ENVIRONMENTAL EFFECTS DUE TO CHANGES IN CONSTRUCTION TECHNOLOGY

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Abstract:

The construction of facilities requires a tremendous amount of energy, which in turn emit out high levels of pollutant emissions. Usage of materials in construction is very much energy intensive so it is necessary to study the influences of the usage of materials to energy intensity and consequently the amount of carbon dioxide emissions. The major focus of this paper is the identification of feedback loops that reveal the interactions between construction technology, energy requirements and carbon dioxide pollutant emissions. The structural system of the energy sector and the construction sector is decomposed to distinguish the influences present between the energy sector and the construction sector.

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1. INTRODUCTION

Sustainable development is a worldwide and very important environmental concept. It means that in order to safeguard our environment from depletion of non-renewable resources and from its destruction, strategies should be developed to support our environment for today and for future generations.

Some approaches, which are developed, are the relationships between the environment and the whole economic system. A well-known methodology, which relates environmental loads and the economic system, is the environmental input-output model.

The conventional Input-Output model has been employed to estimate environmental loads due to the production processes of the entire economic system. Leontief (1970) was the pioneer for the use of the extended input-output system to calculate environmental loads. He augmented the basic structural matrix of the economy to include environmental externalities such as air pollution. Hayami et al.(1993) estimated the amount of CO_2 emission per unit of commodity production using Japan's 1985 input-output tables. Gale (1995), on the other hand, estimated the carbon dioxide emissions from the changes in the level of structure of production and consumption activity in Mexico following the liberalization of trade. Weir (1998) explored the anatomy of the Danish energy consumption and emissions of 3 pollutants. In addition, Gerilla, et al.(2000) estimated the amount of nitrogen oxides, sulfur dioxides and carbon dioxide emissions from building and road construction. These studies failed to consider the changing energy prices in the world, which more or less affects the values of the estimated carbon emissions. Bullard & Herendeen (1975), Beutel (1984) resolved the problem of changing energy prices by the use of physical units for energy sectors. Piantanakulchai et al. (1999) in their study used the hybrid static Input-Output model to calculate the carbon emissions. However, the studies are limited to the calculation of the environmental impacts of a given final demand.

To be able to have a better understanding of the importance of the complex interactions between the environment and the economy, important interconnections should be identified which leads to the contribution to the total emissions. Sonis & Hewings (1990) proposed a method to show the paths of direct and indirect dependencies in the economy. They called it the Hierarchical Feedback Loop Analysis wherein they decomposed the economic structure to be able to understand the paths of changes that occurred within the economy. This method was applied to different multi-regional economies to analyze the trade structures of the different economies in Europe and Asia (1993,1995). Fritz, et al. (1998) also applied Sonis' framework to analyze the interaction between polluting and non-polluting sectors. Weber and Schnabl (1998), on the other hand, proposed an approach wherein the total energy requirements were partitioned into production layers and energy consuming sectors. They applied it to the hybrid IO model. The studies using the commodity by commodity framework have inherent problems due to the assumption of product mix. The problem of secondary production is not considered. Kagawa & Inamura (2000) applied the hierarchical decomposition techniques to the hybrid rectangular input-output model (HRIO) to analyze the energy requirements of non-energy sectors. The proposed HRIO reduced the problems inherent to the commodity by commodity framework. They also identified the structural changes in energy consumption between 1985 and 1990 using the structural decomposition analysis. Furthermore, they revealed that the construction industry is one sector, which is a cause of a major increase in energy requirement.

With this in mind, a study on the carbon emissions and its primary sources and changes in the construction industry and the economy is necessary. This paper tries to deal with the construction of facilities and its impacts on the environment mainly due to carbon emissions by using the hybrid rectangular input-output model. The analysis of the linkages between the construction sector, non-construction sector and the energy supply sector is studied using the hierarchical decomposition technique.

The paper is organized as follows; the framework of the study is provided in the second section showing a brief description of the hybrid rectangular input-output (HRIO) tables and the model that is used in the analysis. Following it is the empirical application of the model using the 1990 data in Japan. Concluding comments closes the paper in Section 4.

2. FRAMEWORK OF THE STUDY

The flow of the study is shown in Figure 1. The flowchart shows the methodology used in the paper. The procedure for the construction of the hybrid rectangular input-output table is shown in the flow. Before the HRIO tables are constructed, the commodity by commodity tables are first transformed into a hybrid matrix and then aggregated to match the total number of industries available in the industry by commodity table. A more detailed explanation of the methodology is presented in the following sections.

FIGURE 1 HERE

2.1 Rectangular Input Output Model

The commodity by industry framework has several analytical advantages, it not only can handle the same features as the Leontief square model but it also can differentiate between industry and commodity accounts.

Moreover, several variations of the total requirements matrix can be derived in the context of a commodity based or industry based technology assumption (Miller & Blair, 1985).

The rectangular system is an alternative way of constructing input-output tables that accurately accounts for secondary production of industries. The problem of secondary production is important to consider as it affects environmental loads when the shares of primary and secondary products of industries change. The commodity based technology assumption is utilized to formulate the model.

Here, we assume that the commodity-input structure is independent of the producing industry. In the assumption, we have:

$$q = (I - BC^{-1})^{-1} f \tag{1}$$

$$g = I \quad C^{-1} B C^{-1} f \tag{2}$$

where:

q = vector of commodity gross output;

g = vector of industry total outputs;

C = industry output coefficient matrix, $V^{'}(\hat{g})^{1}$;

B = direct requirements matrix, $U(\hat{g})^{1}$;

I = n x n unit matrix;

$\hat{g}$ = Diagonal matrix with g as its elements;

V'= transpose of V;

The input output tables in Japan does not include the use matrix, U, so B is redefined into $A = BC^{-1}$. Redefining B, we have B = AC. Another advantage of the rectangular system is the identification of the environmental loads from energy supply industries, construction industries and non-construction industries. The following section will show the formulation of the hybrid concept and the distinction between the ordinary rectangular system and the framework used in this paper.

2.2 Hybrid Concept

The use of monetary units instead of physical units to express physical dependencies is less than perfect. (Bullard & Herendeen, 1975) Hybrid units trace the flow of energy flows within the economy in physical units and non-energy flows in monetary units. With changing energy prices, the amount of carbon emissions can be over or under estimated, using the hybrid concept wherein the monetary flows of the carbon-producing sectors are replaced with its physical flows, this problem of over or under estimation is reduced. The corresponding model of the hybrid concept is shown in following matrices.

The direct requirements matrix B and the output coefficient matrix, C are divided into the carbon-producing sector or energy supply sector (**es**), the non-construction sector (**nc**) and the construction sector (**cs**), respectively.

The energy supply sector is defined as the sector of primary sources of carbon emission. These include the primary energy sectors and the limestone sector.

The non-construction sector, on the other hand, is determined to be the sectors that are not included in the construction and energy supply sectors.

The energy supply sector has a unit of ton-carbon (ton-C) while the non-construction and construction sectors have units in million yen (MY).

