LIFE-CYCLE ASSESSMENT FOR CONSTRUCTION PROCESSES IN BUILDING CONSTRUCTION: A PROPOSED CONCEPTUAL FRAMEWORK

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ABSTRACT

Life Cycle Assessment (LCA) is a powerful tool which can be used to analyse the environmental effects associated with buildings. Even though there are numerous LCA studies carried out on buildings only a handful of studies have concentrated on the construction phase of buildings. The few studies that have considered the construction phase have been reluctant to investigate commercial buildings largely due to lack of data. Most of the studies either ignore or approximate the effects of the construction phase, stating the insignificance of them compared to the total environmental impacts of a building over its life cycle. Many studies have concluded a total effect of 3 to 11percent in the construction phase compared that to the total effects. However, the large impacts at an aggregate level that would concern the designers and the builders have been ignored by these studies. Thus this paper attempts to comprehensively analyse the significance of the construction phase and suggest a methodology for analysing the environmental effects in the construction phase of a building. The outcome of this paper would provide a guideline for the researchers to concentrate on the construction phase in their analyses.

Keywords: *Buildings; Construction Management; Construction Process; Environmental Emissions; Life Cycle Assessment.*

1. INTRODUCTION

Environmental impacts associated with buildings are one of the major concerns that govern the research interest around the globe. Almost all the phases of a building (Guggemos, 2003; Mao *et al.*, 2013) (from the design phase to the end of life phase) contribute to a considerable amount of environmental impacts throughout its life cycle. Most of the studies have categorised the life cycle of a building into material acquisition, construction, operation and end of life when evaluating these environmental impacts (Acquaye and Duffy, 2010; Guggemos, 2003; Junnila *et al*., 2006; Mao *et al*., 2013).

In spite of a well-defined Life cycle, Life Cycle Assessment (LCA) of a building is often associated with three major issues, i.e., defining the scope and the system boundary, creating a reliable inventory, identifying the most important impact factors for impact assessment. The first issue is the difficulty of defining a proper system boundary for the analysis. The high complexity and difficulty of data acquisition has restricted most of the studies to concentrate on selected life cycle phases although there have been attempts to assess the environmental impacts for the whole life cycle (Guggemos and Horvath, 2006; Junnila *et al*., 2006). The second issue of not having a sound inventory pressurises the researchers to concentrate on some components or life cycle phases. The main reason for not having a complete inventory can be due to the difficulty of acquiring data of all the phases in the building with a limited amount of time. The final issue is identifying which impact factors are most suitable when LCA in built environment is concerned. Usually most of the studies only considered greenhouse gas emissions in their analysis. These studies have ignored emissions such as particulate matter, nitrous oxide compounds and sulphur dioxide compounds which are common emission elements in construction phase. However careful assessment of each issue to properly address the research requirement will pave the way to a complete analysis with reliable results. Although a handful of studies have made attempts to evaluate the environmental effects of whole life cycle -of commercial buildings (Guggemos and Horvath, 2006) many studies have concentrated only on selected life cycle phases of a building. For instance, one study considered only on the effects of construction materials (Chau *et al*., 2007) while other studies focused on embodied energy use in buildings

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(Chang *et al.*, 2012; Chen *et al*., 2001) while some analysed embodied energy and operational energy (Yohanis and Norton, 2002) others analysed greenhouse gas emissions (Chau *et al*., 2012, Mao *et al*., 2013, Seo and Hwang, 2001, Suzuki and Oka, 1998).

