SUSTAINABILITY OF INFRASTRUCTURE PROJECTS IN HONG KONG: AN EVALUATION OF ENVIRONMENTAL IMPACTS FROM THE PERSPECTIVES OF EMBODIED ENERGY AND CO_2 EMISSION

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Abstract: With an increasing awareness of the relationship between greenhouse-gases and climate change, environmental concerns in the construction industry have started to focus on the associated embodied energy (EE) and embodied carbon dioxide (ECO_2). However, the implementation of sustainable construction has tended to focus on buildings, with less regard on infrastructure. This paper identifies that EE/ECO_2 from infrastructure projects are not negligible. Using a recent highway project in Hong Kong as a case study, the assessment of the EE/ECO_2 for a bridge infrastructure is illustrated. Careful choice of bridge-forms/materials could make a considerable change to environmental impacts. Such assessment framework could form a basis for achieving emission-reduction targets for infrastructure projects. It is suggested that consideration should be given to incorporate the EE/ECO_2 assessments to the infrastructure project implementation process in Hong Kong.

1. Introduction

Sustainability has been widely addressed from different perspectives since the Brundtland Report on '*Our Common Future*'. The global recognition of the need to strive for sustainable development was subsequently displayed in several major meetings, including the 1992 Earth Summit at Rio de Janeiro, the 1997 Kyoto Protocol and recently the 15th Conference of the Parties in Copenhagen in 2009.

In recent years, sustainability focus has been put on the construction sector because it is now realized that construction work currently accounts for about 50% of all global resource use (CIOB, 2002). The general definition of sustainability is collectively represented by three broad aspects, namely environment, economy and society. Fundamental to this concept is the establishment of the link between environment and development (Steele, 2004). As there is a close interaction between construction works and the environment, environmental performance is increasingly being seen as a principle against which construction projects should be measured. Therefore, the main focus of this paper is on the environmental part of the whole sustainability framework. The remaining two parts viz. economy and society will not be covered in this paper.

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Over the past decade, the environmental impact assessment of construction projects in many places, including Hong Kong, has mainly focused on aspects such as air quality, noise, water quality, with no regard to climate-change. However, findings released by the Intergovernmental Panel on Climate Change have revealed that warming of the global climate system is unequivocal and most of the increase in the global average temperature in the past 50 years is very likely due to an increase in greenhouse gas concentrations arising from human activities (Parry, 2007). In light of this, global environmental concerns that have been raised more recently are now concentrating on the embodied energy (EE) and emissions of carbon dioxide (CO_2) (the main contributor to greenhouse gas emissions) of major construction projects (Collings, 2006).

Currently, most of the sustainability focus in the construction industry has been put on measuring the said climate-change parameters for buildings as distinct from other infrastructure such as bridges, roads or tunnels. Although many sustainability assessment tools for the construction industry have been developed, almost all of them are only for buildings. Apart from these, there has also been attention on the embodied energy and carbon footprint of buildings, as demonstrated in the growing popularity of CO_2 emission calculators, such as the CO_2 Estimator Tool from the Centre for Sustainability (Transport Research Laboratory) and the Carbon Calculator by the Environment Agency. However, for infrastructure projects, there isn’t any published research on the sustainability assessment nor carbon footprint evaluation. In UK, there is a sustainability rating framework for civil projects called the Civil Engineering Environmental Quality Assessment and Awards Scheme (CEEQUAL). Launched in 2003, CEEQUAL is still developing its popularity for application in the infrastructure projects in the UK, and is still a long way from being made compulsory for all major infrastructure projects in the UK, not to mention other countries. Apart from CEEQUAL, there isn’t any sustainability rating tool elsewhere in the world for infrastructure projects which is as well-established as that for buildings. The situation in Hong Kong is similar, with more attention on evaluating the embodied-energy/CO_2-emissions for building projects. Very little, if any, research on these aspects for bridge infrastructure appears to have been undertaken in Hong Kong.

In fact, the environmental impacts by infrastructure projects as a whole are not insignificant to be ignored, which mainly come from the construction stage instead of the operation stage.

