site activities such as site cleanliness do directly affect environmental performance. Second, the regulatory compliance should be included in *EPIs* (Jasch, 2000, Tam *et al.*, 2002b, Thoresen, 1999, White and Zinkl, 1999) since the legislation sets the minimum standard for environmental protection. Jasch (Jasch, 2000) pointed out that environmental auditing activities could also provide quality documentation information for controlling and monitoring environmental performance. In summarizing the previous research, five main indicators (*EPIs*) for output performance are proposed:

EPI-1: Site Environment

Site environment including cleanliness and tidiness can determine the environmental performance. For example, poor positioning and maintenance of storage areas for materials always result in accidental damages. Proper control and documentation on material flow can minimize material wastage. *Overall site environment* (*EPI-11*) is used to measure the site environmental performance.

EPI-2: Regulatory Compliance

There are a number of regulations and ordinances related to environmental protection in Hong Kong (Hong Kong Government - Environmental Protection Department, 2006) and in Australia (Environmental Protection Agency, 2007). The EPA program helps assess the achievement in environmental regulatory requirements (Benneth and James, 1999a; 1999b, Jasch, 2000, Kuhre, 1998, Meyer, 2001). *EPI-21: Number of prosecutions received; EPI-22: Number of complaints / warnings received;* and *EPI-23: Amount of fines and penalties paid* are the sub-indicators.

<u>EPI-3: Auditing Activities</u>
Auditing activities provide information on the performance of the system. Further, construction organizations need to provide sufficient preparations for pre-auditing, auditing and post-auditing activities (Jasch, 2000) through which it can improve the operational system. *EPI-31: Non-conformance report* and *EPI-32: Report of marginal cases put under observation*, provide relevant knowledge in understanding the performance on auditing activities.

<u>EPI-4: Waste Generation</u>
Waste generation is always the main concern for any organization. Whatever the organization does for environmental management, the main issue is to lower its waste levels. Therefore, *EPI-41: Monthly waste generation (in tons)* should be considered.

<u>EPI-5: Accident Rate</u>
Quality, environmental and safety are the main constraints for a construction project (Shen and Tam, 2002). Among them, safety is directly affected the human life. Therefore, *EPI-51: Accident rate (per 1,000 mandays)* should be considered on site.

Robust Fitting Method

The robust fitting method uses an iteratively re-weighted least-squares algorithm, with the weights at each iteration are calculated by applying the bisquare function to the residuals from the previous iteration. This algorithm gives a lower weight to points that do not fit well. The results are less sensitive to outliers in the data as compared with an ordinary least-squares linear regression method. This can show the "real" correlation between *EOIs* and *EPIs*.

Spectral Methods

The interpolation method is used to estimate the results of output tests from input tests. From that, it is possible to determine redundancy among the tests, in turn, significantly lowers the number of tests. To further study the correlation among the tests, spectral methods using the power spectrum and bispectrum are employed. The power spectrum $P(f)$ of a data set $x(t)$ is given in Eq. (1) as (Lathi, 1998, Le *et al.*, 2003):

$$P(f) = |X(f)|^2, \qquad (1)$$

where $X(f)$ is the Fourier transform of the data or input signal.

To further study the data, a bispectral method is introduced which shows the correlation among the tests at various "frequencies". The "frequencies" in this case is inversely proportional to the time at which the test samples were taken. For example, if the samples are taken every 2 seconds, then its frequency is 0.5 Hz. The bispectrum $B(f_1, f_2)$ has been widely employed in the field of high-order statistics to study data correlation in 3-D and is given by (van Milligen *et al.*, Jan. 1995):

$$B(f_1, f_2) = X(f_1)X(f_2)X^*(f_1 + f_2), \qquad (2)$$

where the symbol " * " means complex conjugate.