(3)

$$C_h \quad \begin{array}{c|c|c|c} & es & nc & cs \\ es & C_{11}(ton\;\; C/ton\;\; C) & C_{12}(MY/ton\;\; C) & C_{13}(MY/ton\;\; C) \\ \hline nc & C_{21}(ton\;\; C/MY) & C_{22}(MY/MY) & C_{23}(MY/MY) \\ \hline cs & C_{31}(ton\;\; C/MY) & C_{32}(MY/MY) & C_{33}(MY/MY) \end{array} \qquad (4)$$

where:

B_{11} = input coefficient sub-matrix of carbon producing commodities required by energy supply industries;

B_{12} = input coefficient sub-matrix of carbon producing commodities required by non-construction industries;

B_{13} = input coefficient sub-matrix of carbon producing commodities required by construction industries;

B_{21} = input coefficient sub-matrix of non-construction commodities required by energy supply industries;

B_{22} = input coefficient sub-matrix of non-construction commodities required by non-construction industries;

B_{23} = input coefficient sub-matrix of non-construction commodities required by construction industries;

B_{31} = input coefficient sub-matrix of construction commodities required by energy supply industries;

B_{32} = input coefficient sub-matrix of construction commodities required by non-construction industries;

B_{33} = input coefficient sub-matrix of construction commodities required by construction industries;

C_{11} = output coefficient sub-matrix of energy supply industries producing energy supply commodities;

C_{12} = output coefficient sub-matrix of energy supply industries producing non-construction commodities;

C_{13} = output coefficient sub-matrix of energy supply industries producing construction commodities;

C_{21} = output coefficient sub-matrix of non-construction industries producing energy supply commodities;

C_{22} = output coefficient sub-matrix of non-construction industries producing non-construction commodities;

C_{23} = output coefficient sub-matrix of non-construction industries producing construction commodities;

C_{31} = output coefficient sub-matrix of construction industries producing energy supply commodities;

C_{32} = output coefficient sub-matrix of construction industries producing non-construction commodities;

C_{33} = output coefficient sub-matrix of construction industries producing construction commodities;

The basic V matrix is converted into a hybrid V_h matrix, together with the hybrid industrial outputs, the hybrid coefficient matrix, C_h is calculated.

As mentioned in the preceding section, the hybrid input coefficient matrix, B_h is gotten using C_h pre-multiplied by the hybrid commodity by commodity technological coefficient, A_h.

After organizing all the basic hybrid matrices, the modeling phase is presented in the proceeding section.

2.3 Hierarchical Decomposition Technique

The economic system is subdivided, in this case, into three sub systems, the energy supply or carbon-producing sector, es, non-construction sector, nc and the construction sector, cs.

Using the hierarchical decomposition best shows the linkages between these sectors.

It is also used to analyze the successive sets of sub-systems incorporated in the whole system.

The hierarchical decomposition or Matrioshka principle is applied to the hybrid rectangular system in order to compare the demand structure of the 3 sectors and to know the strengths of the linkages induced by a certain sector for the production of final demand.

The structure of the hybrid matrices B and C can be decomposed as shown below:

$$\underbrace{\begin{bmatrix} B_{11} & B_{12} & B_{13} \\ B_{21} & B_{22} & B_{23} \\ B_{31} & B_{32} & B_{33} \end{bmatrix}}_{B} \quad \underbrace{\begin{bmatrix} B_{11} & B_{12} & B_{13} \\ B_{21} & 0 & 0 \\ B_{31} & 0 & 0 \end{bmatrix}}_{B_{es}} \quad \underbrace{\begin{bmatrix} 0 & 0 & 0 \\ 0 & B_{22} & B_{23} \\ 0 & B_{32} & 0 \end{bmatrix}}_{B_{nc}} \quad \underbrace{\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & B_{33} \end{bmatrix}}_{B_{cs}} \qquad (5)$$

$$\underbrace{\begin{bmatrix} C_{11}^{-1} & C_{12}^{-1} & C_{13}^{-1} \\ C_{21}^{-1} & C_{22}^{-1} & C_{23}^{-1} \\ C_{31}^{-1} & C_{32}^{-1} & C_{33}^{-1} \end{bmatrix}}_{C^{-1}} \quad \underbrace{\begin{bmatrix} C_{11}^{-1} & C_{12}^{-1} & C_{13}^{-1} \\ C_{21}^{-1} & 0 & 0 \\ C_{31}^{-1} & 0 & 0 \end{bmatrix}}_{C_{es}^{-1}} \quad \underbrace{\begin{bmatrix} 0 & 0 & 0 \\ 0 & C_{22}^{-1} & C_{23}^{-1} \\ 0 & C_{32}^{-1} & 0 \end{bmatrix}}_{C_{nc}^{-1}} \quad \underbrace{\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & C_{33}^{-1} \end{bmatrix}}_{C_{cs}^{-1}} \qquad (6)$$

C^{-1} represents the market share structure using the commodity based technology assumption. Under this assumption the amount of industry's total outputs is made up of commodities in fixed proportions.

C_{11}^{-1} = market share sub-matrix of energy supply commodities produced by the energy supply industries;

C_{12}^{-1} = market share sub-matrix of non-construction commodities produced by the energy supply industries;

C_{13}^{-1} = market share sub-matrix of construction commodities produced by the energy supply industries;

C_{21}^{-1} = market share sub-matrix of energy supply commodities produced by the non-construction industries;

C_{22}^{-1} = market share sub-matrix of non-construction commodities produced by the non-construction industries;

C_{23}^{-1} = market share sub-matrix of construction commodities produced by the non-construction industries;

C_{31}^{-1} = market share sub-matrix of energy supply commodities produced by the construction industries;

C_{32}^{-1} = market share sub-matrix of non-construction commodities produced by the construction industries;

C_{33}^{-1} = market share sub-matrix of construction commodities produced by the construction industries;

The hierarchical decomposition of the commodity and industry output in equations (1) and (2) are shown in Table 1.

The production function for commodity (equation 1) and industry (equation 2) were decomposed according to the structure of the B and C matrices in equations (5) and (6). This decomposition will show the strengths of the linkages between the non-construction sector, the construction sector and the energy supply industries, which induces the amount of emissions from the construction sector.

Letting:

$B = B_{es} + B_{nc} + B_{cs}$ $\quad C^{-1} = C_{es}^{-1} + C_{nc}^{-1} + C_{cs}^{-1}$

$B = B_{es} + B_{a}$ $\quad C^{-1} = C_{es}^{-1} + C_{a}^{-1}$

$B_a = B_{nc} + B_{cs}$ $\quad C_a^{-1} = C_{nc}^{-1} + C_{cs}^{-1}$

we have,

$$q_1 = (I - BC^{-1})^{-1} f$$

$$= (I - BC^{-1})\{(I-B_aC^{-1})(I-B_aC^{-1})^{-1}\}f$$

$$= (I + L_0B_{es}C^{-1})(I-B_aC^{-1})^{-1}\{(I-B_aC_a^{-1})(I-B_aC_a^{-1})^{-1}\}f$$

$$= (I + L_0B_{es}C^{-1})(I + L_1B_aC_{es}^{-1})(I-B_aC_a^{-1})^{-1}\{(I-B_{nc}C_a^{-1})(I-B_{nc}C_a^{-1})^{-1}\}f$$

$$= (I + L_0B_{es}C^{-1})(I + L_1B_aC_{es}^{-1})(I + L_2B_{cs}C_a^{-1})(I + L_3B_{nc}C_{cs}^{-1})(I-B_{nc}C_{nc}^{-1})^{-1}f$$

where:

$L_0 = (I - BC^{-1})^{-1}$ $\quad$ $L_2 = (I - B_aC_a^{-1})^{-1}$

$L_1 = (I - B_aC^{-1})^{-1}$ $\quad$ $L_3 = (I - B_{nc}C_a^{-1})^{-1}$

Therefore, the decomposed production function is shown below:

$$q_1 = (I + L_0B_{es}C^{-1})(I + L_1B_aC_{es}^{-1})(I + L_2B_{cs}C_a^{-1})(I + L_3B_{nc}C_{cs}^{-1})(I - B_{nc}C_{nc}^{-1})^{-1}f \quad (7)$$

The identity on the right hand side of the equation can be explained by reading it from right to left.

$(I - B_{nc}C_{nc}^{-1})^{-1}f$ represents the total production vector in the non-construction sector for the production of final demand f;

$(I + L_3B_{nc}C_{cs}^{-1})$ represents the intermediate input requirements of the construction commodity needed to produce final demand;

$(I + L_2B_{cs}C_a^{-1})$, means that the output requirements of the construction and non-construction industry need construction commodity input requirements to produce final demand;

$(I + L_1B_aC_{es}^{-1})$, means that the output requirements of the energy supply industry need construction and non-construction commodities' input requirements to produce final demand.