Table 1: Comparison of embodied CO_2 per m^2 between buildings and bridges

	Buildings[2]	**Bridges**[3]
Average embodied CO_2 in kg/m^2	598.7 (Concrete building)	1,883 (Average for concrete viaduct); 3,726 (Average for concrete-deck cable-stayed bridge)

Table 1 above shows that the CO_2-emission from bridges (up to the construction stage) is higher than that of buildings. Compared to the annual emission of 95 $kgCO_2/m^2$ of construction floor area (CFA) (Energy Information Administration (2003)) for the operation of a typical office building in New York City, the CO_2-emission from the construction of a cable-deck bridge is comparable to the amount emitted over 50 years of the building life (4,750 $kgCO_2/m^2$). It is therefore reasonable to say that the contribution from infrastructure (at least for bridges) to the CO_2-emission is not negligible.

2. Sustainability assessment of infrastructure projects in Hong Kong

Before 2001, sustainability of infrastructure projects in Hong Kong mainly focused on environmental aspects. A project that was defined as a ‘designated project’[4] was required by the Environmental Impact Assessment Ordinance (EIAO) of Hong Kong to undertake an environmental impact assessment (EIA), which considered the impacts on air quality, noise, water quality, waste management, ecology, fisheries, visual and landscape, as well as cultural heritage (EPD, 1997). Other aspects relating to wider context of climate-change were not evaluated in the project implementation process.

In 1997, the Hong Kong government commissioned a study on Sustainable Development for the 21st Century (SUSDEV 21). Strictly speaking, SUSDEV 21 was not a sustainable development strategy, but was only to introduce ‘the concept of sustainability into decision-making’ (PlanD, 2000). After 2001, all government departments were required to conduct sustainability assessments on their new project proposals by means of a computer program called Computer Aided Sustainability Evaluation Tool (CASET) developed under SUSDEV 21. However, the sustainability assessment by CASET only gave a very broad comparison on sustainability implications for the situations with and without the project-proposals, without any significant influence on the outcome of the projects. After all, in terms of infrastructure development, the concept of ‘sustainability’ in Hong Kong has remained mainly qualitative on paper without any specific quantitative targets, and only covered discrete aspects without an organized framework to coordinate all the key aspects of sustainability nowadays, the key aspects of which include the climate-change.

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[2] Embodied CO_2 data obtained from Friedberg & Yang (2009), measured up to the end of construction stage. The unit of ‘per square metre’ refers to the construction floor area.

[3] Embodied CO_2 data obtained from Collings (2006), measured up to the end of construction stage. The unit of per square metre refers to the plan area of the bridge deck.

[4] According to Schedule 2 of the Environmental Impact Assessment Ordinance (Cap. 499) of Hong Kong, ‘designated projects’ are projects or proposals that may have adverse impacts on the environment, ranging from large-scale developments such as the construction and operation of infrastructure to decommissioning of heavy industrial facilities.

On the other hand, as for building structures, the Hong Kong government seems to have taken a big step forward to address the issue of sustainability. In 2002, the Electrical and Mechanical Services Department initiated a consultancy study - Life Cycle Energy Analysis of Building Construction (EMSD, 2008a), which aimed to develop a life-cycle assessment tool for buildings and to promote the concept of sustainable building construction. The final outcome of the study also included a computer program called Life Cycle Energy Analysis (LCEA), which was designed to facilitate building designers to predict the life-cycle environmental impact of commercial buildings in Hong Kong. However, there is no such LCA tool for infrastructure projects in Hong Kong, and the existing LCEA tool is not applicable to infrastructure projects owing to the incompatibility of the input-parameters. Therefore, it is prudent for relevant stakeholders to consider the quantitative impacts on sustainability specifically for infrastructure projects.

3. Case study on EE/ECO$_2$ assessments for a Hong Kong's major bridge infrastructure

The case study project Hong Kong-Shenzhen Western Corridor (HK-SWC)[5] is a cross-border highway in the southern part of China (See Figure 1 for the location plan and Figure 2 for the project photo). Opened to traffic in 2007, HK-SWC links the Hong Kong Special Administrative Region (HKSAR) with the Shenzhen Special Economic Zone (Shenzhen). HK-SWC straddles over the Deep Bay, which is an area of particular environmental importance. Whilst the environmental impacts at a local scale (i.e. around the bridge location) were minimized, the environmental impact brought about by the infrastructure works of HK-SWC with respect to climate-change has not been considered at all. Therefore, consideration is given to evaluate the sustainability performance of the HK-SWC project from the perspective of energy consumption and CO$_2$ emissions – the major contributors of climate-change to supplement the original purely environmental EIA.

