Estimating the Costs, Energy Use and Carbon Emissions of Concrete Recycling Using Building Information Modelling

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Abstract -

The economic and environmental benefits achievable through concrete recycling depend on many parameters including, but not limited to, travelling distances between demolished building and concrete recycling plant and/or landfills, prices of natural and recycled aggregates and the desired quality of the recycled aggregates which itself depends on a number of other parameters including the properties of parent concrete and the recycling procedure used. The overlapping effects of such parameters makes decision making about the selection of the concrete recycling strategy and appropriate level of recycling difficult. This paper presents a framework for assessment of costs, energy use and emissions incurred by adopting the concrete recycling strategy in a particular building project using the information made available by building information models. The estimated costs, energy use and emissions may be helpful in decision making about selection of the concrete recycling strategy in a particular project. An illustrative example is presented to highlight the potential benefits of the proposed method.

Keywords -

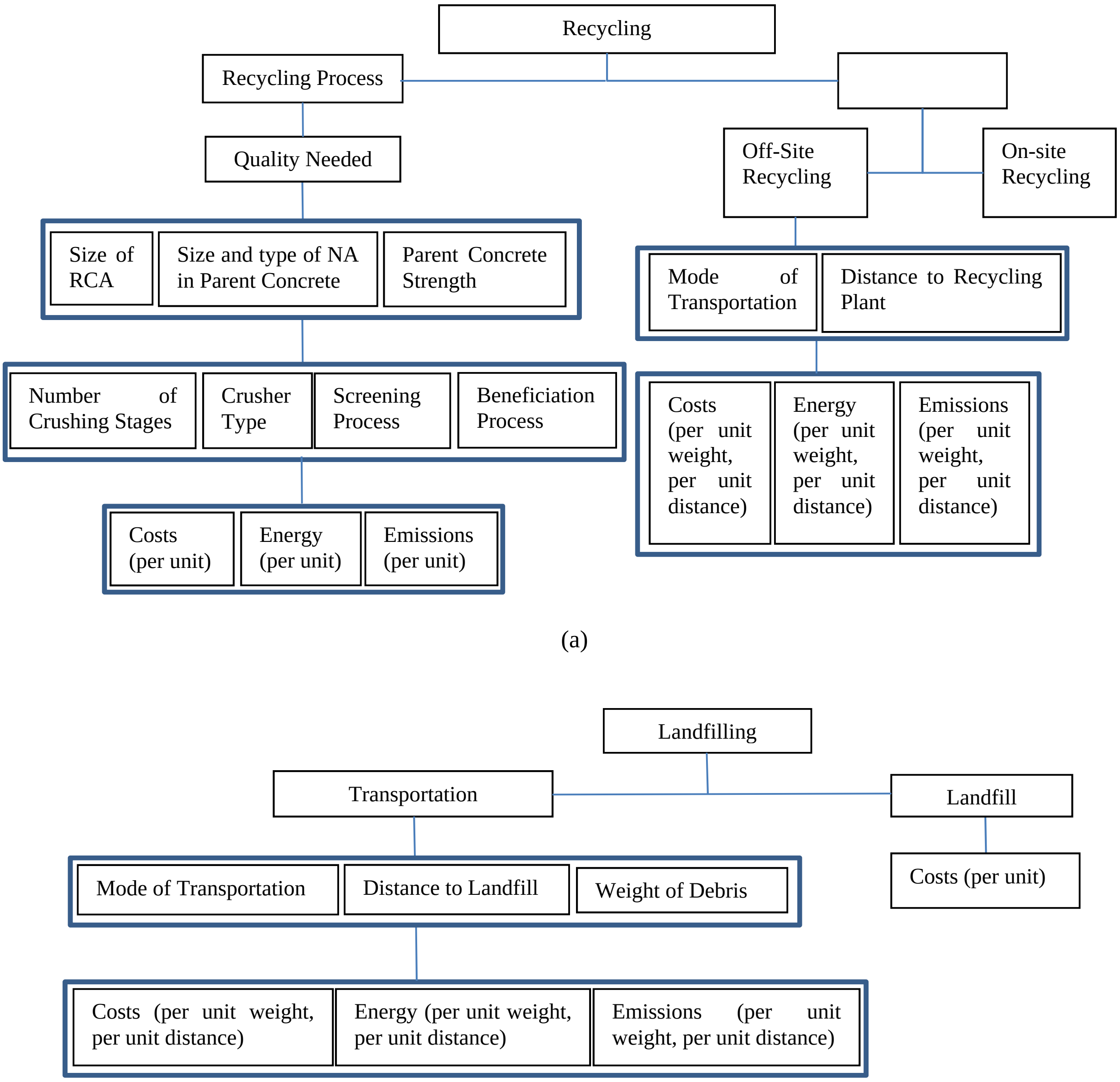
Building Information Modelling, Concrete, Recycling, Cost, Carbon