This can be ignored in the equation because input requirements from the construction and non-construction industry to the output requirements of energy supply industries can not be calculated;

$(I - L_0 B_{es} C^{-1})$, means that the output requirements of the whole system needs commodity input requirements from the energy supply industry.

For a better understanding of the equation, the production process is depicted in figure 2.

The economic system is a complex system, which is divided into 3 sub-systems namely, the energy supply industry, the construction industry and the non-construction industry. To be able to explain these complex structure and the interactions of each subsystem in the economy, the hierarchical decomposition is applied.

We take the example of the production of steel for construction use, the non-construction industry requires construction commodity inputs.

The energy industry in turn requires commodity inputs from both the construction industry and the non-construction industry.

These industries require commodity inputs from the energy supply industry.

The circular flow of the economy is depicted in this diagram and these direct and indirect linkages produce carbon dioxide emissions.

The carbon emission structure is bounded as shown in the figure.

FIGURE 2 HERE

Using the expression: $g = C^{-1}q$, we can get the decomposed industry production function as:

$$g_1 = (C^{-1} - C^{-1}L_0 B_{es} C^{-1})(I - L_1 B_a C_{es}^{-1})(I - L_2 B_{cs} C_a^{-1})(I - L_3 B_{nc} C_{cs}^{-1})(I - B_{nc} C_{nc}^{-1})^{-1} f \quad (8)$$

Since there are 3 subsystems in the model, there will be 6 decomposition schemes presented.

Each decomposition scheme shows the different inter-relationships of the 3 subsystems, which affect the carbon emission structure induced by the non-construction sector.

The six decomposition schemes of the commodity production function are equivalent ($q_1 \equiv q_2 \equiv q_3 \equiv q_4 \equiv q_5 \equiv q_6$).

Similarly, the industry production functions are also equivalent ($g_1 \equiv g_2 \equiv g_3 \equiv g_4 \equiv g_5 \equiv g_6$).

TABLE 1 HERE

From equation (8), we have E_g as the matrix of total carbon emission coefficient of industries induced by the non-construction sector for the production of final demand.

$$E_g = (C^{-1} - C^{-1}L_0 B_{es} C^{-1})(I - L_1 B_a C_{es}^{-1})(I - L_2 B_{cs} C_a^{-1})(I - L_3 B_{nc} C_{cs}^{-1}) \quad (19)$$

Equation 19 can be presented in matrix form as follow:

$$E_g = \begin{bmatrix} E_{g11} & E_{g12} & E_{g13} \\ E_{g21} & E_{g22} & E_{g23} \\ E_{g31} & E_{g32} & E_{g33} \end{bmatrix} \quad (20)$$

where:

E_{g11} = carbon producing industry output submatrix of energy supply industries induced by the final demand of the energy sector;

E_{g12} = carbon producing industry output submatrix of energy supply industries induced by the final demand of the non-construction sector;

E_{g13} = carbon producing industry output submatrix of energy supply industries induced by the final demand of the construction sector;

E_{g21} = non-construction output submatrix of energy supply industries induced by the final demand of the energy sector;

E_{g22} = non-construction output submatrix of energy supply industries induced by the final demand of the non-construction sector;

E_{g23} = non-construction output submatrix of energy supply industries induced by the final demand of the construction sector;

E_{g31} = construction output submatrix of energy supply industries induced by the final demand of the energy sector;

E_{g32} = construction output submatrix of energy supply industries induced by the final demand of the non-construction sector;

E_{g33} = construction output submatrix of energy supply industries induced by the final demand of the construction sector;

The carbon emission coefficient vector of energy supply industries is given in the matrix below:

$$E_{ge} \quad E_{g11} \,\vdots\, E_{g12} \,\vdots\, E_{g13} \tag{21}$$

E_{ge} is defined as the direct and indirect emission output that is acquired from the production of energy goods that are absorbed into the production processes of the non-construction and the construction sectors.

2.4 Final Demand

The total hybrid final demand matrix, f_h is a vector composed of the final demand sub-matrices of each sector.

$$f_h \quad \begin{array}{c} f_{es} \\ \hline f_{nc} \\ \hline f_{cs} \end{array} \tag{22}$$

where

f_{es} = final demand of the energy supply industry;

f_{nc} = final demand of the non-construction industry;

f_{cs} = final demand of the construction industry;

The final demand used in this study for the production of a construction commodity such as a bridge or pavement is a final demand converter.

A final demand converter is used for the construction final demand since no detailed construction category is given in the basic I-O table.

This converter is taken from the input transactions of the construction sector.

The final demand converter is defined as the input coefficient for construction as shown in equation 23.

$$f^{c}_{ij} \quad \frac{p_{ij}}{{}_{i}\, P_{ij}} \tag{23}$$

where:

p_{ij} = input coefficient from sector i for the construction sector j;

P_{ij} = cost of input from sector i to the construction sector j

The final demand for the construction sector induced by the non-construction sector is given as a vector:

$$f_j^c = \begin{bmatrix} f_{es}^c \\ \hdashline f_{nc}^c \\ \hdashline f_{cs}^c \end{bmatrix} \qquad (24)$$

where:

f_j^c = final demand converter for every construction commodity j;

From equations (8), (21) and (24), the total carbon emission intensity from the energy supply industries induced by the non-construction sector for the production of a construction commodity is given by:

$$C_{es} = E_{ge} * (I - B_{nc} * C_{nc}^{-1})^{-1} * f_j^c \qquad (25)$$

where:

C_{es} =Total carbon emission intensity (ton-C/MY);

E_{ge}= Carbon emission coefficient vector of energy supply industries;

f^c_j = Final demand for every construction commodity j;

$(I - B_{nc}C^{-1}_{nc})^{-1}$= total requirements matrix induced by the non-construction sector;

The total carbon intensity can be divided into the direct carbon emission intensity and indirect carbon emission intensity.

$$C_{esd} \quad E_{ge} *(I \quad B_{nc} * C_{nc}^{1})* f_{j}^{c} \qquad (26)$$

$$C_{esi} \quad E_{ge} *[(B_{nc} * C_{nc}^{1})^{2} \quad (B_{nc} * C_{nc}^{1})^{3} \quad (B_{nc} * C_{nc}^{1})^{4} *(I \quad B_{nc} * C_{nc}^{1}) \quad ^{1}]* f_{j}^{c} \qquad (27)$$

3. EMPIRICAL APPLICATION OF THE MODEL

The next step is the empirical application of the model, as mentioned earlier, since all are equivalent, one model (equation 8) will be used for the numerical experiment.

The data used is as follow: 1990 Basic Input Output Tables, 1990 V table, Carbon intensity for 1990 (provided by the Environmental Agency of Japan) and the 1990 I-O for Construction Work.

Figure 3 shows the contribution of the energy supply industries to the construction commodity for the total emission coefficient.

It shows that the coal products industry is the main contributor to emissions in the production of bridge and other construction works.

The petroleum refinery industry, on the other hand, is the main carbon polluter for the construction of pavement and repair of construction works.

The carbon emission intensity from the Limestone industry is high in earthworks and improvement of construction facilities.

The gas supply industry almost contributes a negligible effect of carbon emission due to the construction of all the construction commodities under inspection.

FIGURE 3 HERE.

Figures 4 and 5 show the direct and indirect emission intensity due to the energy supply industries for the production of each construction commodity.

For carbon emissions which occurs directly for the production of the construction commodities, the limestone industry contributes a high percentage compared to other energy supply industries.

Petroleum refinery products also contribute much in the direct emissions for pavement construction and earthworks.

FIGURE 4 HERE.

FIGURE 5 HERE

The next figures identify the main non-construction industry contributors to the total carbon emission for the production of the construction commodity.