Figure 1 Location Plan of HK-SWC

Figure 2 Bird's-eye view of HK-SWC

HK-SWC comprises a viaduct section with typical span of 75m in the form of a precast segmental prestressed concrete box girder, a section of viaduct with span of 75m in the form

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[5] For further details about the projects, reference could also be made to the project website: Project website: http://www.hyd.gov.hk/eng/major/road/projects/6759th/index.htm

of an orthotropic steel deck, and a section of bridge in the form of a steel-deck cable-stayed bridge to provide a navigation span of 210m. The variety of bridge components of HK-SWC offers a good opportunity for comparing the embodied energy and CO_2 emissions between different structural options with the same traffic configuration along the same highway. However, for completeness of the study, the assessment in this case study will also include some conceptual cases for comparison purposes (e.g. a concrete cable-stayed bridge scheme) which have not been constructed. Nevertheless, since these conceptual cases are developed based on the constructed bridgeworks of HK-SWC as well as the professional judgment of the author, these conceptual cases are considered to be realistic.

3.1 Quantitative assessment of environmental impacts from HK-SWC's bridgeworks

3.1.1 Why use embodied-energy/CO_2-emissions as indicators?

Reducing greenhouse gas emissions, of which CO_2 is the most significant, has been widely accepted as vital to reducing the severity of the impact of climate change on future generations (Symons & Symons, 2009). The terms 'embodied energy (EE)'[6] and 'embodied carbon dioxide (ECO_2)'[7] are used in the construction industry to refer to the energy consumed or CO_2 emitted in the construction and operational phases of a structure. Research into the relationship between EE and ECO_2 has shown a high correlation, that every GJ of embodied energy produced 0.098 tonnes of carbon dioxide (CSIRO, 2001). Therefore, although there are no direct environmental impacts associated with EE, the link to ECO_2 suggests a good way for interpreting the environmental impact data. The use of EE/ECO_2 data is a simplified way of evaluating the embodied impacts of different construction elements.

3.1.2 Assessment methodology

To avoid EE/ECO_2 from being double-counted or omitted, the calculations in this study considered two distinct categories that cover the entire process from cradle to site: (i) EE/ECO_2 of the material itself (i.e. the Material Energy) and (ii) EE/ECO_2 of transportation of the materials / partially-completed structural components (e.g. precast concrete segments) to site (i.e. the Transportation Energy). Concerning the boundary of the EE/ECO_2 assessment in this study, the Material Energy covers the part of the energy from 'cradle-to-factory gate' for the material, whereas the Transportation Energy further extends the EE/ECO_2 calculations from 'factory gate-to-site'. Ideally, the boundaries would be set from the extraction of raw materials to the end of the products lifetime (including the

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[6] Embodied energy (EE) is defined as the total primary energy consumed over a defined part of the life-cycle of a product. Cradle-to-gate EE is frequently cited for many materials and includes all the energy used in producing the material up to the point it leaves the factory gate. Such a value should include the extraction of raw materials, their transportation and all manufacturing process.

[7] Embodied CO_2 (ECO_2), which is the term given in the Inventory of Carbon and Energy by the University of Bath (Hammond & Jones, 2008), is an alternative name to CO_2 emissions as mentioned in the earlier parts of this paper. It is defined as the CO_2 produced over a defined part of the life-cycle of the product. As with EE, cradle-to-gate ECO_2 values are frequently cited. CO_2 is primarily associated with the consumption of energy directly as a result of the production process up to leaving the factory gate but excludes energy or CO_2 used for transport to the construction site.