1 Introduction

Concrete recycling is considered as a sustainable alternative to traditional demolition and landfilling. Concrete recycling eliminates the need for the costly and energy intensive transportation to the usually remote landfills and reduces the need for the extraction of natural aggregates by converting the concrete debris to recycled concrete aggregates (RCA) [1]. However, an important fact that is often overlooked is that the recycling process involves a number of energy intensive operations including transportation between demolition site and recycling plant, breaking the large concrete chunks into smaller pieces that can be fed to the crushers, removal of non-concrete impurities and reinforcing bars, multiple crushing stages, possible beneficiation stages and sieving which may result in significant costs, energy use and carbon emissions.

The energy and carbon implications of concrete recycling have been investigated in a number of recent studies [2]. However, the average embodied energy and carbon reported in such studies have been mainly estimated through life cycle analysis of a particular recycling procedure and may not be a good representative of the recycling process required to achieve a particular RCA quality in many projects. The recycling process used in practice varies widely from a recycling plant to another and depends highly on the expected quality of the RCA products. There is always a tradeoff between the quality of RCAs and the costs and energy use of the recycling process. The quality of RCAs and thus their future application depend on a number of parameters including the properties of parent concrete and the recycling procedure [1]. As a result of the variation in the nature, sequence and number of the operations required to achieve a particular desired quality of RCA, any generalization on the costs, carbon and energy implications of the recycling process should be avoided.

Besides the costs and emissions incurred by the recycling operations, the economic and environmental impacts of concrete recycling strategy are influenced by many other project specific parameters including the distance to the landfills available, distance to the recycling plant, price and embodied energy of the alternative sources of natural aggregates available, amount of the concrete debris, etc. Therefore, assessment of carbon and energy implications of concrete recycling using the average values reported in available literature seems unrealistic. The objective of present study is to develop a framework and methodology for estimating the costs, energy use and associated emissions of the concrete recycling and conventional landfilling strategies by considering the project specific conditions and requirements. The estimated costs, energy use and emissions may be helpful in decision making about selection of the concrete recycling strategy in a particular project. A computer application was developed to automatically assess the economic and environmental impacts of the “concrete recycling” and conventional “demolition and landfilling” strategies using the information imported from building information models (BIM). An illustrative example is presented to highlight the potential benefits of the proposed method.



(a)

(b)

Figure 1. Important parameters to be considered in estimating the economic and environmental impacts of a) concrete recycling strategy b) demolition and landfilling strategy

2 Methodology

2.1 Identifying the Required Recycling Process to Achieve Desired RCA Quality

All the operations involved in concrete recycling process consume energy and thus lead to carbon emissions. The important parameters (operations) contributing to the economic and environmental impacts of the “concrete recycling” strategy are summarized in Figure 1a. As shown, besides the effects of the demolition operation which is common between the landfilling and recycling strategies, the impacts of concrete recycling strategy can be generally divided into two general groups; impacts of the recycling operations and impacts of transportation. The costs, energy use and emissions incurred in the recycling process depend basically on the operations used in a particular recycling plant. The type and sequence of the operations involved in the recycling process are basically a function of the quality of the RCA needed as well as the properties of the concrete debris available. The parent concrete properties and information on the availability of various local recycling technologies can be used to identify the recycling procedure needed to achieve a desired RCA quality. In this study, a computer application was developed to identify the required recycling operations to achieve the expected RCA quality for a given set of parent concrete properties (input by user or imported from BIM), the expected density (water absorption) of the recycled concrete aggregates or the expected maximum reduction in strength of the new concrete to be made with RCAs (referred to as recycled aggregate concrete (RAC)). The algorithm used was based on the experimental results reported in references [1, 3]. Similarly, to estimate the economic and environmental impacts of conventional demolition and landfilling strategy for comparison and decision making purposes, the main parameters affecting the costs, energy use and emissions in this strategy should be identified. These parameters are summarized in Figure 1b. These are on the top of the economic and environmental impacts of demolition.