The figures represent the partitioning of the emission structure for each construction commodity in terms of the non-construction industry sectors.

It shows that cement and cement products dominate the emission contribution for all construction commodities.

Steels and steel products also contribute a high percentage in the emission.

To a large extent, the sectors rely on energy inputs from other sectors as well to produce the commodity.

The figures also point out that the bulk of the most of the relevant contributions from the energy supply sector is concentrated on a few sectors.

4. CONCLUSION

The use of the hybrid rectangular system under the commodity technology assumption for carbon emission intensity was done to avoid the effects of changes in energy prices which affects the intensities in carbon emissions.

The structural linkages between the non-construction industry and the energy supply-industry to produce a construction commodity were shown through the use of the hierarchical decomposition analysis.

It shows that energy supply industry inputs to the non-construction sector are very important for the construction industry.

The bulk of the relevant contributions from the energy supply industry are concentrated on a few sectors thereby reduction of carbon emissions from the construction industry can be achieved by reduction of material usage from the major contributors of emission such as cement and steel.

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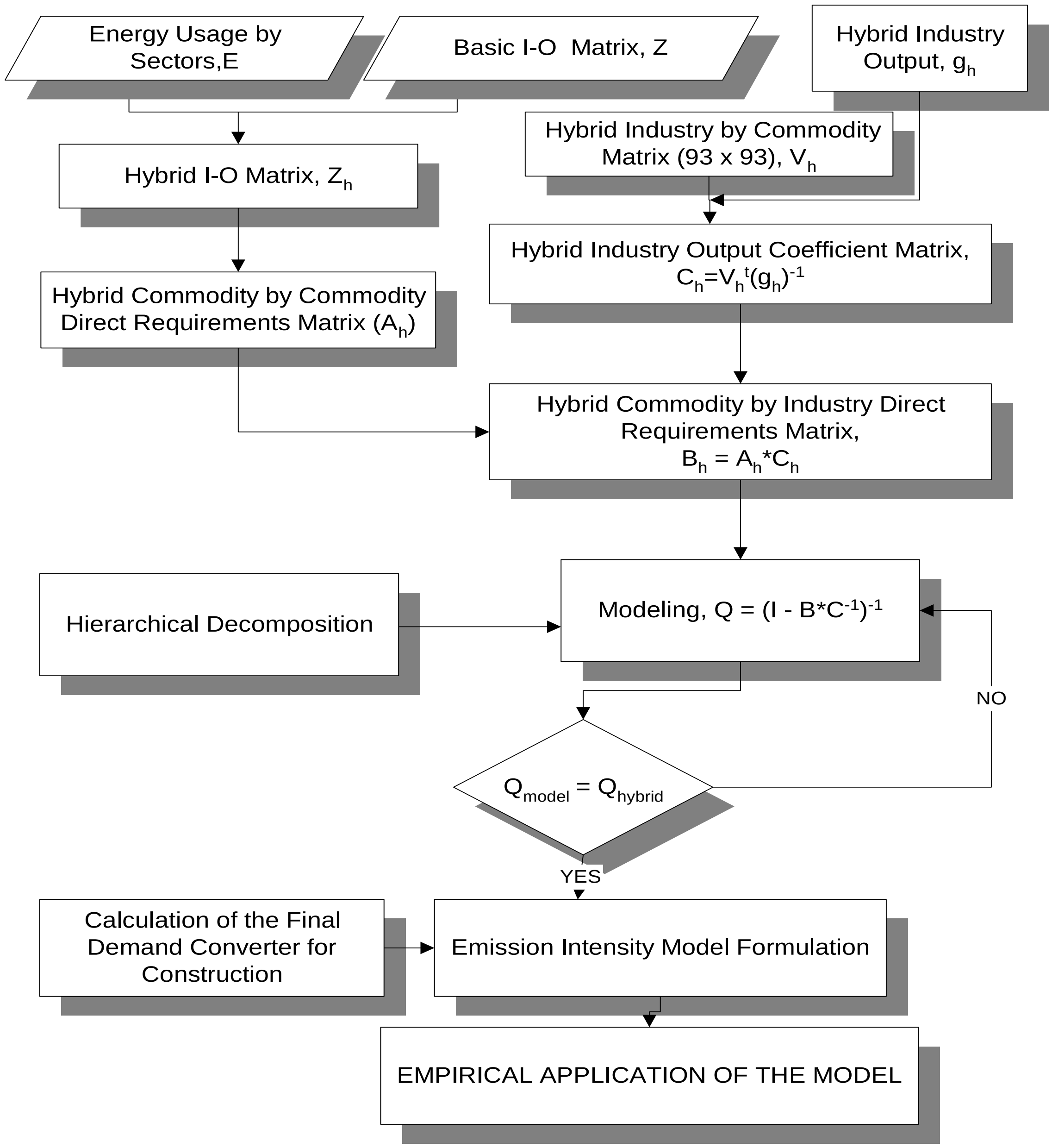

Figure 1. Study Flow.

Table 1. Six different decomposition schemes of the commodity and industry output