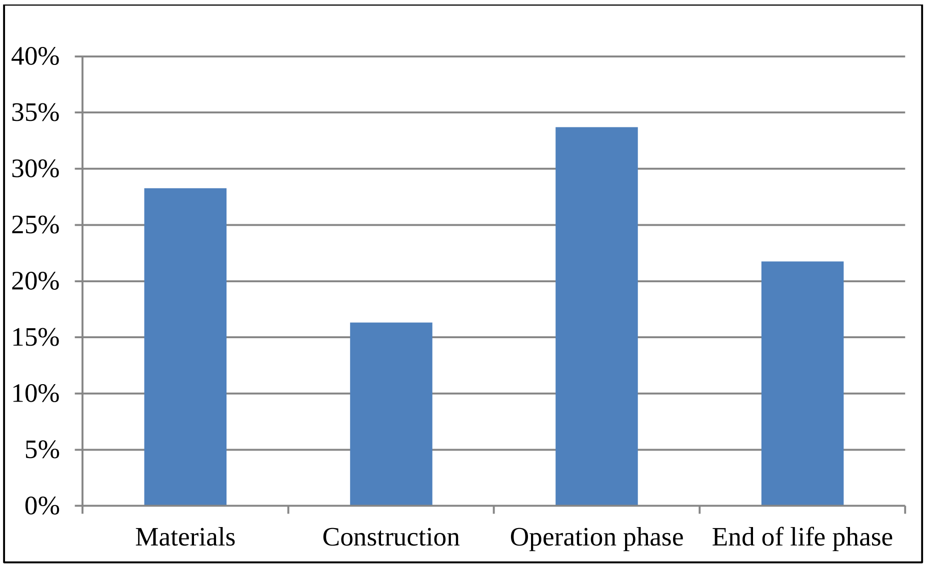

Figure 1: Distribution of Each Phase of a Building Used in Different Literatures

It is evident that (refer Figure 1) most of the studies have ignored environmental effects of the construction phase based on the approximation that the impacts are too small. Usually the studies conclude that construction phase encounters for 3-11percent (Junnila and Horvath, 2003) of the total impacts over the life cycle. The main reason for the low percentage figure is that the construction period (Usually 1 to 3 years) is relatively shorter when compared to the considerably long (Around 50 years) use phase. Since the results in Figure 1 shows the lack of concern given towards the environmental impacts of construction phase it draws the concern of the significance of evaluating the impacts of construction phase. Analysis of environmental impacts is of greater importance to the designers and contractors. The results will provide guidance to the designers and the contractors to adopt a more environment friendly construction techniques and designs. It would enable the designers and the builders to make critical decisions on the performance of current techniques and possible methods of improvements in order to minimise the environmental impacts in the construction phase.

2. LIFE CYCLE ASSESSMENT

Life cycle assessment is known to be a technique that has been widely used to measure and compare environmental impacts of a certain product or process. Thus, LCA can evaluate the environmental impacts of a building from cradle to grave. A researcher would have to analyse the effects of raw material acquisition and manufacture, construction, use and operation, maintenance and repair and end of life. According to ISO 14040, four steps are required to carry out a typical LCA study. The first step discusses how to define the goal and scope for the study. This step is one of the most important steps as it critically identifies the possible system boundary and objectives of the analysis which will draw the initial research framework. Proper identification of goal and scope is crucial in built environment because of the practical difficulty of including all the activities associated with building into the analysis. Thus, as the standard explains, the exclusion of certain activities is possible as long as proper justification is made for. Therefore it is important to initially identify the activities which critically contribute towards environmental effects for the analysis.

The second stage in the four step procedure is as important as the first stage as it includes the inventory phase. Typically this inventory phase includes interpretation of system boundary with the corresponding unit processes, collection of data and summation of the total impacts across the whole process which is under consideration. Life cycle inventory (LCI) stage uses three major LCA methods, input-output based LCA and process based LCA and hybrid based LCA to evaluate the environmental effects. Input-output based LCA is a top down economic technique which uses national average data of each sector in an input-output matrix for calculating the impacts (Acquaye and Duffy, 2010; Treloar, 1997). This method has inherent limitations like age of data, use of national averages, proportionality assumption and homogeneity assumption etc. (Crawford, 2008; Hendrickson *et al*., 1997; Lenzen, 2000).

Process based LCA method is the most commonly used method (refer Table 1) by most of the researchers across the globe for evaluation of environmental impacts (Acquaye and Duffy, 2010; Chau *et al.*, 2007; Chau *et al.*, 2012; Mao *et al.*, 2013). The main reason is that process based LCA makes it easier to address the model and the system boundary as long as enough data is available for analysis. Process analysis collects environmental inputs for all activities in a process to evaluate the environmental impacts in the form of output. Therefore the accuracy and the reliability of the analysis mainly depend on the quality and the accuracy of the input data used for the analysis. Unavailability of enough quality data has always been a major issue when adopting process analysis in built environment. It also suffers from limitations such as issues with system boundary, data accuracy and reliability and upstream truncation errors etc. As long as the quality, accuracy and availability of data can be assured process analysis is the most accurate method available for analysing environmental impacts (Hendrickson *et al*., 1997).

