Preliminary study on the estimation of urban embodied emissions using case-based reasoning

S. Kang, G. Kang, H. Cho & K. Kang
School of Civil, Environmental & Architectural Engineering, Korea University, Korea

Abstract

As the urban population increases and embodied carbon emissions become more important, urban embodied emissions should also be considered. This study proposes the concept of urban embodied emissions and suggests an alternative for estimating the emissions using case-based reasoning (CBR). Among different types of CBR, we used statistical methods and developed cause–effect models. For cause features, we selected structures, uses and locations of buildings to consider materials used and transportation; for effect features, we selected embodied emissions from different phases of building. Life cycle embodied emissions of buildings were then computed to estimate embodied emissions of cities. Here, we applied additional dimensions, spatial and temporal, to describe the urban trend in region and time. This approach can be used to analyse the urban life cycle of embodied emissions.
Keywords: embodied emissions, urban life cycle, case-based reasoning, sustainable development.

1 Introduction

The importance of cities is increasing as population increases in urban districts. According to the United Nations report “World Urbanization Prospects: The 2014 Revision”, 54% of the world’s population live in urban areas, and this number is expected to increase to 66% by 2050 [1]. Much of the expected urban growth will take place in countries of the developing regions. As a result, these countries will face numerous challenges in meeting housing, infrastructure, transportation and energy needs. Buildings are among the most important sectors when investigating CO_2 emissions, as they are responsible for a significant amount of CO_2 emissions in cities [2]. Thus, this paper studies different types of CO_2 emissions from

WIT Transactions on The Built Environment, Vol 168, © 2015 WIT Press
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/SD150161

buildings in cities and suggests a simple alternative for estimating the embodied carbon emissions.

Carbon emissions are emitted by buildings during their entire life cycle: construction, operation, renovation, demolition and reconstruction. Since 1998, numerous studies have focused on analysing these emissions [3, 4] with the development of Life Cycle Analysis theory. Recently, embodied carbon emissions (ECO_2) from buildings have attracted interest and a number of studies have focused on carbon emissions from buildings during their operational phase, given that this phase accounts for a large proportion of CO_2 in a building's life cycle [5]. The focus of previous studies was on minimizing the final CO_2 in the operational phase, whereas CO_2 emissions in other phases were often neglected.

Because most carbon emissions result from human activities during a building's operation period, operational carbon emissions (OCO_2) are relatively easy to calculate from monthly utility bills or by using advanced energy simulation tools. Compared with the process of calculating OCO_2, determining ECO_2 impacts of construction accurately is difficult, because the sources of ECO_2 include numerous manufacturing and transporting activities such as chemical reactions and freight transport.

Innovations and technological advances for reducing OCO_2 such as zero energy balance [6] and passive houses [7] have emerged. Accordingly, OCO_2 have decreased and the proportion of ECO_2 has increased. Moreover, ECO_2 usually increase with a reduction in OCO_2 because of the increased amount of material use or energy demand for the complex processes for production [5].

Considering the growing interest in urban and embodied emissions, this study proposes an alternative for estimating urban embodied emissions based on the urban life cycle concept using case-based reasoning (CBR).

2 Embodied carbon emissions

According to Ibn-Mohammed *et al.* [5], ECO_2 may be divided into initial and recurring emissions. The initial embodied emissions (ECO_2-I) of buildings are the emissions incurred at the initial construction of the building. This represents the CO_2 emitted during the acquisition of raw materials, their processing, manufacturing, transportation to site, and construction. ECO_2-I can be further divided into direct and indirect emissions. Direct emissions are those related to transporting building products to the site and various on-site and off-site operations such as construction, prefabrication, transportation and administration. Indirect emissions are those incurred to acquire, process, and manufacture the building materials, including any transportation related to these activities. Because of the different procedures for estimating ECO_2, this study distinguishes between embodied emissions of transportation (ECO_2-T) and ECO_2-I, and defines ECO_2-T as emissions related to transportation from the whole life cycle of buildings.