Equation No.	Decomposition Schemes		
(7) (8)	$q_1 \quad (I \quad L_0B_{es}C^{1})(I \quad L_1B_aC_{es}^{1})(I \quad L_2B_{cs}C_a^{1})(I \quad L_3B_{nc}C_{cs}^{1})(I \quad B_{nc}C_{nc}^{1})^{1} f$ $g_1 \quad (C^{1} \quad C^{1}L_0B_{es}C^{1})(I \quad L_1B_aC_{es}^{1})(I \quad L_2B_{cs}C_a^{1})(I \quad L_3B_{nc}C_{cs}^{1})(I \quad B_{nc}C_{nc}^{1})^{1} f$	$L_0 \quad (I \quad BC^{1})^{1} \quad L_2 \quad (I \quad B_aC_a^{1})^{1}$ $L_1 \quad (I \quad B_aC^{1})^{1} \quad L_3 \quad (I \quad B_{nc}C_a^{1})^{1}$	$B \quad B_{es} \quad B_a \qquad B_a \quad B_{nc} \quad B_{cs}$ $C^{1} \quad C_{es}^{1} \quad C_a^{1} \quad C_a^{1} \quad C_{nc}^{1} \quad C_{cs}^{1}$
(9) (10)	$q_2 \quad (I \quad L_0BC_{es}^{1})(I \quad L_1B_{es}C_a^{1})(I \quad L_2B_aC_{cs}^{1})(I \quad L_3B_{cs}C_{nc}^{1})(I \quad B_{nc}C_{nc}^{1})^{1} f$ $g_2 \quad (C^{1} \quad C^{1}L_0BC_{es}^{1})(I \quad L_1B_{es}C_a^{1})(I \quad L_2B_aC_{cs}^{1})(I \quad L_3B_{cs}C_{nc}^{1})(I \quad B_{nc}C_{nc}^{1})^{1} f$	$L_0 \quad (I \quad BC^{1})^{1} \quad L_2 \quad (I \quad B_aC_a^{1})^{1}$ $L_1 \quad (I \quad BC_a^{1})^{1} \quad L_3 \quad (I \quad B_aC_{nc}^{1})^{1}$	$B \quad B_{es} \quad B_a \qquad B_a \quad B_{nc} \quad B_{cs}$ $C^{1} \quad C_{es}^{1} \quad C_a^{1} \quad C_a^{1} \quad C_{nc}^{1} \quad C_{cs}^{1}$
(11) (12)	$q_3 \quad (I \quad L_0B_aC^{1})(I \quad L_1B_2C_a^{1})(I \quad B_{nc}C_{nc}^{1})^{1} f$ $g_3 \quad (C^{1} \quad C^{1}L_0B_aC^{1})(I \quad L_1B_2C_a^{1})(I \quad B_{nc}C_{nc}^{1})^{1} f$	$L_0 \quad (I \quad BC^{1})^{1} \quad L_1 \quad (I \quad B_{nc}C^{1})^{1}$	$B \quad B_a \quad B_{nc} \qquad B_a \quad B_{es} \quad B_{cs}$ $C^{1} \quad C_a^{1} \quad C_{nc}^{1} \quad C_a^{1} \quad C_{es}^{1} \quad C_{cs}^{1}$
(13) (14)	$q_4 \quad (I \quad L_0B\,C_a^{1})(I \quad L_1B_aC_{nc}^{1})(I \quad B_{nc}C_{nc}^{1})^{1} f$ $g_4 \quad (C^{1} \quad C^{1}L_0B\,C_a^{1})(I \quad L_1B_aC_{nc}^{1})(I \quad B_{nc}C_{nc}^{1})^{1} f$	$L_0 \quad (I \quad BC^{1})^{1} \quad L_1 \quad (I \quad BC_{nc}^{1})^{1}$	$B \quad B_a \quad B_{nc} \qquad B_a \quad B_{es} \quad B_{cs}$ $C^{1} \quad C_a^{1} \quad C_{nc}^{1} \quad C_a^{1} \quad C_{es}^{1} \quad C_{cs}^{1}$
(15) (16)	$q_5 \quad (I \quad L_0B_{cs}C^{1})(I \quad L_1B_aC_{cs}^{1})(I \quad L_2B_{es}C_a^{1})(I \quad L_3B_{nc}C_{es}^{1})(I \quad B_{nc}C_{nc}^{1})^{1} f$ $g_5 \quad (C^{1} \quad C^{1}L_0B_{cs}C^{1})(I \quad L_1B_aC_{cs}^{1})(I \quad L_2B_{es}C_a^{1})(I \quad L_3B_{nc}C_{es}^{1})(I \quad B_{nc}C_{nc}^{1})^{1} f$	$L_0 \quad (I \quad BC^{1})^{1} \quad L_2 \quad (I \quad B_aC_a^{1})^{1}$ $L_1 \quad (I \quad B_aC^{1})^{1} \quad L_3 \quad (I \quad B_{nc}C_a^{1})^{1}$	$B \quad B_a \quad B_{cs} \qquad B_a \quad B_{es} \quad B_{nc}$ $C^{1} \quad C_a^{1} \quad C_{cs}^{1} \quad C_a^{1} \quad C_{es}^{1} \quad C_{nc}^{1}$
(17) (18)	$q_6 \quad (I \quad L_0BC_{cs}^{1})(I \quad L_1B_{cs}C_a^{1})(I \quad L_2B_aC_{es}^{1})(I \quad L_3B_{es}C_{nc}^{1})(I \quad B_{nc}C_{nc}^{1})^{1} f$ $g_6 \quad (C^{1} \quad C^{1}L_0BC_{cs}^{1})(I \quad L_1B_{cs}C_a^{1})(I \quad L_2B_aC_{es}^{1})(I \quad L_3B_{es}C_{nc}^{1})(I \quad B_{nc}C_{nc}^{1})^{1} f$	$L_0 \quad (I \quad BC^{1})^{1} \quad L_2 \quad (I \quad B_aC_a^{1})^{1}$ $L_1 \quad (I \quad BC_a^{1})^{1} \quad L_3 \quad (I \quad B_aC_{nc}^{1})^{1}$	$B \quad B_a \quad B_{cs} \qquad B_a \quad B_{es} \quad B_{nc}$ $C^{1} \quad C_a^{1} \quad C_{cs}^{1} \quad C_a^{1} \quad C_{es}^{1} \quad C_{nc}^{1}$