It is clear that the bispectrum is strongly dependent on the Fourier transform of the input signal. From Eq. (2) the term $X^*(f_1 + f_2)$ represents the correlation among various frequency terms in the $(f_1 + f_2)$ plane. To estimate the bispectrum, the mean value of the data is removed to eliminate sudden spikes and pulses which could lead to misleading interpretation. In MATLAB, this can be done by using a **detrend(·)** function. After that, the data are windowed using a Hanning window via the command **hanning(·)** provided in MATLAB. In addition, the data are also normalised by diving each column by its largest item so that abrupt changes are nullified. The Fourier transforms of the detrended data are then calculated, in this case, there are twenty one out of twenty three tests having numerical results, yielding twenty one Fourier transforms. For data size of more than 1,024, which is very common in signal processing, substantial computing work is required which makes the bispectrum sometimes hard to estimate and not practical. However, it reveals vital information to the understanding of data characteristics and especially correlation among various criteria at different frequencies. In this paper, the bispectrum of an error matrix of 210×10 is calculated to show correlation among the fitting errors and also error uniformness.

RESULTS

Robust Fitting Method

The robust-fitting linear regression method is used to mathematically link the same set of input and output indicators. The main advantage of this method is that it assigns a lower weight to outliers which are considered as measurement errors or noise. As a result, a better fit to the data can be achieved. Eqs. (3) to (10) mathematically describe the relationship among the output indicators and input indicators in Hong Kong construction industry. The R^2 factors of all equations are also estimated.

$$EPI-11 = 0.2870EOI-11 - 0.1241EOI-21 + 0.1437EOI-31 + 0.0649EOI-41 + 0.0902EOI-42 + 0.0557EOI-51 + 0.3456EOI-52 - 0.2041EOI-61 - 0.0919EOI-62 + 0.0118EOI-63 - 0.0812EOI-71 + 0.1902EOI-72 + 0.0752EOI-73 + 0.4374EOI-74 - 0.1202EOI\text{-}81 \text{ (with R Square of 0.99)} \quad (3)$$

$$EPI-21 = -0.0831EOI-11 + 0.1637EOI-21 - 0.3762EOI-31 - 0.3091EOI-41 + 0.2054EOI-42 + 0.0991EOI-51 - 0.2808EOI-52 + 0.0325EOI-61 + 0.2172EOI-62 - 0.0803EOI-63 + 0.2620EOI-71 - 0.2798EOI-72 - 0.1135EOI-73 - 0.1876EOI-74 + 0.0895EOI\text{-}81 \text{ (with R Square of 0.98)} \quad (4)$$

$$EPI-22 = -0.2443EOI-11 - 0.2135EOI-21 + 0.1556EOI-31 - 0.0698EOI-41 - 0.3799EOI-42 - 0.1538EOI-51 - 0.1370EOI-52 + 0.3290EOI-61 + 0.2340EOI-62 - 0.0753EOI-63 - 0.1512EOI-71 + 0.4247EOI-72 + 0.0985EOI-73 - 0.3137EOI-74 + 0.0388EOI\text{-}81 \text{ (with R Square of 0.99)} \quad (5)$$

$$EPI-23 = -0.1138EOI-11 + 0.1076EOI-21 - 0.2368EOI-31 - 0.1747EOI-41 + 0.1372EOI-42 + 0.0960EOI-51 - 0.1716EOI-52 + 0.0733EOI-61 + 0.1216EOI-62 - 0.1100EOI-63 + 0.2475EOI-71 - 0.2372EOI-72 - 0.0432EOI-73 - 0.1104EOI-74 + 0.0691EOI\text{-}81 \text{ (with R Square of 0.97)} \quad (6)$$

$$EPI-31 = -0.4104EOI-11 + 0.0630EOI-21 - 0.3601EOI-31 - 0.5230EOI-41 - 0.3749EOI-42 + 0.4186EOI-51 - 0.1717EOI-52 - 0.4423EOI-61 + 0.8759EOI-62 - 0.0431EOI-63 + 0.6806EOI-71 + 0.7597EOI-72 - 0.0300EOI-73 - 0.2529EOI-74 - 0.7343EOI\text{-}81 \text{ (with R Square of 0.99)} \quad (7)$$