Hybrid based LCA method is a combination of both process method and input-output method. The main objective of combining the two methods is to utilise the advantages inherent to both the methods while trying to minimise the limitations associated with each method. Process based hybrid method and Input-Output based hybrid method are the two hybrid methods which are in use. Process based hybrid analysis uses input-output data in the upstream stages to minimise the limitation of truncation errors at the upstream stage inherent with process analysis and uses process based data in the downstream stage (Bilec *et al.*, 2009; Chang *et al.*, 2010; Chang *et al.*, 2012; Dong *et al*., 2013). This method is useful when the whole life cycle of the building is analysed because it's the upstream data (data on material acquisition and production) which are hard to collect. On the other hand, input-output based hybrid analysis initially uses available process based data to build the inventory and remaining gaps created are filled by input-output data. This method was initially implemented successfully by Graham Treloar (Crawford, 2008; Treloar, 1997) in the field of construction and found out to be more effective when accuracy of data is limited and studies have shown that it exhibits only 20% of incompleteness (Crawford, 2008) in embodied energy evaluation.

Table 1: Matrix Analysis of Selection of Different Methods and Life Cycle Phases by Different LCA Studies Related to Buildings

Method of analysis	Material extraction	Construction	Use and Maintenance	End of Life
Input-Output Method	1. (Seo and Hwang, 2001) 2. (Su *et al*., 2010) 3. (Chen and Zhang, 2010) 4. (Kok *et al*., 2006)	1. (Seo and Hwang, 2001) 2. (Chen *et al*., 2011) 3. (Su *et al*., 2010) 4. (Chen and Zhang, 2010)	1. (Seo and Hwang, 2001) 2. (Chen *et al*., 2011) 3. (Su *et al*., 2010) 4. (Chen and Zhang, 2010) 5. (Kok *et al*., 2006)	1. (Seo and Hwang, 2001) 2. (Chen *et al*., 2011) 3. (Su *et al*., 2010) 4. (Chen and Zhang, 2010)
Process Method	1. (Guggemos, 2003) 2. (Guggemos and Horvath, 2006) 3. (Chau *et al*., 2012) 4. (Yohanis and Norton, 2002) 5. (Citherlet, 2001) 6. (Xing *et al*., 2008) 7. (Treloar *et al*., 2003) 8. (Huberman and Pearlmutter, 2008) 9. (Verbeeck and Hens, 2010) 10. (Junnila and Horvath, 2003) 11. (Junnila *et al*., 2006) 12. (Mao *et al*., 2013) 13. (Monahan and Powell, 2011) 14. (Chau *et al*., 2007) 15. (Junnila and Horvath, 2003) 16. (Kua and Wong, 2012)	1. (Guggemos, 2003) 2. (Guggemos and Horvath, 2006) 3. (Mao *et al*., 2013) 4. (Chen and Zhu, 2008) 5. (Citherlet, 2001) 6. (Li *et al*., 2010) 7. (Junnila and Horvath, 2003) 8. (Kua and Wong, 2012) 9. (Li *et al*., 2010)	1. (Guggemos, 2003) 2. (Guggemos and Horvath, 2006) 3. (Chau *et al*., 2012) 4. (Yohanis and Norton, 2002) 5. (Citherlet, 2001) 6. (Xing *et al*., 2008) 7. (Treloar *et al*., 2003) 8. (Verbeeck and Hens, 2010) 9. (Junnila and Horvath, 2003) 10. (Junnila *et al*., 2006) 11. (Kua and Wong, 2012) 12. (Li *et al*., 2010) 13. (Mao *et al*., 2013) 14. (Monahan and Powell, 2011) 15. (Chau *et al*., 2007) 16. (Junnila and Horvath, 2003) 17. (Kneifel, 2010) 18. (Kua and Wong, 2012) 19. (Li *et al*., 2010) 20. (Yohanis and Norton, 2002) 21. (Yan *et al*., 2010) 22. (Yu *et al*., 2011) 23. (Xing *et al*., 2008)	1. (Guggemos, 2003) 2. (Guggemos and Horvath, 2006) 3. (Chau *et al*., 2012) 4. (Mao *et al*., 2013) 5. (Citherlet, 2001) 6. (Junnila and Horvath, 2003) 7. (Kua and Wong, 2012) 8. (Treloar *et al*., 2003) 9. (Verbeeck and Hens, 2010) 10. (Li *et al*., 2010) 11. (Yan *et al*., 2010) 12. (Yu *et al*., 2011) 13. (Xing *et al*., 2008)