2.2 Estimation of the Costs, Energy use and Emissions of Individual Operations

In the next step, the costs, energy use and associated emissions of individual recycling operations are estimated. The procedure used is summarized in Table 1. The input data for estimating the actual costs, energy use and associated emissions of a particular operation include the price, embodied energy and embodied carbon of the equipment, service life of the equipment and the estimated production rate of recycling plant. The embodied energy and embodied carbon of equipment refer to the energy use and the associated carbon emissions, respectively, incurred during the manufacturing process, transportation and installation of the equipment and can be estimated through life cycle analysis. Present study assumes that such information is made available by equipment manufacturers or can be obtained from available life cycle inventories. In the present study, a database was created to store price, energy, carbon, and service life information for the machineries commonly used by the local recycling plants and demolition contractors. The costs, energy use and carbon emissions incurred in the recycling process were then estimated using the methodology described in the following.

Table 1. Estimating the costs, energy use and carbon emissions of the various operations involved in concrete recycling

Input Information Required	**Parameters Estimated using the Input Info**	**Analysis Output**
Original value: • Cradle to site embodied energy and embodied carbon of equipment • Purchase price of equipment	Depreciation in the embodied energy value, embodied carbon value and economic value of equipment per tonne RCA production.	✓ Overall energy use per tonne RCA production ✓ Overall emissions per tonne RCA production ✓ Overall costs per tonne RCA production
Service life of the equipment		
Salvage Value: Residual economic value, embodied energy and embodied carbon of equipment at the end of service life		
Energy consumption of equipment per tonne RCA production	Operational costs, energy use and emissions of equipment per tonne RCA production.	
Emissions of equipment per tonne RCA production		
Energy tariff		
Estimated maintenance costs of equipment		

The energy use of the recycling process is estimated as:

$$\mathrm{ER} = \left(\sum_{i=1}^{n} \mathrm{EU_i} + \mathrm{DEE_i} \right) \times \mathrm{W} \qquad (1)$$

Where, ER is the total energy consumed in production of W ton of RCA, $\mathrm{EU_i}$ is the operation energy used by equipment number i, n is the total number of the recycling operations and $\mathrm{DEE_i}$ is the predicted depreciation in the embodied energy of the equipment i when used to produce 1 ton of recycled concrete aggregate. Similarly one could derive similar expression for the associated carbon emission and costs of the recycling process as follows:

$$\mathrm{CR} = \left(\sum_{i=1}^{n} \mathrm{C_i} + \mathrm{DEC_i} \right) \times \mathrm{W} \qquad (2)$$

$$\mathrm{CoR} = \left(\sum_{i=1}^{n} \mathrm{Co_i} + \mathrm{DEV_i} \right) \times \mathrm{W} \qquad (3)$$

Where, CR and CoR are respectively the carbon emissions and costs incurred by the recycling process to produce W tonne of RCA, C_i and Co_i are respectively the carbon emissions and costs incurred to operate the equipment/machine i in the recycling plant (per tonne production of RCA), DEC_i and DEV_i are respectively the predicted depreciation in the embodied carbon and economic value of the respective equipment when used to produce 1 tonne of recycled concrete aggregate, i is the number associated with each equipment and n is the total number of the equipment used to produce RCA in the recycling plant.