$$EPI-32 = 0.0304EOI-11 + 0.2856EOI-21 - 0.3065EOI-31 + 0.2836EOI-41 - 0.2999EOI-42 - 0.3404EOI-51 - 0.3928EOI-52 - 0.0414EOI-61 + 0.3566EOI-62 + 0.0205EOI-63 - 0.1657EOI-71 + 0.3422EOI-72 + 0.4520EOI-73 - 0.1404EOI-74 + 0.2685EOI\text{-}81 \text{ (with R Square of 0.99)} \quad (8)$$

$$EPI-41 = -1.6740EOI-11 + 0.9179EOI-21 + 2.4328EOI-31 + 2.9321EOI-41 - 2.4342EOI-42 - 1.3383EOI-51 - 12.3228EOI-52 + 11.5250EOI-61 + 0.6660EOI-62 - 1.5464EOI-63 + 0.6320EOI-71 + 4.2996EOI-72 - 8.2585EOI-73 - 1.9137EOI-74 + 6.8380EOI\text{-}81 \text{ (with R Square of 0.99)} \quad (9)$$

$$EPI-51 = 0.3851EOI-11 + 4.1705EOI-21 + 0.6068EOI-31 + 1.3474EOI-41 + 1.8506EOI-42 - 0.2591EOI-51 - 4.0959EOI-52 - 0.6672EOI-61 + 1.9631EOI-62 - 0.8706EOI-63 - 3.2431EOI-71 + 3.0415EOI-72 + 0.0862EOI-73 + 0.7523EOI-74 - 1.0677EOI\text{-}81 \text{ (with R Square of 0.99)} \quad (10)$$

Eqs. (11) to (18) mathematically describe the relationships among the *EPIs* and the *EOIs* in the Australian construction industry.

$$EPI-11 = 0.2349EOI-11 - 0.2557EOI-21 + 0.1984EOI-31 + 0.0357EOI-41 + 0.0964EOI-42 + 0.0744EOI-51 + 0.4541EOI-52 - 0.3268EOI-61 - 0.0946EOI-62 + 0.0243EOI-63 - 0.0731EOI-71 + 0.1236EOI-72 + 0.0913EOI-73 + 0.4674EOI-74 - 0.1572EOI\text{-}81 \text{ (with R Square of 0.97)} \quad (11)$$

$$EPI-21 = -0.0932EOI-11 + 0.1335EOI-21 - 0.4672EOI-31 - 0.3546EOI-41 + 0.3683EOI-42 + 0.0825EOI-51 - 0.3562EOI-52 + 0.0572EOI-61 + 0.3156EOI-62 - 0.0737EOI-63 + 0.3571EOI-71 - 0.3627EOI-72 - 0.2125EOI-73 - 0.2521EOI-74 + 0.0789EOI\text{-}81 \text{ (with R Square of 0.98)} \quad (12)$$

$$EPI-22 = -0.1893EOI-11 - 0.2935EOI-21 + 0.2893EOI-31 - 0.0936EOI-41 - 0.3978EOI-42 - 0.2267EOI-51 - 0.2456EOI-52 + 0.3683EOI-61 + 0.3167EOI-62 - 0.0735EOI-63 - 0.2467EOI-71 + 0.5227EOI-72 + 0.0942EOI-73 - 0.4277EOI-74 + 0.0578EOI\text{-}81 \text{ (with R Square of 0.99)} \quad (13)$$

$$EPI-23 = -0.1368EOI-11 + 0.2477EOI-21 - 0.2437EOI-31 - 0.1962EOI-41 + 0.1349EOI-42 + 0.0848EOI-51 - 0.163EOI-52 + 0.0612EOI-61 + 0.1323EOI-62 - 0.1437EOI-63 + 0.2782EOI-71 - 0.2947EOI-72 - 0.03226EOI-73 - 0.1827EOI-74 + 0.0722EOI\text{-}81 \text{ (with R Square of 0.99)} \quad (14)$$