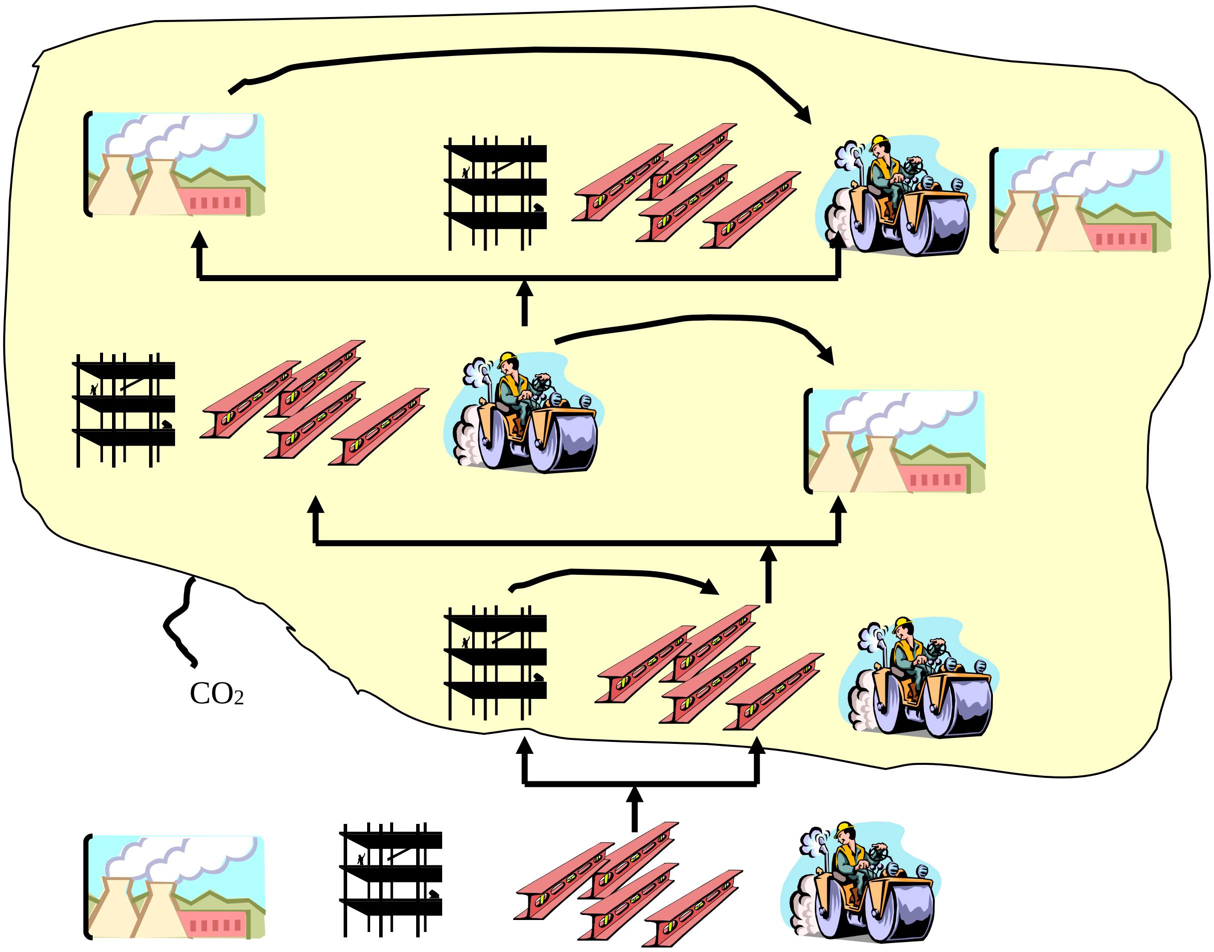

Figure 2. Model of the hierarchical decomposition

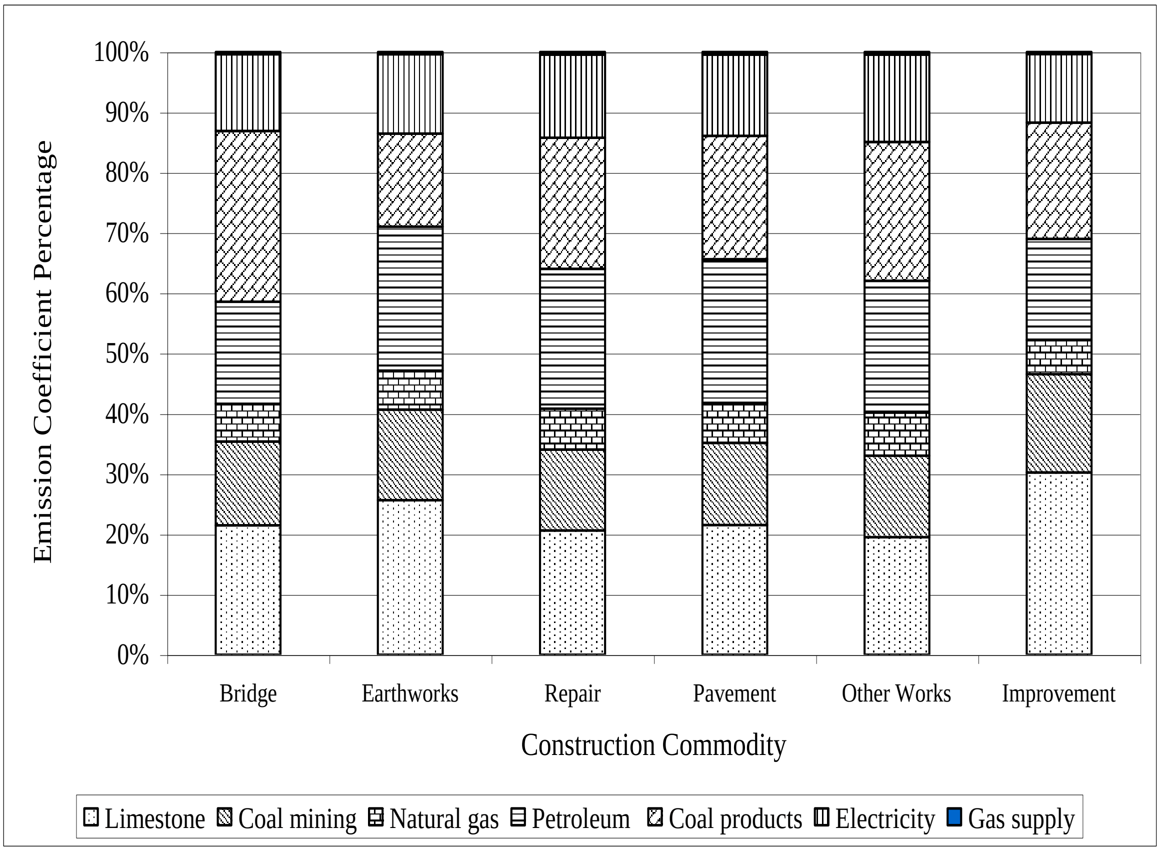

Figure 3. Total emission coefficient contributed by each energy supply sector to each construction commodity

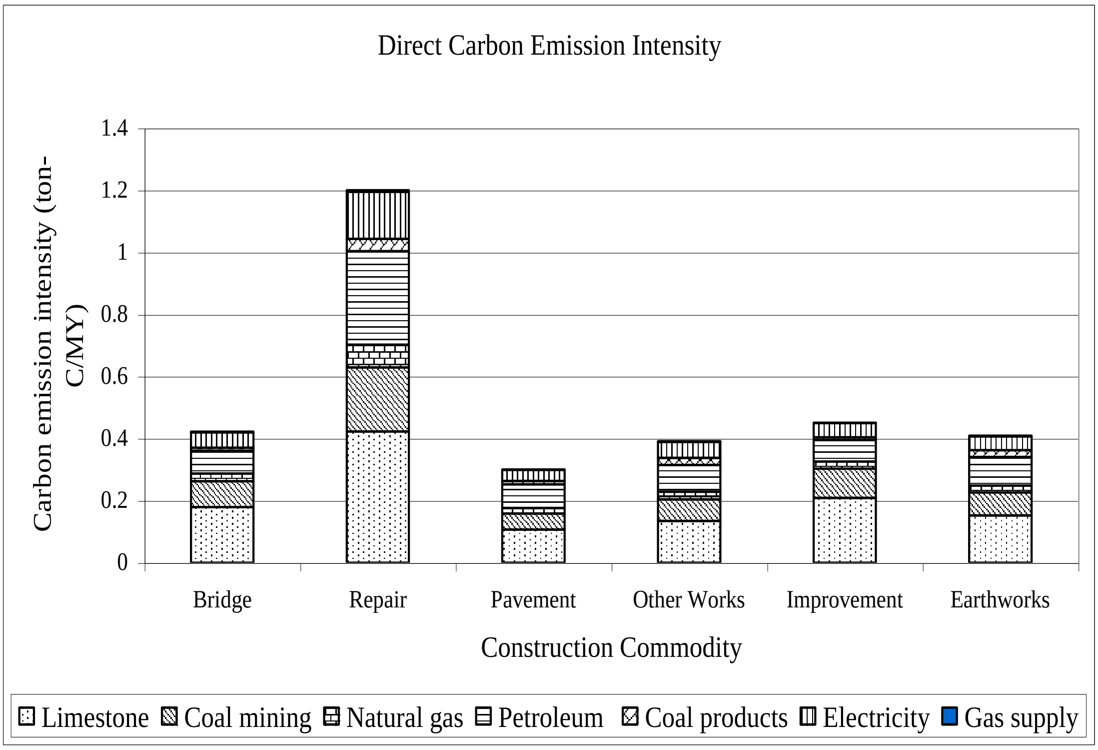

Figure 4. Direct emission coefficient contributed by each energy supply sector to the production of each construction commodity

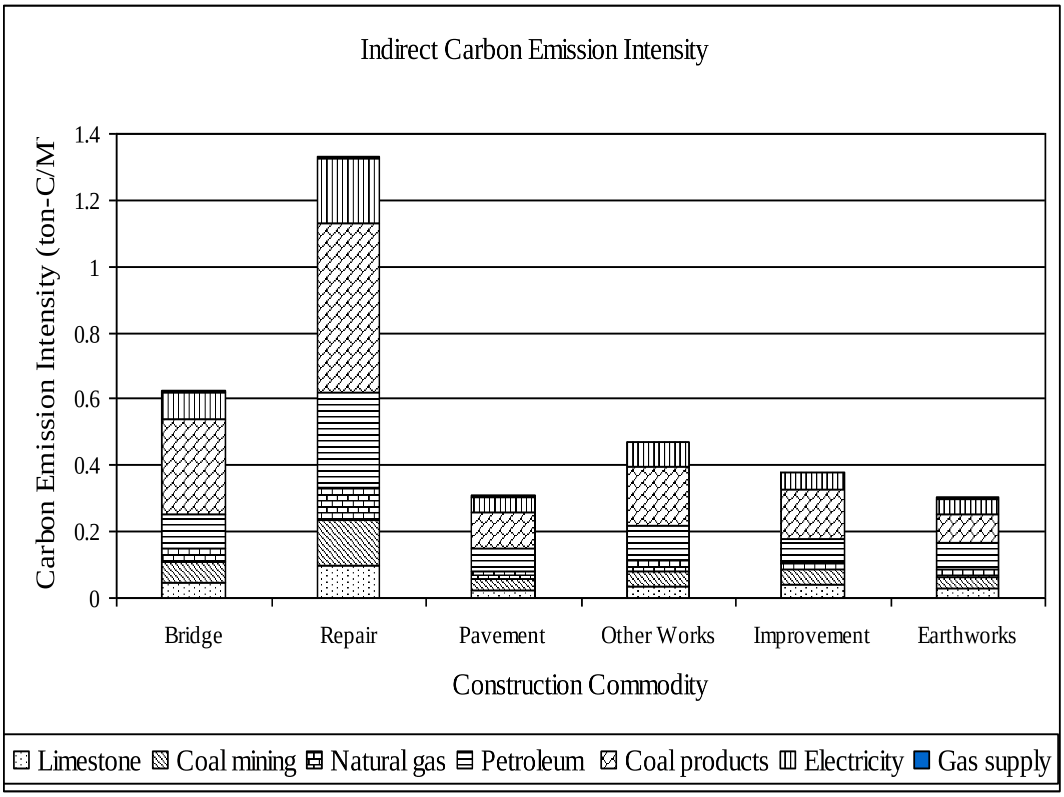

Figure 5. Indirect emission coefficient contributed by each energy supply sector to the production of each construction commodity