Various depreciation methods may be used to estimate the depreciation in the embodied energy, embodied carbon and economic value of the equipment per ton production of RCA. The method used in the present study is based on the estimated production capacity of the equipment during its service life, the salvage value (economic value, embodied carbon and embodied energy of the salvaged equipment) and the initial value (economic value, embodied carbon and embodied energy) of the equipment. The depreciation in the embodied energy value, embodied carbon value and economic value of equipment due to production of 1 ton of RCA may be estimated using the following equations:

$$DEE_i = \frac{(EE_i - SEE_i)}{TSLP_i} \qquad (4)$$

$$DEC_i = \frac{(EC_i - SEC_i)}{TSLP_i} \qquad (5)$$

$$DEV_i = \frac{(EV_i - SEV_i)}{TSLP_i} \qquad (6)$$

Where, EV_i, EE_i and EC_i are respectively the initial economic value, embodied energy and embodied carbon of equipment i and SEV_i, SEE_i and SEC_i are respectively the salvage economic value, embodied energy and embodied carbon of equipment i. $TSLP_i$ is the estimated total amount of RCA producible through the service life of the respective equipment (in tons). The embodied energy, embodied carbon and economic values of various equipment can be estimated using various local and international inventories available and are occasionally made available by the manufacturers. The salvage embodied carbon and embodied energy of equipment is estimated by taking into account the potential use for the salvaged equipment at the end of its service life.

Once the costs, energy use and emissions of individual operations have been estimated, the respective total values for recycling strategy (and/or demolition and landfilling strategy) can be then estimated by adding up those incurred in the individual operations involved. The methodology used in the present study to obtain the required information to perform such calculations is presented in the following section.

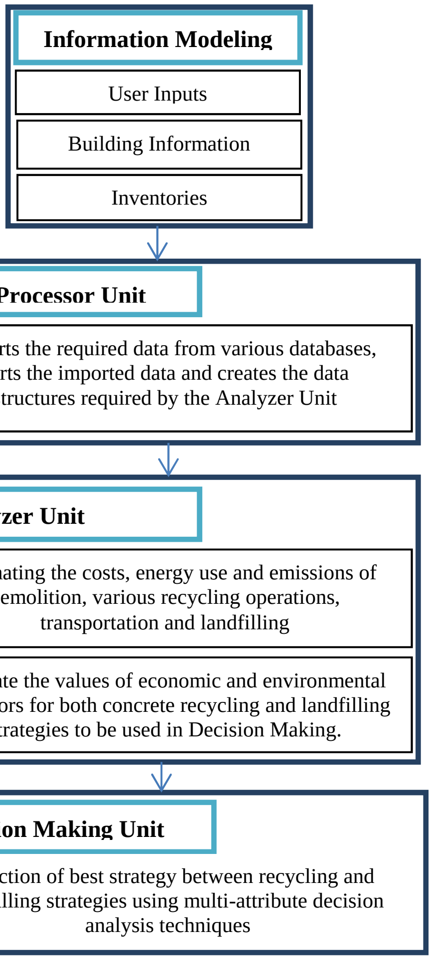


Figure 2. The four main components of the concrete recycling analyzer unit

3 Data Gathering and Analysis

The main components of the framework and the economic and environmental assessment tool developed in the present study are shown in Figure 2.

The *Information Modelling Unit* is responsible for making available the information required for the economic and environmental analysis. The main components of this unit include building information models (BIM), costs, energy and carbon database, location database and user interface (Figure 3). The subunits of the information modelling unit are briefly described in the following.

Structural BIM subunit: Typical structural detailing BIM models created in state-of-the-art structural BIM software contain information that can be useful in economic and environmental analysis of concrete recycling strategy. These may include properties of the parent concrete, amount of the recyclable concrete available, location of the building and any other information related to the special considerations such as potential hazards and contamination. Such information can be added manually by building designers or imported automatically from components libraries used frequently by the design team.

Cost, Energy and Carbon (CEC) Database: This database provides the information required to estimate the overall cost, energy consumption and emissions incurred by the recycling operations and transportation of debris to the recycling plant. The information stored in this database includes the unit cost, energy use and emissions incurred by various recycling operations including crushing, conveying, sieving, etc. In addition, this database includes information on the present market price of RCA and natural aggregates and the costs, energy use and emissions incurred by various modes of transportation.