$$EPI-31 = -0.4883EOI-11 + 0.0723EOI-21 - 0.3932EOI-31 - 0.5283EOI-41 - 0.3969EOI-42 + 0.4893EOI-51 - 0.1237EOI-52 - 0.4527EOI-61 + 0.8536EOI-62 - 0.0126EOI-63 + 0.6172EOI-71 + 0.7892EOI-72 - 0.0152EOI-73 - 0.2496EOI-74 - 0.696EOI\text{-}81 \text{ (with R Square of 0.97)} \quad (15)$$

$$EPI-32 = 0.0425EOI-11 + 0.2983EOI-21 - 0.2673EOI-31 + 0.2925EOI-41 - 0.3262EOI-42 - 0.3135EOI-51 - 0.4321EOI-52 - 0.0325EOI-61 + 0.3278EOI-62 + 0.0468EOI-63 - 0.1835EOI-71 + 0.3839EOI-72 + 0.4859EOI-73 - 0.1532EOI-74 + 0.2926EOI\text{-}81 \text{ (with R Square of 0.99)} \quad (16)$$

$$EPI-41 = -1.7324EOI-11 + 0.9759EOI-21 + 2.3788EOI-31 + 2.9436EOI-41 - 2.3324EOI-42 - 1.3327EOI-51 - 12.4788EOI-52 + 11.5526EOI-61 + 0.6277EOI-62 - 1.5624EOI-63 + 0.6734EOI-71 + 4.3527EOI-72 - 8.2267EOI-73 - 1.8278EOI-74 + 6.9273EOI\text{-}81 \text{ (with R Square of 0.98)} \quad (17)$$

$$EPI-51 = 0.3313EOI-11 + 4.2277EOI-21 + 0.7277EOI-31 + 1.4278EOI-41 + 1.789EOI-42 - 0.2275EOI-51 - 4.1277EOI-52 - 0.6826EOI-61 + 1.9927EOI-62 - 0.8962EOI-63 - 3.3227EOI-71 + 3.0625EOI-72 + 0.0893EOI-73 + 0.7322EOI-74 - 1.0852EOI\text{-}81 \text{ (with R Square of 0.98)} \quad (18)$$

From Eqs. (3) and (11), it can be noted that *EOI–74 chemical waste treatment* is the dominant factor on *EPI–11 overall site performance* with the regression coefficient of 0.4374 and 0.4674 respectively. From one of the interview discussions with a project manager, it was highlighted that chemical materials need to be continuously monitored using storage management and waste treatment. This project was carried out to lower chemical waste which is sent for special treatment before being dumped to landfill, incurring a high dumping charge. Further, if one can provide efficient chemical waste management, the other environmental management can be easily dealt with using the experience gained from chemical waste management. Therefore, *EOI–74 chemical waste treatment* directly affects the overall site performance.

From Eqs. (4) and (6), (12) and (14), *EOI –31 maintenance of equipment* is one of the dominant factors affecting the output performance *EPI–21 prosecutions received* and *EPI–23 fines and penalties paid* with regression coefficients of 0.3762 and 0.2368 respectively in Hong Kong and 0.4672 and 0.2437 respectively in Australia. This result is consistent with the interview discussions with the project managers. They explained that noise pollution is the main element, rather than air, water and waste pollution, which caused prosecution. As noise pollution is the main concern from the nearby sensitive parties, if construction activities cause high noise pollution, the company will receive prosecutions or fines and penalties are then applied. Therefore, regular maintenance of equipment is important for an efficient operation and to effectively control their noise generation.

From Eqs. (7) and (8), (15) and (16), *EOI–72 waste reuse and recycling* is one of the main factors affecting the output performance *EPI–31 non-conformance auditing report* and *EPI–32: auditing report of marginal cases* with regression coefficients of 0.7597 and 0.3422 respectively in Hong Kong and 0.7892 and 0.3839 respectively in Australia. Waste is considered to be a major pollution problem contributing to about 38% along with noise, air and water pollution (Hong Kong Government - Environmental Protection Department, 2006). Thus, if waste reuse and recycling is carried out effectively, then auditing performance can be improved.