An enormous variety of materials is used in building construction, and it may be the case that some of these materials have a shorter lifespan than the building. As a result, to rehabilitate the building, these materials are replaced. Moreover, buildings require regular maintenance to keep them in good condition. The emissions from these repairs and replacements should be accounted for during the entire life of a building. These emissions are termed recurring embodied emissions (ECO_2-R) in buildings and therefore represent the emissions incurred to maintain, repair, restore, renovate or replace material components during the effective life of a building.

The total life cycle emissions of a building are the sum of its embodied emissions and operational emissions. OCO_2 depend on the occupants, whereas ECO_2 depend on the types of materials used, primary energy sources and efficiency of conversion processes in making building materials and products [5]. Therefore, while OCO_2 accumulate over time and can be controlled throughout the effective life of a building, almost all ECO_2 are incurred once, namely, at the initial construction stage of buildings; the remainder are incurred during maintenance and renovation [5]. OCO_2 reduction could be more optimally accomplished with energy-efficient appliances, renewable energy technologies and advanced insulating materials, which are readily available. ECO_2 can be reduced either through optimization of the building fabric to reduce material use or through intelligent specification and selection of materials with a lower embodied carbon and energy intensity.

In this paper, we take a holistic approach that considers the whole life cycle of a building, but we exclude OCO_2 because of the ample relevant literature and improvements already available. Figure 1 describes the scope of this paper.

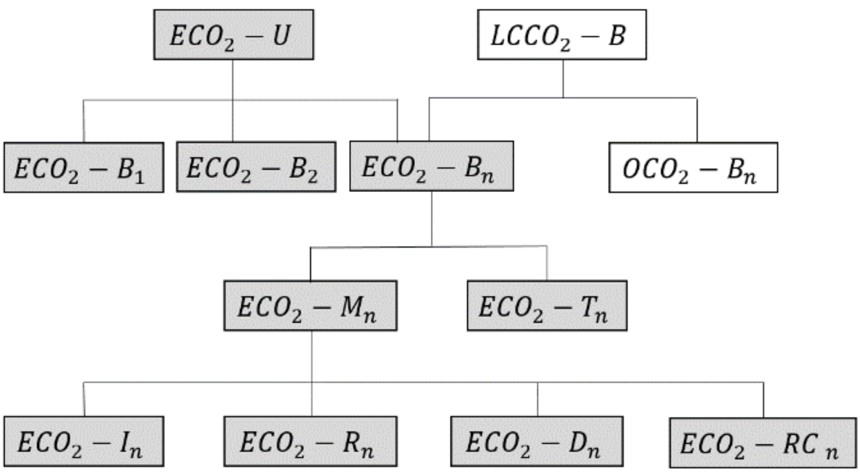

Figure 1: Carbon emissions hierarchy.

ECO_2-U is urban embodied emissions; $LCCO_2$-B is building life cycle carbon emissions; ECO_2-B and OCO_2-B are building embodied and building operational emissions, respectively; ECO_2-M and ECO_2-T are embodied emissions of manufacturing and transportation, respectively; ECO_2-I, ECO_2-R, ECO_2-D and ECO_2-RC are embodied emissions of initial, recurring, demolition and reconstruction, respectively.

3 Methodology for estimation of ECO2

3.1 Case-based reasoning (CBR)

There is currently no generally accepted method to compute embodied emissions accurately and consistently; therefore, wide variations in measurements are inevitable [5]. To estimate the ECO_2 of buildings, all materials that compose the building should be identified. However, this method is time-consuming and its accuracy is not reliable because the life cycle inventory database (LCI DB), which provides emission factors, does not include every material that is used in construction. In addition, there is no way to verify the estimation since there is no standard amount of ECO_2 with which it can be compared.

Another issue is that districts are commonly urbanized in regions and not in specific buildings. In the regional case, decision-makers are more interested in approximate rather than accurate emissions. Thus, there seems to be a demand to estimate the overall ECO_2 simply and quickly. In this paper, we propose an alternative for ECO_2 estimation.

CBR is a problem-solving method that can generate solutions for new situations based on previous similar cases [8]. CBR is generally composed of four steps: retrieving similar past cases from the case base, reusing the similar cases to infer a new effect to a given cause, revising the effect if necessary, and retaining the new effect in the original case base for future effect estimation.