Location and Technology (LT) Database: The framework and tool developed in the present study uses the geographic coordinates of the building defined in the building information model and the geographic coordinates of the recycling plants from the location database to calculate the travelling distances required to estimate the costs, energy use and emissions incurred by transportation.

In addition, the location and technology data base used in the present study includes information on the equipment available in the various local recycling plants listed in the database.

The *data processor unit* developed in this study imports the selected data from the structural information models, costs, energy and carbon databases and the location database, sorts out these data and creates the required data structure which can then be used by the analyzer unit to perform various economic and environmental analyses. In this study, a pilot Analyzer Unit (programmed in Visual Basic) was developed and used to perform the economic and environmental analyses (Figure 4). In the first step, the analyzer unit uses the input information on the required quality of RCA, strength of the parent concrete and size of the aggregates in the parent concrete to estimate the number of the crushing stages required to achieve the required quality. At the same time, based on the information available in the "location and technology database", the possibility of using the RCA beneficiation technologies based on the availability and various operation alternatives are identified. In the second step, the analyzer uses the information imported from the building information model including the dimensions of the elements, number of the similar elements in the model and the size and number of the reinforcing rebar to estimate the total amount of the recyclable concrete and recyclable reinforcing rebars available. If the strength of parent concrete varies in the model, the quantities of concrete are grouped into different groups requiring different recycling operations to achieve the required quality.

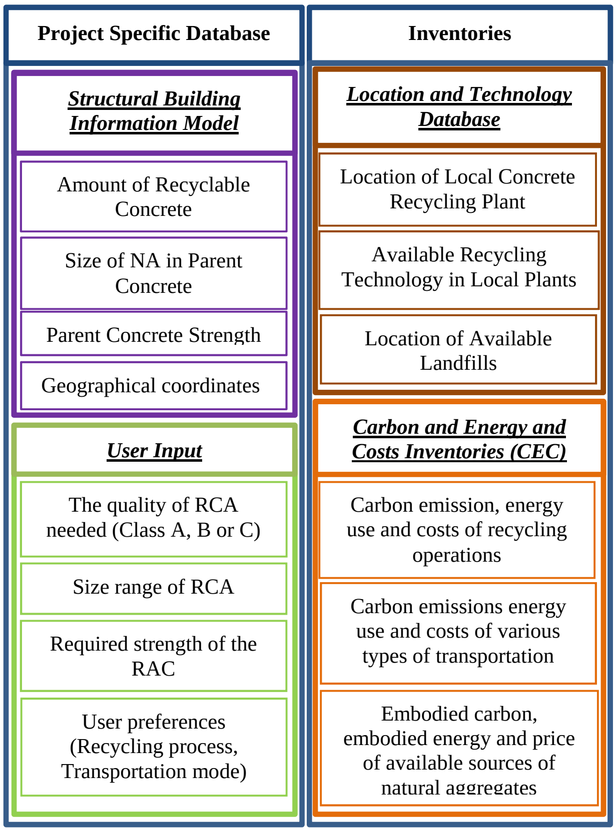


Figure 3. Components of the Information Modelling Unit

In the third step, the analyzer unit uses the information made available by the CEC database including the unit costs, energy use and emissions of the individual operations (as imported from inventories), the information on the recycling operations required as determined in the first step and the estimated amount of the recyclable concrete and steel calculated in the second step to estimate the overall costs, energy use and emissions associated with the recycling process. In the fourth step, the analyzer uses the information made available by the location and technology database to estimate the transportation distance required and to identify the mode of transportation based on the options available. Next, the unit costs, energy use and emissions of the selected mode of transportation are identified from the CEC database. These values and the estimated amount of the recyclable materials estimated in step 2 are used to estimate the economic and environmental impacts of the transportation. The overall impacts are then estimated by the adding up the impacts of the recycling process and the transportation. To estimate the costs, energy use and emissions of the landfilling operation, the transportation distance is calculated using the information provided by the LT database. The amount of the materials as estimated in the step 2 and the unit values of costs, emissions and energy use of transportation looked up from the CEC database are then used to estimate the economic and environmental impacts due to the transportation to landfill.