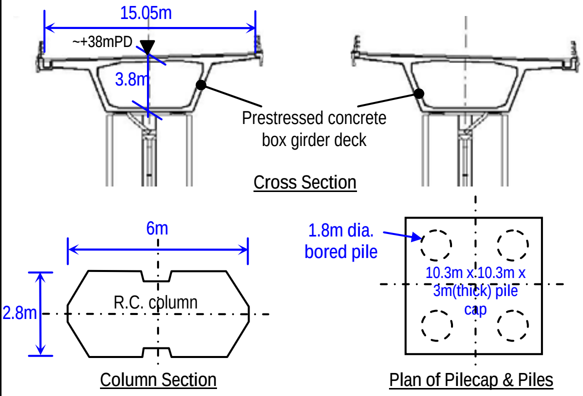
amount of energy from manufacturing, transport to demolition). This boundary condition is known as ‘cradle-to-grave’. However, no data on the associated EE/ECO_2 values for demolition of bridges was found in the literature. This is in part likely to be due to the relatively long design life of bridges (about 120 years) and also scarcity of information on this topic. The assessment in this study mainly covers up to the point just before the bridge is in operation, and does not cover the operational phase and decommissioning of the bridge i.e. ‘cradle-to-grave’. Furthermore, it is assumed in this assessment that the EE/ECO_2 from site operations such as the electricity-consumption by the construction plant on site is ignored. This is considered to be a reasonable assumption since, according to Smith (2008), the carbon emissions from the construction process only contributed to 4% of the whole life cycle of a new construction.

Quantities of various structural elements of the bridges were obtained from the as-built drawings, except for the case of concrete-deck cable-stayed bridge and haunched bridge which are deduced from conceptual design drawings. The EE/ECO_2 associated with the transportation of materials is calculated based on the actual route in the construction stage with reference to the contractor’s documents. In this paper, the source of EE/ECO_2 data is mainly from the United Kingdom, instead of those from Hong Kong. This is because there is no such consistent inventory of data in Hong Kong. The sources of energy/carbon data for this study are: (i) Inventory of Carbon & Energy of the University of Bath (BUICE) (Hammond & Jones, 2008), which is an inventory of building materials with values of embodied energy and carbon coefficients created by the University of Bath, providing averaged coefficients for many common construction materials within a cradle-to-gate boundary; and (ii) Guidelines to DEFRA’s Greenhouse Gas Conversion Factors for Company Reporting (DEFRA, 2009), which is an guideline issued by the Department for Environment, Food and Rural Affairs (DEFRA) in the UK to help businesses convert existing data sources e.g. fuel consumption of cars, into CO_2 equivalent data.

This study involves the comparison of EE/ECO_2 for three cases: Case (1) 75m-span viaducts with different materials for bridge deck; Case (2) Cable-stayed bridges (CSB) with different materials for bridge deck; Case (3) Different bridge forms to provide a span of 210m. These cases are shown in Figure 3 below.

Figure 3: Bridgeforms considered in the case study

Case (1a): 75m-span viaduct (concrete deck)



Case (1b): 75m-span viaduct (steel deck)

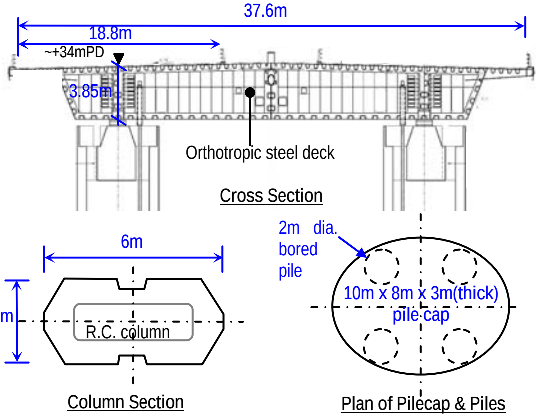
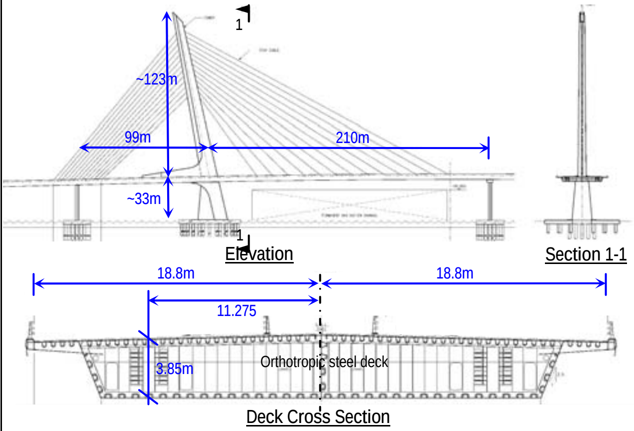
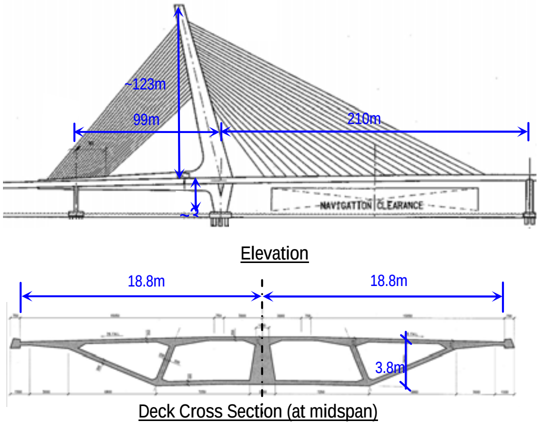