From Eqs. (9) and (17), it is clear that *EPI–*

41 is strongly affected by *EOI–52: mitigate measure of noise pollution control* with regression coefficients of 12.3228 and 12.4788 respectively. From the interview discussion with site managers, this relationship can be laterally viewed as effective control of noise level creating better working environment for workers on site and for the surroundings as less complaints from noise sensitive parties are filed, thus reducing waste generation. The use of more efficient machinery instead of old and less-efficient equipment can significantly lower noise level, also resulting in a lower waste level.

From Eqs. (10) and (18), it is clear that the accident rate is also dependent on *EOI–52: mitigate measure of noise pollution control* with the regression coefficients of 4.095 and 4.1277 respectively. As explained earlier, the use of better equipment instead of old and insufficient equipment results in lower waste generation and an accident rate. It should also be noted that the *EOI–21 energy consumption* possesses an inverse effects to those of *EOI–52: mitigate measure of noise pollution control,* in which the effects of both indicators can cancel each other. Under this condition, the accident rate is dependent on *EOI–72 waste reuse and recycling* with the regression coefficients of 3.0415 and 3.0625 respectively. The cancellation of *EOI–21 energy consumption* and *EOI–52: mitigate measure of noise pollution control* occurs when too-expensive equipment are used to minimise the noise level which is not unusual in the construction industry. This situation can be referred to as saturation in noise control, i.e. beyond certain standard in special circumstances; better equipment cannot be used to improve the noise level.

It is clear that the robust-fitting method provides satisfactory fitting to the data with the R^2 factors of all equations are in the range of 0.97 and 0.99, meaning that these equations can be effectively used to predict the results of output indicators. Individual coefficients can also be used to identify dominant input indicators with respect to a particular output indicator. From that, it is possible to reduce the number of input indicators, resulting in a simpler measurement process of analyzing input and output indicators.

The results obtained in Hong Kong and Australia are similar which suggests that conditions in these two countries are similar.

Spectral Methods Using the Power Spectrum and Bispectrum

The spectral methods of using the power spectrum and bispectrum aim to estimate the energy contained in input and output indicators. From that, it is possible to identify the most dominant indicator(s). To do that, the peak of the power spectrum of an indicator is located and all peaks of individual power spectra are compared. The largest spectral peak of an indicator's power spectrum is then identified as the most dominant indicator. If there are a number of peaks which similar magnitude or in the same range of magnitude, then it is difficult to identify the most dominant indicator. As a result, the first three largest peaks are considered as the most dominant indicators. The power spectra of input and output indicators are separated for comparison purposes.

The bispectrum of all indicators is used to study coupling or correlation among indicators, i.e. internal relationships. The bispectrum is used to further validate findings obtained using the power spectra of indicators. The bispectrum of all indicators is given in Figure 2 and its contour plot is given in Figure 3 in which strong coupling and correlation among the input indicators is present. This means that it is possible to reduce the number of input indicators without altering the results. Among the output indicators, their correlation is weaker which means that these indicators are quite independent and it may not be possible to establish a strong mathematical link among them. More work towards this research direction is under progress.

CONCLUSION

Construction and demolition activities can easily generate pollution and affect the environment. To manage these, Environmental