4 Case Study

The case project considered in the present study is a commercial-residential building with the total site area of 25170.398 m^2 constructed using a fully precast concrete structure system with the 3D model shown in Figure 5. The structure was modelled in Tekla Structures BIM software. It was assumed that all the structural concrete used had a 28 compressive strength of 30 MPa and were made using granite aggregates with a maximum size of 20 mm. As shown in the proposed framework such information are crucial to estimate the quality of the recycled aggregates produced using a particular recycling process. It was also assumed that owners require any recycling strategy to produce RCAs which are suitable for use in structural concrete at a NA replacement percentage of at least 50% while limiting the strength reduction of the new concrete with respect to the concrete made with 100% natural aggregates to less than 10%. This information was

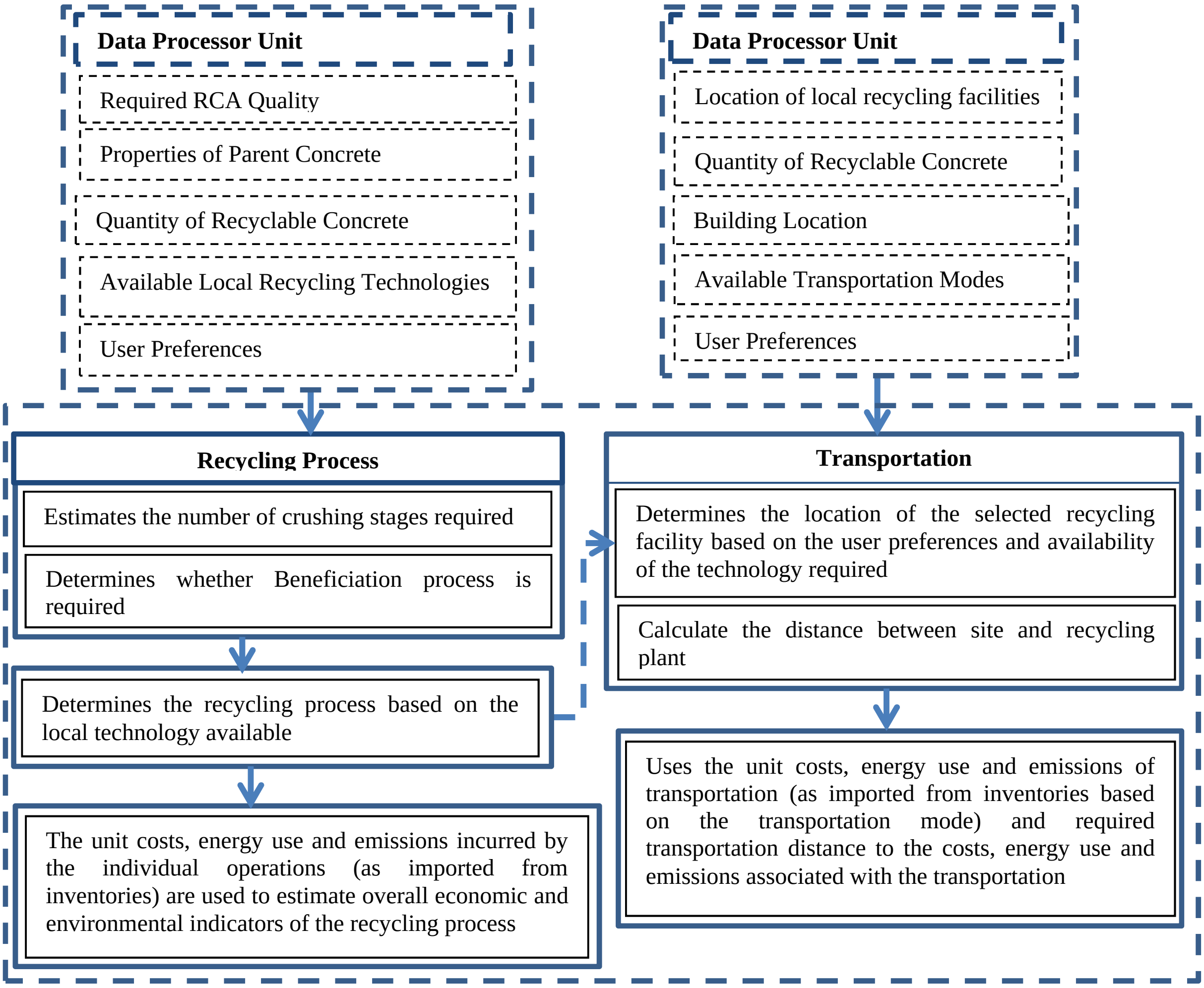


Figure 4. The analyzer unit

used by the computer algorithm developed in this study to identify the recycling operations required to achieve the desired quality. The transportation distances to the recycling plant and landfills were assumed to be 10 km and 50 km, respectively. The transportation was assumed to be performed by a fleet of 10 ton and 5 ton motor Lorries.

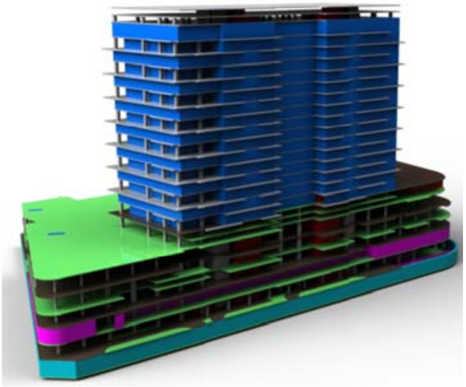
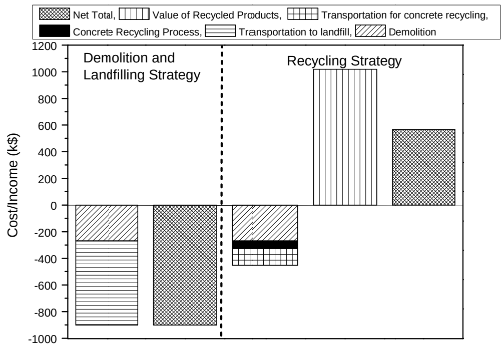


Figure 5. 3D representation of the case building modeled in Tekla Structures

The results of the economic and environmental analyses performed based on our proposed framework are presented in Figures 6, 7 and 8. Figure 6 shows the costs incurred during various stages of "recycling" and "landfilling" strategies as well as the earnings through the sale of recycled products in the concrete recycling strategy. The earnings were calculated by estimating the total volumes of coarse and fine recycled aggregates producible by considering the estimated yield of the recycling process and multiplying the estimated volume of each size fraction of RCA by its estimated market price. The steel rebars were assumed to be sold