Method of analysis	Material extraction	Construction	Use and Maintenance	End of Life
Hybrid Methods	1. (Han *et al*., 2013) 2. (Fay *et al*., 2000) 3. (Chang *et al.*, 2012) 4. (Crawford *et al.*, 2010) 5. (Crawford, 2008) 6. (Dong *et al*., 2013)	1. (Chang *et al*., 2012) 2. (Crawford *et al.*, 2010) 3. (Crawford, 2008)	1. (Han *et al.*, 2013) 2. (Fay *et al.*, 2000) 3. (Crawford *et al.*, 2010) 4. (Crawford, 2008) 5. (Dong *et al*., 2013)	1. (Han *et al*., 2013) 2. (Fay *et al*., 2000) 3. (Crawford *et al.*, 2010)
Number of Studies	**26**	**16**	**31**	**14**

3. PROPOSED CONCEPTUAL FRAMEWORK

Since LCA can be applied to any product or process and hence providing a specific methodology is not practical. This is because each method of analysis carries its own steps of analysis. Input-output analysis requires monetary values with respect to the product under consideration while process analysis will require only the life cycle details of the product and hybrid methods require both the details (Bilec *et al.*, 2009; Chang *et al.*, 2010; Chen and Zhang, 2010; Hendrickson *et al*., 1997). Even within the same analysis method, the product or process which is being evaluated will determine the steps of analysis. A general framework along with the usual steps would provide a basis for anyone who intends to undertake LCA in the built environment. This chapter discuss about the issues that are likely to encounter when developing a proper framework for methodology and flowchart procedure which provides a general guideline in proceeding with the analysis.

3.1. SELECTION OF SYSTEM BOUNDARY AND THE METHOD OF ANALYSIS

The life cycle of a building includes four major stages as shown in Figure 2. The major objective of this paper is to suggest a methodology to critically analyse the impacts in the construction phase. Hence the focus of interest in this LCA should be the construction phase of the building. This construction phase should ideally include material, labour and equipment transportation, material usage, construction equipment usage such as diesel consumption and combustion emissions, electricity usage at site, water usage at site, possible repair and maintenance of vehicles and equipment (Mao *et al.*, 2013). Analysis of these activities in the construction stage would draw more comprehensive results within that stage. Therefore the boundary should be selected to include the above activities which would result in a more comprehensive analysis in the construction stage.

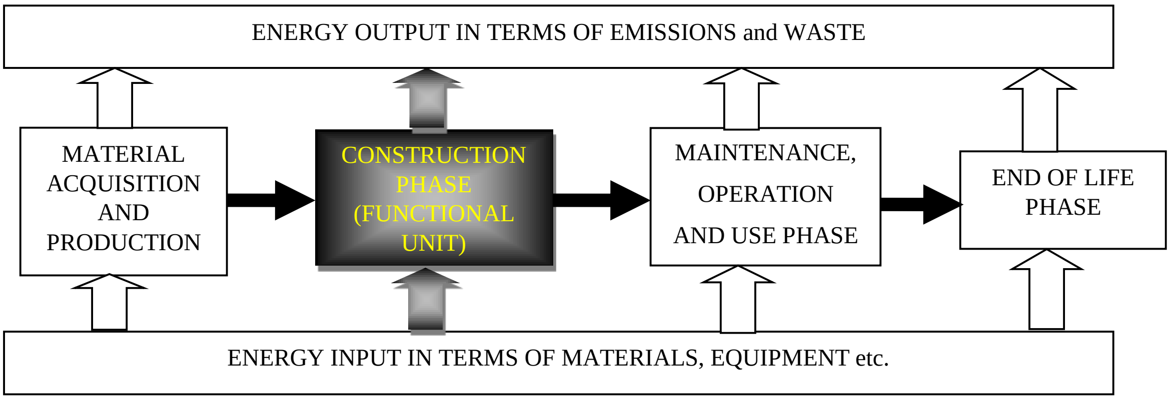

Figure 2: The Life Cycle of a Building (Guggemos, 2003)

Once the activities are selected it is important to select the method of analysis. When built environment is considered the selection of analysis method depends upon the data quality and availability, time consideration and personal choice. Out of the three methods available process analysis and hybrid analysis can be used effectively to analyse the effects in construction phase. The use of process method solely based upon the data quality and the way in defining the boundary for the analysis. A summarised process diagram with the main activities in a construction stage given in Figure 3 explains the necessity of proper data for the analysis. If quality data is available process based LCA can be used for the analysis. If process data is unavailable for all the activities considered in the system boundary, the completeness of the analysis would be an issue and hybrid methods would make a perfect method of analysis in that situation. Another concern is that whether to analyse the whole life cycle of the building or certain selected life cycle phases. Undoubtedly analysis of whole life cycle would draw complete analysis results but with restrained time schedule and data acquisition restrictions may limit the analysis to concentrate on certain phases of a building. But if only some phases are included for the analysis it is important to justify the choice with appropriate reasoning as one can argue that analysis of only certain phases would provide distorted results.