In general, intelligent methods such as genetic algorithms can produce more accurate adaptation results than statistical methods [9]. However, the drawback of the former lies in the fact that a sufficient case database is needed in the process of case adaptation, which could involve expensive computational cost when working on datasets with large numbers of case attributes. Statistical methods are a relatively more suitable option for CBR adaptation than intelligent methods because they do not need abundant computational data and are good for small datasets with many parameters. Therefore, this paper used the weighted mean (WM) method as the basic model.

While some statistical methods use only most similar case as the candidate in the adaptation process and ignore the impacts of other useful similar cases, WM calculates the weighted average of the values of K similar cases. The performance of WM models strongly relies on the importance of similar cases for the new case. The similarity between existing cases and the new case can be described in a similarity matrix (SM). When it comes to the relationship matrix (RM), there has been little discussion on the effects of the mutual relationships between cause and effect features for the adaptation results. In Hu *et al.* [9], the problem–solution (PS) relationship was referred to in order to represent the relationship between input and output. In this study, we changed the previous model (PS) to a cause–effect (CE) relationship, so that we can better describe the relationship between features. In this paper, grey relational analysis (GRA) was used to convey this implicit knowledge. The advantage of GRA is its capability of solving complicated interrelationships between designated feature values and its ability to address problems involving poor, insufficient and uncertain information.

Our goal here is to integrate the CE relational information into the basic WM model to facilitate efficient case adaptation in the application of CBR. We call this model 'CBR of WM using GRA with CE relationship' (CWGCE). CWGCE not only considers the mutual relationships between cause and effect features, but studies the performance of the WM model, which was improved with CE relationship information. The major advantages of the CWGCE method are that the results are based on the original data and calculations are simple and straightforward.

3.2 Parameters for estimating ECO_2

Previous studies have produced different results of embodied emissions. These differences could be attributed to a number of factors such as the structure of the building being assessed, the uses of the building, the building materials used, construction methods employed and geographical differences. In this study, we selected 'structures', 'uses' and 'locations' of buildings as parameters because these parameters are strongly affected by materials and transportation. In South Korea, for example, recent building structures are mostly built of reinforced concrete (RC), and some are built of steel (S) or steel-reinforced concrete (SRC). Because these structures determine the main materials that compose the building, it is logical to state that the ECO_2 are affected by the structures of the buildings. In the same context, uses of buildings are also different in terms of materials used. For example, the finishing levels of housing and office buildings are different, and these levels also affect the amount of ECO_2. The locations of buildings are related to distance between quarry, storage, factory and construction site. In other words, a building at site A will have a different nearest quarry, storage and factory than a building at site B.

3.3 Maintenance rate and cycle

The process of accumulating data to create a database is an extremely complex and important process involved in the estimation of ECO_2. The process can be divided into material production and transportation. The source of data for material production was the LCI DB and the bill of quantities (BOQ). Selected ECO_2-I values for a number of materials were calculated by multiplying emission factors by the quantity of the material per gross floor area [10]. Equation (1) explains the ECO_2-I calculation process:

$$(\mathrm{ECO_2} - \mathrm{I}) = \mathrm{EF} \times \mathrm{QM}/\mathrm{GFA}, \tag{1}$$

where EF is the emission factor, QM is the quantity of a material and GFA is the gross floor area.

To calculate the materials' ECO_2-R values, the maintenance rate was multiplied by the ECO_2-I value. When the ECO_2-R value is multiplied by the frequency of maintenance, the result is the total maintenance emissions. The frequency of maintenance was calculated by dividing the observation period by the maintenance cycle. Equations (2) and (3) describe the ECO_2-R calculation process:

$$(ECO_2 - R) = (ECO_2 - I) \times MR \times FM, \tag{2}$$

$$FM = OP/MC, \tag{3}$$

where MR is the maintenance rate, FM is the frequency of maintenance, OP is the observation period and MC is the maintenance cycle.

To estimate the demolition emissions (ECO_2-D), the waste emission factor was multiplied by the quantity of the material per GFA. Equation (4) describes the ECO_2-D calculation process:

$$(ECO_2 - D) = WEF \times QM/GFA, \tag{4}$$

where WEF is the waste emission factor.