at the market price for the steel scraps. The demolition costs were estimated by calculating the total volume of concrete to be demolished using quantity takeoffs from BIM and multiplying the latter by the unit cost of demolition using the user-selected demolition method. Similar method was applied to estimate the energy use and emissions incurred during the building demolition.

As can be seen in Figure 6, the costs incurred by various concrete recycling operations including breaking, crushing, sieving and conveying accounted for about only 12.5% of the total costs of the recycling process whereas demolition and transportation accounted for about 59.5% and 28% of the total recycling costs. This indicates that the recycling process is not the main cost factor even when relatively more sophisticated recycling operations are used to produce higher quality RCAs (suitable for up to 50% replacement in structural concrete). Therefore, production of high quality RCAs through the use of relatively costlier recycling operations should be considered as a potential strategy.

As can be seen in Figure 6, while the demolition costs are relatively similar for concrete recycling and landfilling strategies, the longer travelling distance to the landfill than to recycling plant, as assumed in this case study, resulted in considerably higher transportation costs in the landfilling strategy. As shown, while the transportation costs accounted for almost 28% of the total costs in the recycling strategy, this figure was about 70% in the landfilling strategy. In general, transportation is also one of the most important factors contributing to the economic and environmental impacts of the concrete recycling and landfilling strategies. Therefore, transportation requirements may be considered as an important decision criteria for selection of the optimal deconstruction strategy for dealing with the concrete debris.



*It is assumed that steel scraps are sold to the recycling plant.

The income from the sale of steel scraps has been considered in evaluating the value of the recycled products.

Figure 6. Costs incurred by concrete recycling and landfilling strategies.