Figure 2: Bispectrum of all indicators

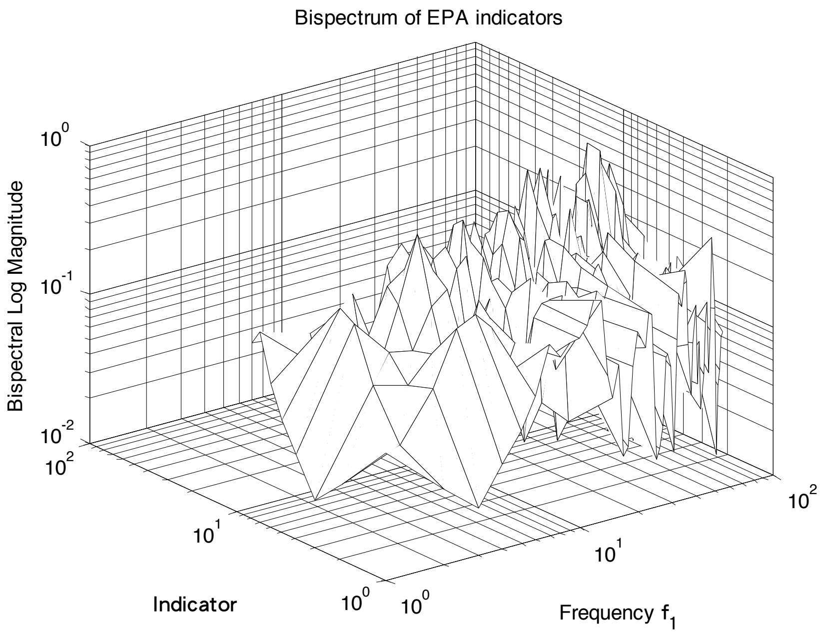
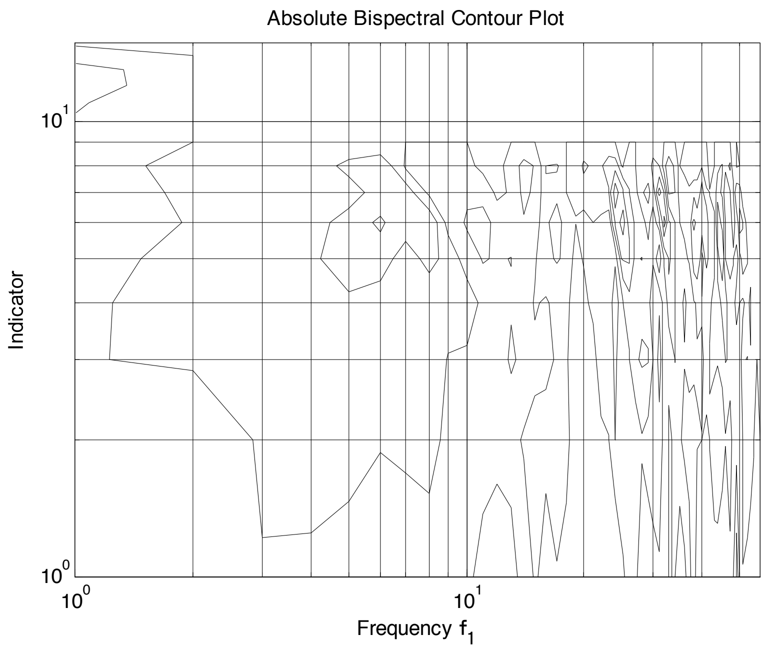


Figure 3: Contour plot of the bispectrum of all indicators



Management Systems (EMSs) can be implemented. However, there is no evidence regarding the effectiveness of such systems. Environmental performance assessment (EPA) is then suggested to make regular assessment on sites at operational levels. EPA provides information about the achievement of the environmental policy so as to enable the organizations to direct resources to improve their environmental performance. To support the applications of EPA, a set of input (*EOIs*) and output (*EPIs*) indicators have been proposed to provide information on environmental operational performance. The proposed *EOIs* are: *i) Environmental Site Planning; ii) Energy Consumption; iii) Maintenance of Equipment; iv) Air Pollution Control; v) Noise Pollution Control; vi) Water Pollution Control; vii) Waste Pollution Control;* and *viii) Ecological Control;* and the *EPIs* are*: i) Site Environmental; ii) Regulatory Compliance; iii) Auditing Activities; iv) Waste Generation;* and *v) Accident Rate*.

By studying the correlations between the *EOIs* and *EPIs*, the effectiveness of these input and output factors were evaluated. It was found that linear regression and spectral methods are effective in establishing mathematical relationships among input and output indicators in environmental management and close relationships between input and output indicators in predicting environmental performance were also found.

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