Finally, for reconstruction, we assumed that the embodied emissions from reconstructions (ECO_2-RC) were the same as the emissions from the initial construction, ECO_2-I. The difference would be the number of times reconstruction occurred, which is related to the reconstruction cycle. The number of reconstruction times (NRC) was calculated by dividing the OP by the persisting period (PP). Equations (5) and (6) describe the ECO_2-RC calculation process:

$$(ECO_2 - RC) = (ECO_2 - I) \times NRC, \tag{5}$$

$$NRC = OP/PP. \tag{6}$$

So far, we have considered the process concerning raw materials and products. In reality, transportation accounts for considerable amounts of ECO_2 [11]. For transportation, we need to know the total distance the material is transported and the fuel consumption per distance. The embodied ECO_2-T can be computed by multiplying these two parameters and the emission factor and by dividing the result by the GFA. Equation (7) describes the ECO_2-T calculation process:

$$(ECO_2 - T) = EF \times D \times FE/GFA, \tag{7}$$

where D is distance and FE is fuel efficiency.

3.4 Estimation of ECO_2

To estimate embodied emissions, we selected three “cause” features (structure, use and location) and five “effect” features (ECO_2-I, ECO_2-R, ECO_2-D, ECO_2-RC and ECO_2-T). Note that more than one type of ECO_2-R can be selected when multiple materials are involved. The reason we termed the features “cause and effect” rather than “problem and solution” was that the structures, uses and locations of buildings affect ECO_2 rather than solve them.

We then introduced a new case with a given structure, use and location. Next, we chose the number of similar cases that we would like to retrieve, which was three cases of buildings, see Figure 2 for example. After the numbers of features and cases were determined, the SM and RM were formed. SM describes the similarity between “cause” features of the existing cases and the new case. RM represents the strength of relationship between cause and effect features. Based on SM and RM, the intensity weighted mean (IWM) and the normalized weighted mean (NWM) could be constructed to demonstrate the impacts of different similar cases on effect feature adaptations. The calculation of IWM and NWM can be expressed as follows: IWM = SM × RM and NWM is the normalized IWM. Figure 2 illustrates the process. Finally, the effects of the new case can be calculated by $NWM^T \times CEM$ (case–effect matrix). Note that final ECO_2 must multiply the value by the gross floor area.