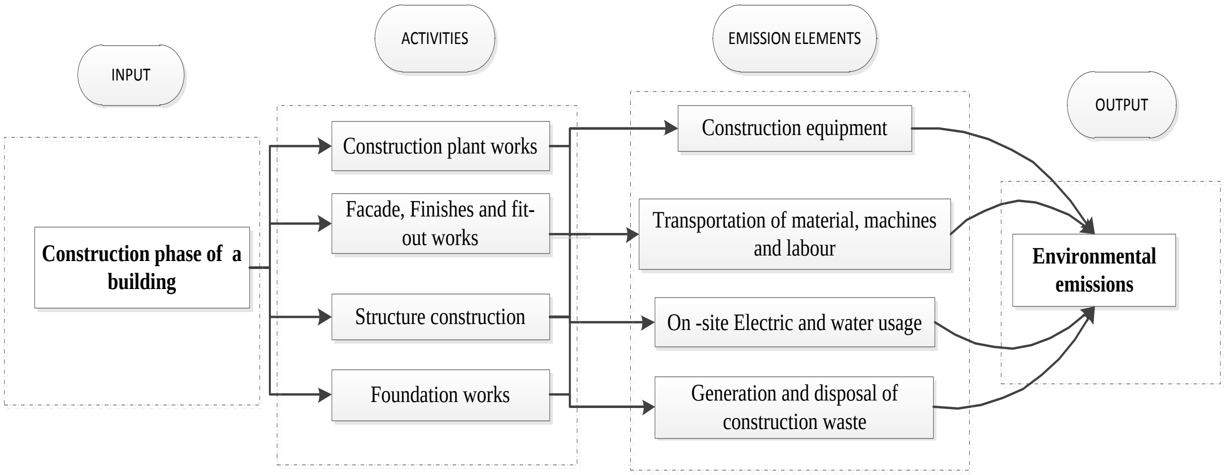

Figure 3: A Presentation of Construction Phase with Associated Environmental Emissions

3.2. *SOFTWARE SELECTION AND ISSUES*

The next issue is the selection of ideal software for analysis. A number of software is available for performing LCA. But selection of the software depends upon several factors such as easiness in modelling the process, availability of quality inventory in the database, data relevancy to the geographical location where the project is undertaken, availability of other in built statistical analyses and ability to convert results into presentable outcomes. This section will provide a brief review of four available analysing tools with the advantages and disadvantages inherent with it.

Table 2: Advantages and Disadvantages of Available LCA Tools

Name of Software	Advantages	Disadvantages
SimaPro	– International databases such as eco-invent is available and hence can be used in many countries – User friendly and self-explanatory – There is a possibility for advanced results analysis – Report maker plug-in allows the model to link with MS word and excel – All life cycle stages of a product can be analysed	– None of the databases in SimaPro provides data for on-site construction processes – Unless a user defined process is available it is difficult to analyse – Cannot be used for hybrid based LCA model – Time consuming
Gabi	– Easier to model the process in to the system – Can include effects due to noise as well – Enables to track cost factors as well along the life cycle of the process – All life cycle stages of a product can be analysed	– Database is mainly based in Germany – Issues with the applicability of databases in different countries – Less amount of data is available for on-site construction processes – Limited construction activities are available
BEES	– Combines an environmental score and an economic score to provide a final score – All life cycle stages of a product can be analysed – Focus mainly on effects due to construction	– Cannot be used for hybrid based LCA model – Lot of uncertainty in data

Name of Software	Advantages	Disadvantages
Athena	– The best construction specific tool compared among the others – Allows to analyse the elements of a building separately – Representation of results is simple and understandable – Number of Impact categories are available – All the life cycle stages can be analysed	– Applicable to only American context – Although defined as a construction specific tool, it does not cover every aspect of the construction stage