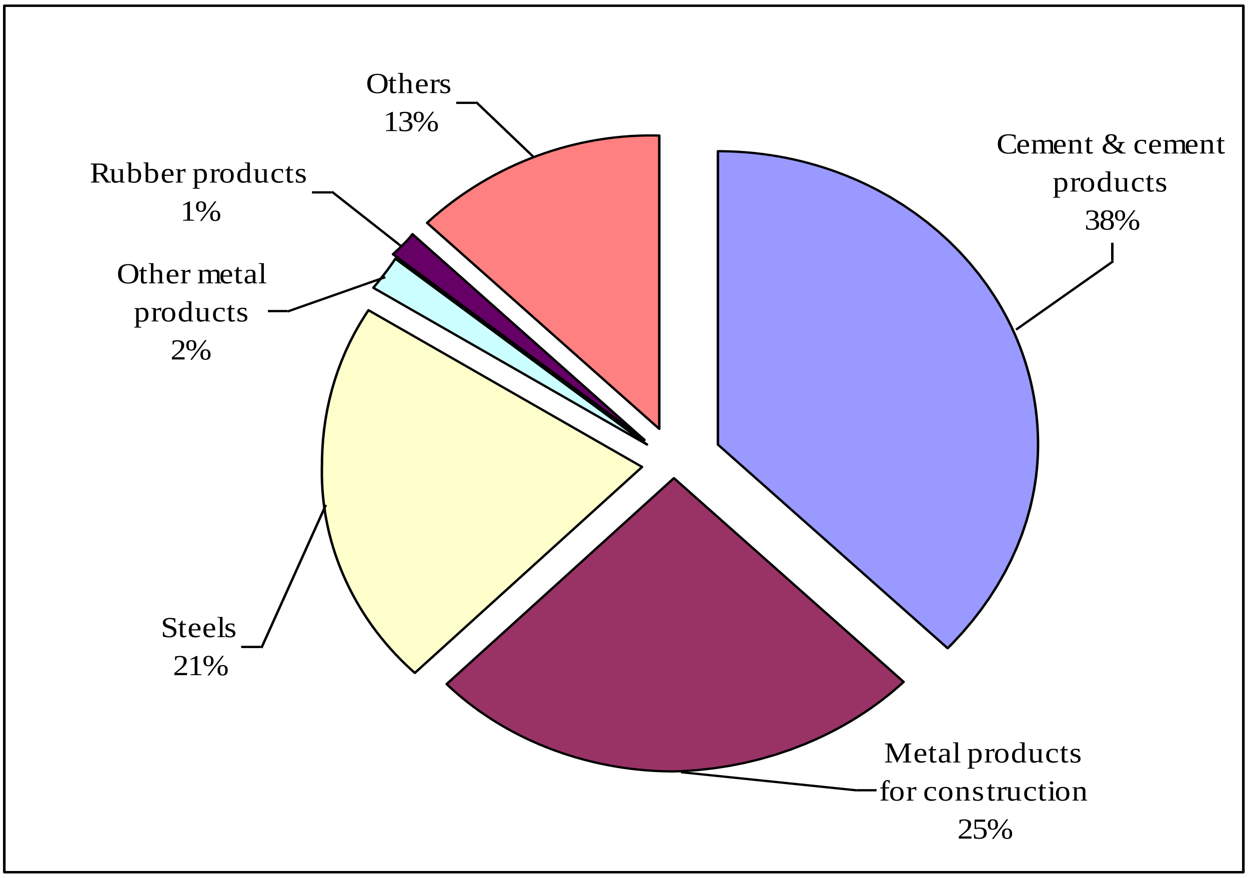

Figure 6. Main non-construction industry contribution to carbon emission intensity for Bridge works

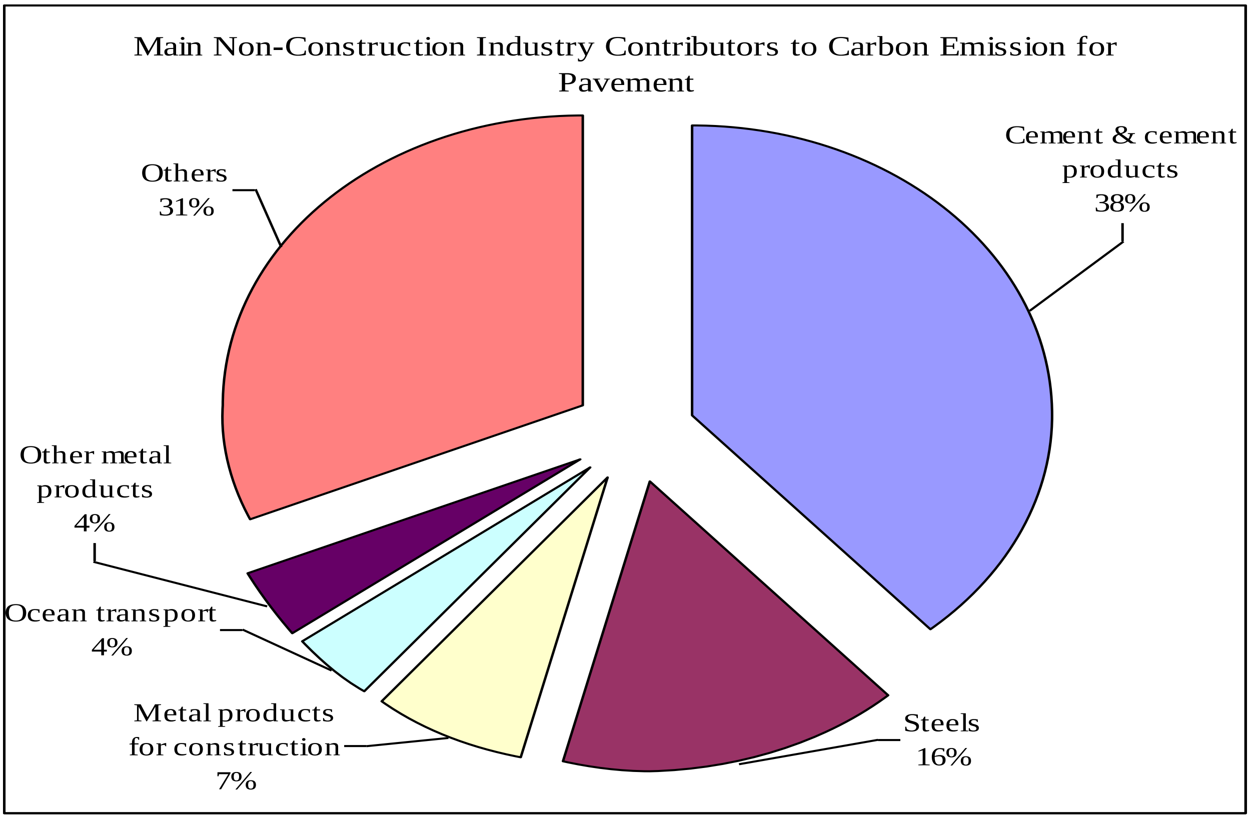

Figure 7. Main non-construction industry contribution to carbon emission intensity for pavement works