As shown, for the case project considered in the present study, the recycling process seemed to result in about 50% lower costs compared to the demolition and landfilling strategy. However, it should be noted that the costs of the recycling strategy can increase considerably if the concrete debris have to be transported for long distances due to the unavailability of local recycling plants.

Another interesting point to be noticed in Figure 6 is the considerably high revenues achievable from the sale of recycled and recyclable products including the RCAs and steel rebars. As shown, such revenues can easily exceed the costs of recycling and may serve as a source of considerable income to the project owners. As shown, in this case study, the significant earnings from the sale of steel scraps and RCA outweighed the costs and resulted in a positive total net economic impact for the concrete recycling strategy.

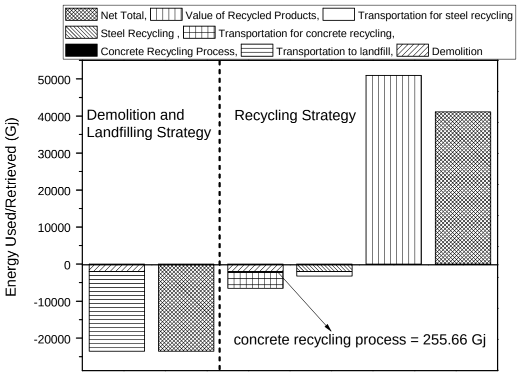


Figure 7. Energy use incurred by concrete recycling and landfilling strategies.

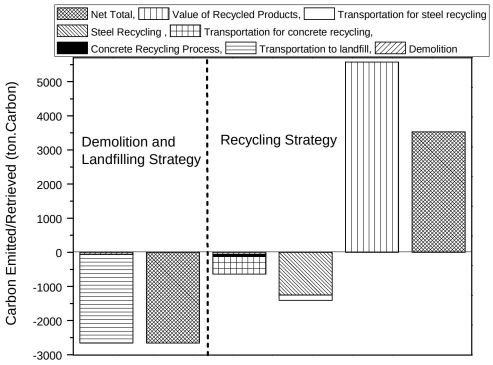


Figure 8. Carbon emissions incurred by concrete recycling and landfilling strategies.

Similarly, Figures 7 and 8 clearly show the benefits of the recycling strategy in terms of energy and carbon implications as compared to the demolition and landfilling strategy. Again, transportation was observed to be a determining factor affecting the overall energy use and associate emissions of both strategies. As a result of the relatively high emissions of land transportation, the contribution of the transportation to the overall energy use and carbon emissions of the recycling strategy in our case study was estimated to be about 65% and 81%, respectively. These figures are considerably than the 28% contribution of the transportation to the costs. This again highlights the importance of the transportation as an important decision parameter in selection of the concrete recycling strategy. The contribution of concrete recycling operations to the energy use and emissions of the recycling strategy were even lower than its contribution to the costs and were about 4% and 9.5%, respectively. This again suggests that producing high quality recycled aggregates through the use of more sophisticated recycling operations may make environmental sense in many projects.

Results presented in Figures 7 and 8 show that a significant amount of energy and carbon can be retrieved in the form of recycled products. As shown, by considering the embodied carbon and embodied energy value of the recycled products achievable, the benefits of the concrete recycling strategy in terms of energy and carbon emissions are appealing. The carbon and energy retrievable by recycling of aggregates were calculated by considering the amount of the RCAs producible at a particular quality level and multiplying the latter by the respective embodied energy and carbon values of original aggregates of relatively similar quality.

The results of this case study clearly show that the carbon costs, energy use and carbon emissions of concrete recycling depend on a variety of project specific parameters. Therefore, the results suggest that the decision about adoption of concrete recycling strategy and the level and degree of recycling should be made after detailed analysis based on all influencing parameters. The framework proposed in this paper may serve as an efficient method to perform such analyses.

5 Conclusion

The BIM based framework and tool presented in this paper can be used to provide decision makers with useful information about the costs and emissions incurred by adopting the recycling strategy in a particular project. The results of these analyses together with other important criteria can be used in multi-criteria decision making to select the optimal level and degree of concrete recycling based on owner preferences.

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