3.3. STEPWISE PROCEDURE

The whole LCA is an iterative process and hence adopting a systematic procedure would be extremely difficult. In such cases, the ideal way to carry out such an analysis is to follow a stepwise flowchart process. The framework provided by the international standard ISO 14040, would only provide a broader framework which needs further expansion. A conceptual framework as shown in Figure 4 gives a general guideline for carrying out analysis is which can estimate the environmental emissions in construction phase. The entire procedure can be classified into three distinct stages. The initial stage is about developing a framework that will provide a strong foundation in carrying out the analysis (Dixit *et al*., 2013; Rebitzer *et al*., 2004). This includes proper identification of goal and scope, drawing the system boundary and creating a methodological framework. This initial stage focuses on one of the most important aspects of the whole analysis which is defining the functional unit. This functional unit if not defined accurately can provide seriously distorted results which will misinterpret the whole analysis (Rebitzer *et al*., 2004). Functional unit will provide the basis of analysing and comparing the outputs of a process or product through its input. LCA in construction usually address the functional unit as amount per area (Guggemos, 2003; Sihabuddin and Ariaratnam, 2009). Another activity in the initial stage which needs careful attention is development of system boundary. The life cycle of a building includes a number of phases which includes a large number of activities which might be difficult to analyse. Even in a concerned phase there are a large number of activities that are practically not possible to analyse at a given stretch. Hence it is important to identify the most crucial activities that contribute to environmental emissions and draw a system boundary around with stating the limitations of the drawn system boundary with accurate justification. Next step includes originating a framework for the method of analysis. In this step it is required to identify the activities inside the system boundary that may have significant contribution towards environmental emissions. This will simplify the analysis because including all the activities inside the system boundary will not only make the analysis more complicated but also will have less effect on the total environmental effects. Final step of the initial stage is to select the method of analysis. Selection of a method requires intensive literature review and data availability. If enough data is available it is always advisable to adopt process analysis as it will provide more comprehensive results. For a comprehensive analysis it is important to define the initial stage precisely as the accurate outcome of other stages solely depends upon the completeness of this stage.

The next stage includes data collection and identification of impact indicators for the analysis. The entire analysis depends upon the data collection because lack of quality data will draw weak conclusions with a lot of inaccuracies. Data collection should be carried out with careful attention and need to make sure that all the sufficient data is collected to evaluate the environmental impacts. Often LCA software includes different impact indicators in impact assessment. Although there are several impact indicators it is important to identify the relevant indicators when construction is considered. Although the middle stage is not important as the initial stage it requires a considerable amount of time and the quality and the validity of the inventory will decide the effectiveness of the entire analysis. In such cases where failure to establish a quality inventory, it is important to repeat the initial stage either by reforming the methodological framework or by changing the method of analysis.