Figure 3: Bridgeforms considered in the case study (Cont'd)

Case (2a): Cable-stayed Bridge (steel deck)

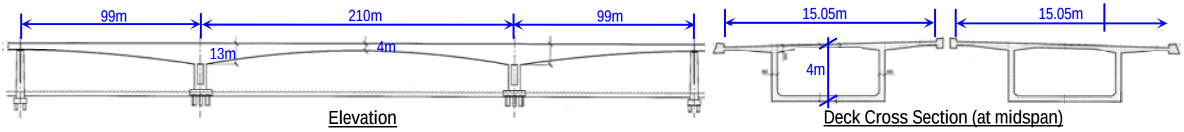


Case (2b): Cable-stayed Bridge (Concrete deck)



Case (3b): Haunched bridge with prestressed concrete box girder deck

(whereas Case (3a) is CSB with concrete deck i.e. same as Case (2b))

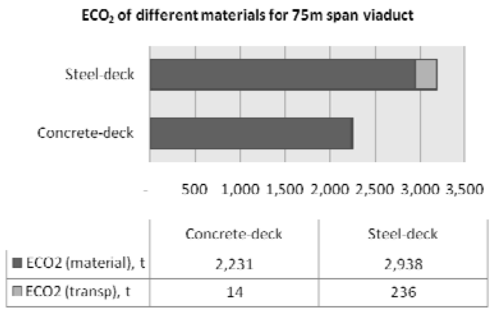


3.1.3 Results of Case (1)

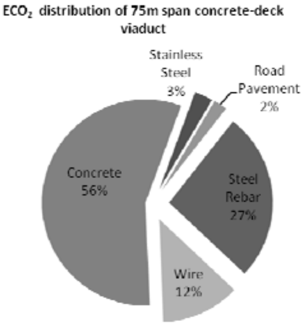
Table 1 summarizes the results of the EE/ECO_2 assessments for Case (1), whereas Graphs 1.1 to 1.3 present a breakdown of the results.

Table 1	Case (1a): 75m span concrete-deck	Case (1b) – 75m span steel-deck
Total EE (ECO_2)	21,886 GJ (2,245 tonnes)	37,110 GJ (3,175 tonnes)
EE/m^2 (ECO_2/m^2)	19.4 GJ/m^2 (2.0 t/m^2)	26.3 GJ/m^2 (2.3 t/m^2)

Graph 1.1



Graph 1.2



Graph 1.3

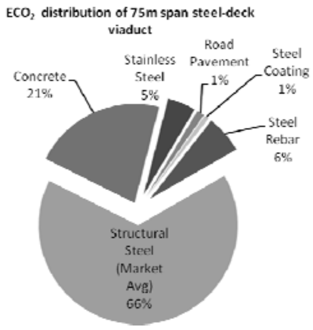


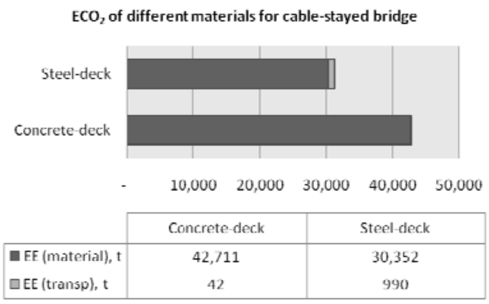
Table 1 show that the steel deck scheme has a higher EE and ECO_2 values per metre length than the concrete deck scheme by 69.5% and 41.5% respectively. This is primarily due to the greater density and EE/ECO_2 of steel compared to that of concrete. Graph 1.1 shows that the transportation ECO_2 of steel deck bridge is much higher (more than 17 times) than that of concrete deck. This is because in HK-SWC, a much longer transportation route was involved for the steel deck segment production.