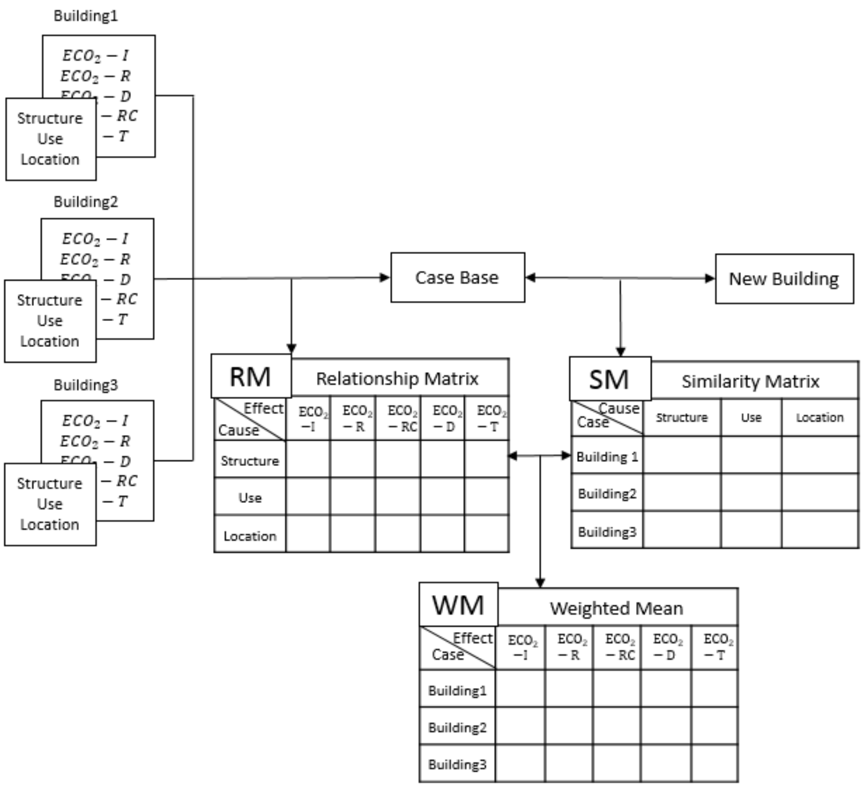

Figure 2: Estimation of ECO_2 using CBR.

3.5 Expression of urban carbon emission

Now that five effect features were computed, we could apply these figures to express the urban carbon emissions (ECO_2-U). To expand ECO_2-B to ECO_2-U, we could sum up ECO_2-B; however, if we simply sum up the ECO_2-B of multiple buildings, we would only estimate the total amount of ECO_2-U. Decision-makers are not only interested in the total ECO_2 value, but also in intermediate values, because sustainable construction with balanced carbon emission is valued. These values can be generated by adding two dimensions, spatial and temporal. By organizing the emission data in a regional time sequence, decision-makers can view the trend of the current and potential ECO_2 values of cities.

4 Conclusions

This preliminary study on estimating ECO_2 introduced the urban life cycle embodied emissions in two steps. First, the sum of the building life cycle embodied emissions was approximately the urban embodied emissions. Then, the urban life cycle embodied emissions were estimated through adding the spatial and temporal dimensions. This study could be integrated with other research, such as operational emissions or embodied emissions of infrastructures. These integrations will enable the estimation of complete building life cycle and urban life cycle of ECO_2. This holistic approach can express the distribution of ECO_2 and the outcome will have important implications when determining when and where to construct, renovate and reconstruct in terms of ECO_2. In the long run, this approach will lead to sustainable development by balancing the embodied emissions of cities.

Acknowledgement

This research was supported by a grant (code11High-tech UrbanG05) from the High-tech Urban Development Program (HUDP) funded by the Ministry of Land, Infrastructure and Transport of Korea.

References

[1] Department of Economic and Social Affairs, World Urbanization Prospects: The 2014 Revision, United Nations, New York, NY10017, US, 2014
[2] U.S.G.B.C., *Building and Climate Change*, www.usgbc.org
[3] Li X., Yang F. and Zhu Y. and Gao Y., An assessment framework for analysing the embodied carbon impacts of residential buildings in China, *Energy and Buildings,* 85, pp. 400-409, 2014
[4] Suzuki M. and Oka T., Estimation of life cycle energy consumption and CO_2 emission of office buildings in Japan, *Energy and Buildings,* 28(1), pp. 33-41, 1998
[5] Ibn-Mohammed T. and Greenough R. and Taylor S. and Ozawa-Meida L. and Acquaye A., Operational vs. embodied emissions in buildings-A review of current trends, *Energy and Buildings*, 66, pp. 232-245, 2013
[6] Ferrante A. and Cascella M. T., Zero energy balance and zero on-site CO_2 emission housing development in the Mediterranean climate, *Energy and Buildings*, 43(8), pp. 2002-2010, 2011
[7] Moran F., Blight T. and Natarajan S. and Shea A., The use of Passive House Planning Package to reduce energy use and CO_2 emission in historic dwellings, *Energy and buildings*, 75, pp. 216-227, 2014
[8] Guo Y., Hu J. and Peng Y., Research on CBR system based on data mining, *Applied Soft Computing*, 11, pp. 5006-5014, 2011

[9] Hu J., Qi J. and Peng Y., New CBR adaptation method combining with problem-solution relational analysis for mechanical design, *Computers in Industry*, 68, pp. 41-51, 2015

[10] Jung Y. S., A study on prediction model of carbon dioxide emission in life cycle for residential buildings, *University of Seoul*, 2010

[11] Department for Business Innovation & Skills, Estimating the amount of CO_2 emissions that the construction industry can influence, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/31737/10-1316-estimating-co2-emissions-supporting-low-carbon-igt-report.pdf