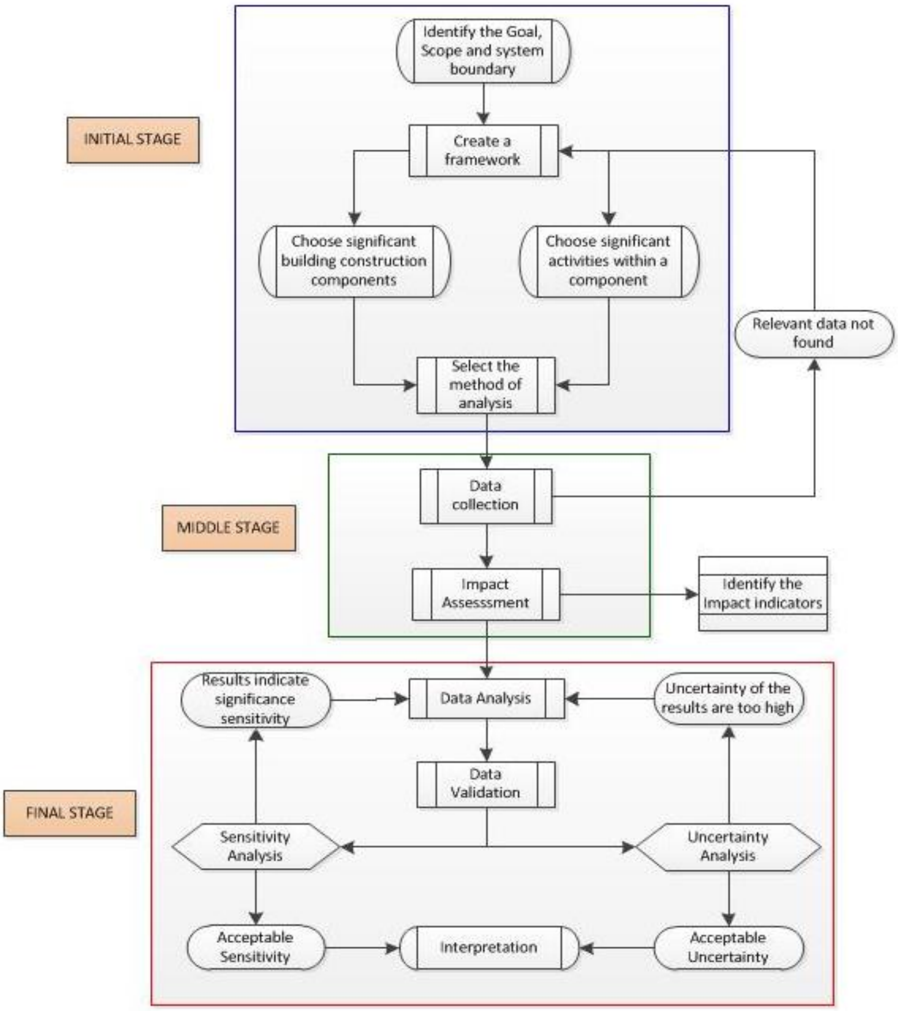

Figure 4: General Methodology for Carrying Out LCA in Buildings

The final stage is as important as the initial stage as it will provide the results of the modelled analysis. Usually this consumes a considerable amount of time as this is an iterative process. Selection of software depends upon the availability, relevancy, easiness and personal preference. LCA in construction is often faced with the difficulties of lack of available data in software databases. In such cases before commencing the analysis it is required to update the database with the required data. This may require intense data collection and continuous surveys to collect emission profiles of construction equipment and machines. Data analysis will be followed up by data validation which often divided into sensitivity analysis and uncertainty analysis. Sensitivity analysis will check the amount of sensitivity between input and outputs of the analysis (Mattila *et al*., 2013; Mokhtari *et al*., 2006; Savolainen, 2013) while uncertainty analysis will determine the uncertainties associated with data and outputs(Ao, 2011; Sonnemann *et al*., 2003). There are number of sensitivity and uncertainty analysis methods that have been used in various studies in LCA (Ardente *et al*., 2005; Dong *et al*., 2013; Hayes, 2011). Selection of proper method for the consistency checks will reduce the work load and they would also provide a reliable outcome.

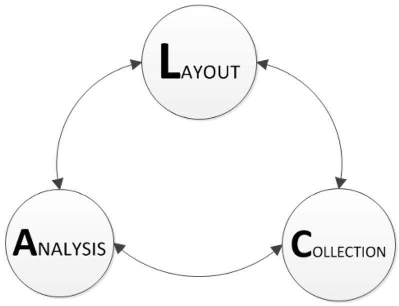

Figure 5: Simplified Methodology (Thumb Rule) for Carrying Out LCA

The methodology for carrying out LCA can be put into general terms of Layout, Collection and Analysis where layout represents creating a methodological framework with identifying scope and the system boundary while collection represents data collection and development of the database. Analysis represents data analysis and reliability checks to validate the results.

4. CONCLUSIONS AND SUGGESTIONS

The significance of analysing environmental impacts in construction phase is highlighted in this paper. It is evident that analysis of impacts in construction phase is an area which has been largely less emphasised by researchers and industry practitioners. Negligence of assessment of environmental impacts in construction phase is due to complexity, time consuming nature and difficulty in acquiring data. In spite of these limitations a proper system boundary and a well-defined scope would reduce the complications associated with the analysis. To draw the best out of the analysis it is important to identify the system boundary as it will highlight the results of the concerned phase rather than outlining the whole scenario. Ideally the assessment of environmental impacts in construction phase should include the impacts of machines and equipment use, impacts due to transportation, maintenance and repair works of machines and equipment and material consumption. Although greenhouse gas emissions is the governing impact indicator related to construction if other indicators such as water and land usage, dust generation can be included in the analysis the results would be more comprehensive. The paper proposed a conceptual framework on how to measure the environmental impacts of construction activities. The methodological framework can be used to develop a toolkit that is able to capture the environmental impacts in construction phase. This will benefit the designers and the contractors to optimise the design process.

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