3.1.4 Results of Case (2)

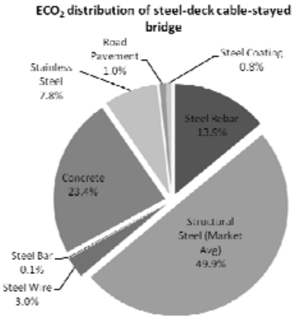
Table 2 summarizes the results of the EE/ECO_2 assessments for Case (2), whereas Graphs 2.1 to 2.3 present a breakdown of the results.

Table 2	Case (2a) – Steel-deck CSB	Case (2b) – Concrete-deck CSB
Total EE (ECO_2)	359,718 GJ (31,342 tonnes)	419,071 GJ (42,753 tonnes)
EE/m^2 (ECO_2/m^2)	31.0 GJ/m^2 (2.7 t/m^2)	36.1 GJ/m^2 (3.7 t/m^2)

Graph 2.1



Graph 2.2



Graph 2.3

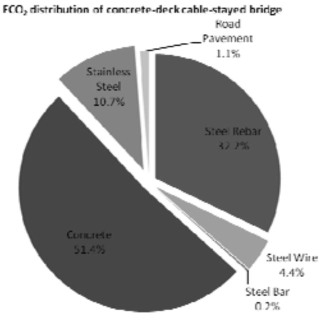


Table 2 above shows that the cable-stayed bridge scheme with concrete deck has larger EE/ECO_2 values per m^2 of deck surface than the same bridge form with steel deck. This result is quite different from the findings in Case (1) for the 75m-span viaduct schemes which showed that steel deck scheme involved higher EE/ECO_2 values per m^2 than the concrete deck scheme. One of the reasons for this is that reinforced concrete, compared to structural steel, is not a structurally-efficient material for such a long-span structure as a cable-stayed bridge. The quantity of concrete used in the bridge deck alone for the cable-stayed bridge is 3.5 times heavier than that of steel in the steel deck. This heavier deck weight leads to more materials being used for the stay cables, concrete tower and foundation. In terms of transportation emission, however, the steel scheme actually consumes much more (about 24 times) than the concrete scheme. This is primarily due to the long distance required to transport the steel plate and bridge-segments.

3.1.5 Results of Case (3)

Table 3 summarizes the results of the EE/ECO_2 assessments for Case (3), whereas Graphs 3.1 to 3.3 present a breakdown of the results.

Table 3	Case (3a) – Concrete-deck CSB	Case (3b) – Haunched bridge concrete-deck
Total EE (ECO_2)	419,071 GJ (42,753 tonnes)	334,752 GJ (33,249 tonnes)
EE/m^2 (ECO_2/m^2)	36.1 GJ/m^2 (3.7 t/m^2)	27.3 GJ/m^2 (2.7 t/m^2)

Table 3 shows the energy content and carbon footprint per m^2 of the deck area for the haunched bridge form are lower than those of the cable-stayed bridge form by approximately 24% and 27% respectively. Although reinforced concrete is not a structurally-efficient material for cable-stayed bridge as mentioned in 3.1.4, it can be made relatively more efficient if the bridge form for this particular span length is changed to a simpler bridge form such as a haunched bridge. Comparing the concrete volumes (including deck and substructure) for both schemes, it is found that the cable-stayed bridge requires about 138 m^3 of concrete per metre run (which mainly comes from the tower structure), whereas the haunched bridge only needs about 76 m^3 per metre run (with a roughly-equal share amongst deck, columns and piles). This 45% saving in concrete materials makes a significant contribution to the lower EE/ECO_2 for the haunched bridge scheme.