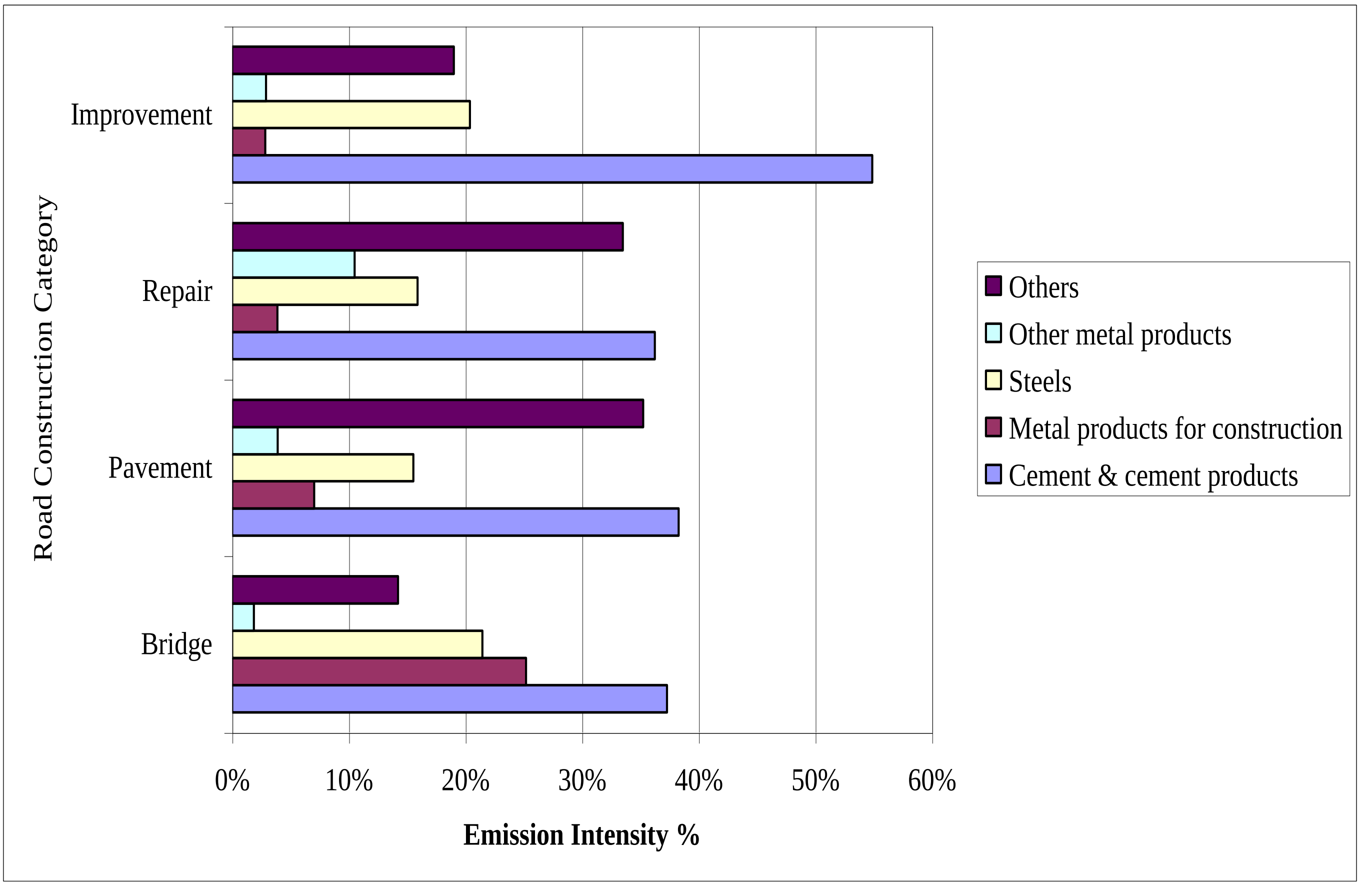

Figure 8. Comparison of the Main Non-Construction Industry contributions to emission

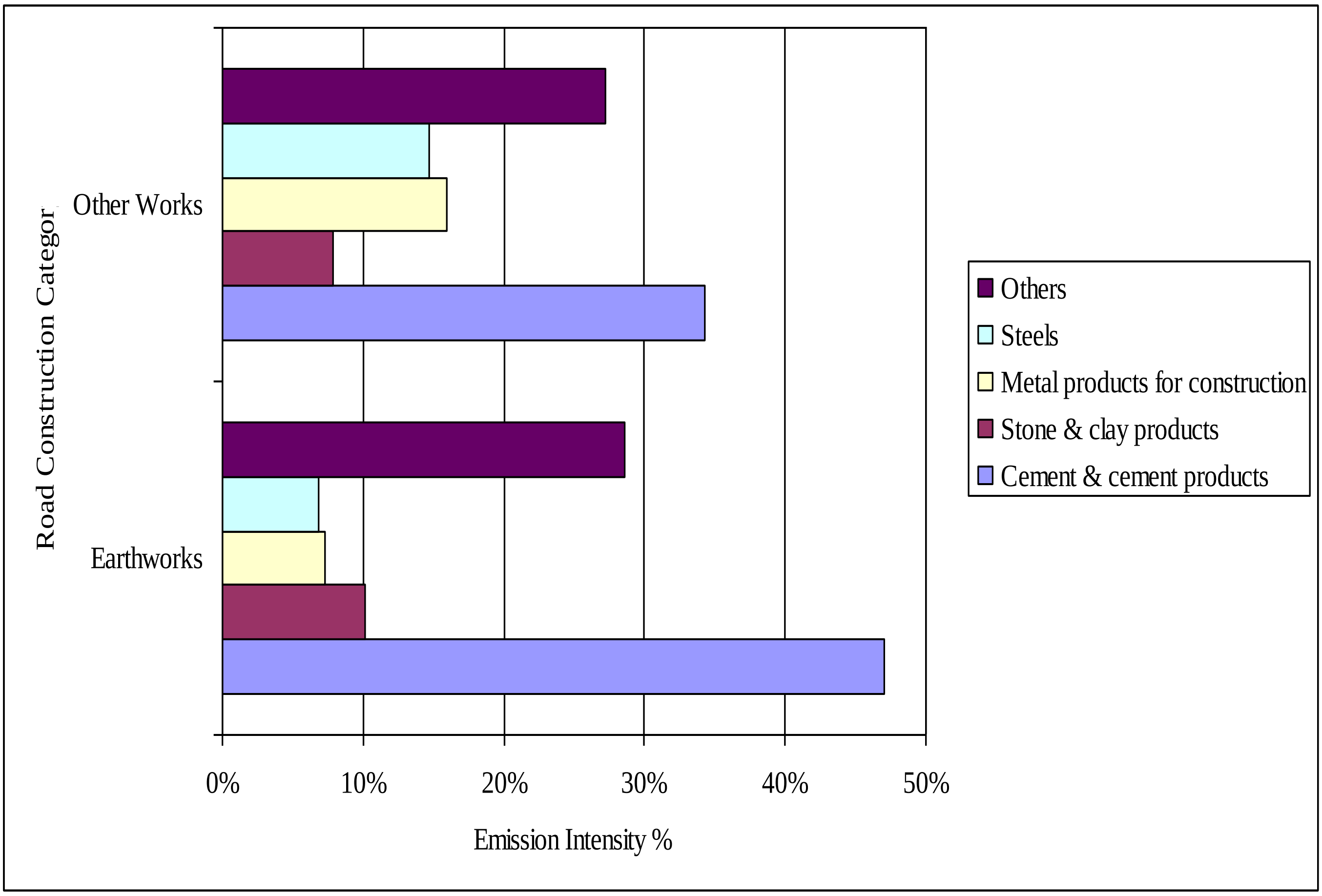

Figure 9. Comparison of the Main Non-Construction Industry contributions to emission for earthworks and other works