4. Further discussion

4.1 EE/ECO_2 assessment to aid design decisions for infrastructure projects

Despite the additional CO_2-emissions from the bridge construction, the overall effect would likely decrease in the long run because of the shorter distance travelled and the alleviation of the traffic congestion. In theory these reductions in emissions from cars eventually are able to offset those created in the whole life of the bridge. In other words, an overall status of 'carbon neutral'[8] is able to be achieved. With the aid of EE/ECO_2 to quantify the environmental impacts of an infrastructure project, consideration could then be given to adopt methods to reduce EE/ECO_2 in the design process. Besides, the EE/ECO_2 assessment

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[8] 'Carbon neutral' is a term used to describe a particular product (which in this case is a highway structure) that has had its carbon dioxide emissions offset. Compared to 'zero carbon', emission offsetting can be viewed as 'externalizing' the issue. In other words, the decision-maker in question is not directly changing its energy efficiency but rather paying to cover its inefficiency.

can also be used as a tool to refine the design of a single bridge scheme, with an aim to achieve ‘carbon neutral’ in a shorter period of time. Besides, consideration could also be given to the use of other materials with lower emissions to replace conventional construction materials such as cement-concrete and steel. For the former, the ground granulated blast-furnace slag (GGBS) is gaining its popularity nowadays in replacing the cement to produce a more sustainable concrete product. Compared to conventional concrete with ECO_2 values of 0.21kgCO_2/kg (Hammond & Jones, 2008), the use of 50% GGBS could achieve a reduction of 41%. To conclude, EE/ECO_2 assessment enables project proponents to carry out scheme-comparison and make design-decisions from the environmental sustainability perspective.

4.2 EE/ECO_2 assessment for infrastructure in Hong Kong

The comparison in Case (1) in Section 3.1.3 shows a difference in EE and ECO_2 of 200 GJ/m and 12.4 t/m respectively (per single bridge) between concrete and steel for the same typical bridge span of 75m with dual 3-lane carriageway. Considering the whole length of HK-SWC highway of 4.5km long dual-carriageway viaduct (excluding the navigation spans), this amounts to approximately 0.6% of the annual energy consumption in Hong Kong in 2006 (288,158 TJ (EMSD, 2008b)) and 0.3% of the annual CO_2 emissions in Hong Kong in 2005 (37.7 million tonnes (ACE, 2007)) for just a single project. In other words, if the environmental impacts in terms of EE/ECO_2 are considered to be one of the criteria in assessing which material to be adopted in the scheme evaluation stage of all projects, there could be a considerable reduction in energy consumption of Hong Kong.

4.3 Incorporation of EE/ECO_2 assessment into Hong Kong’s infrastructure planning

To promote the application of EE/ECO_2 assessment for infrastructure projects in Hong Kong, one of the key steps is to form a local life-cycle inventory (LCI) as there is currently no such comprehensive inventory in Hong Kong. A local LCI database specifically for Hong Kong’s situation enables a more accurate assessment of the EE/ECO_2 values for local projects. With the local LCI database, another key step would be to make the EE/ECO_2 assessment mandatory for the planning and design of every infrastructure project in Hong Kong. Consideration could be given to incorporate such assessment into the infrastructure planning and design process. To this end, it is recommended to incorporate the EE/ECO_2 assessments for designated projects under the EIAO (Environmental Impact Assessment Ordinance). The final outcome would need to consider alternatives with respect to carbon-footprint, and recommended final solution taking account of the EE/ECO_2 assessment results (such as how many years are required to achieve the state of ‘carbon neutral’), with mitigation measures to offset the carbon emissions from the project.

5. Conclusion

This paper pressed for more coordinated efforts from stakeholders of infrastructure projects to address environmental sustainability issues. Through the case study of HK-SWC, the EE/ECO_2 assessment methodology for bridgeworks is illustrated, and the change in environmental impacts of different bridgeforms is evaluated. EE/ECO_2 assessment can help to inform design decisions. This enables the project proponents to understand how their projects could help to achieve the emission targets. For Hong Kong's situation, it is suggested to form a LCI and to mandate EE/ECO_2 assessment for infrastructure projects.

6. Acknowledgements

This paper is part of the thesis for the author's IDBE masters course. The support of the thesis supervisor Dr Campbell Middleton and IDBE course director Dr Sebastian Macmillan from Cambridge University is gratefully acknowledged.

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