AMERICAN UNIVERSITY OF BEIRUT

USING BUILDING INFORMATION MODELING TO ENHANCE THE ACCURACY OF FORECASTING GENERATION RATES OF CONSTRUCTION WASTE

by
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AN ABSTRACT OF THE THESIS OF

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Title: Using Building Information Modeling to Enhance the Accuracy of Forecasting Construction Waste Generation Rates

The continuous increase in worldwide population has led to unprecedented rates of construction activities. In turn, the amounts of waste generated from construction activities are increasing at a steady pace. Such high waste generation rates are putting more pressure on landfills and are encouraging researchers and practitioners to look for alternative waste management strategies (e.g., recycling). In this thesis, a methodology is proposed to determine the required design capacity of a construction waste recycling plant using two essential sets of construction documents. The proposed methodology relies on building information modeling (BIM) technologies such as Revit and common scheduling tools such as Primavera to forecast the quantities of construction waste generated over time. While reported methods on the construction waste quantification are context specific and require significant amounts of field data collection, the proposed method is generic and automated, which makes it applicable to new projects of any type and at any location. The proposed method is illustrated on a real-world case study site, where the results of waste quantities generated over time serve as a baseline for estimating waste from multiple project sites. A set of project specific construction waste S-curves are generated visualizing the waste generation rates across the multiple stages of construction. The integration of several sets of S-curves obtained from different types of projects allows for an accurate forecast of waste generation rates at city, region, or country level, allowing waste management authorities to design the required capacity for recycling plants. Finally, the environmental and economic benefits achieved from recycling are estimated, serving to conclude that recycling could significantly save natural and monetary resources.

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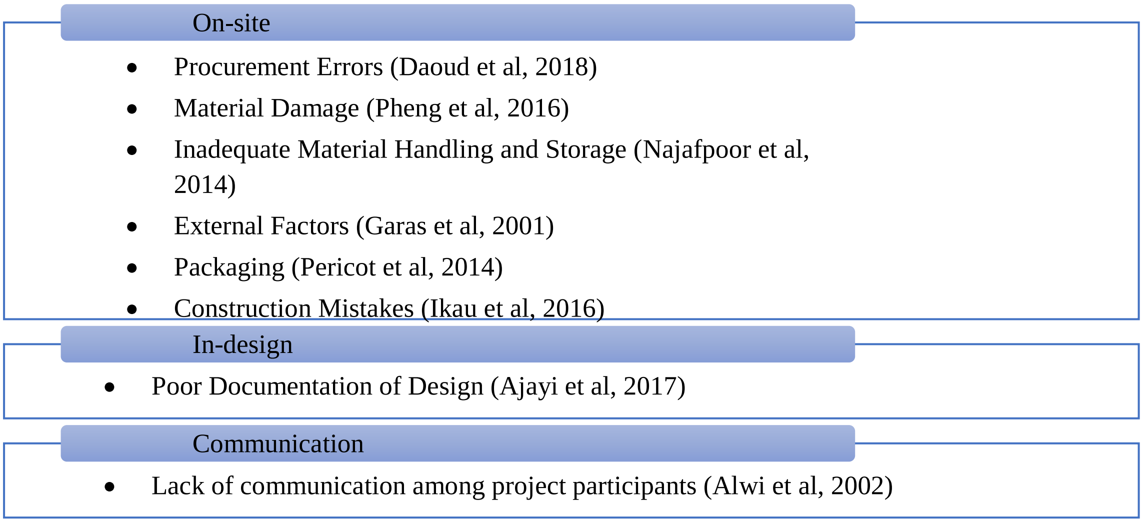
CHAPTER 1

INTRODUCTION

Over a period of 10 years (1997 through 2007), the global waste (in metric tons) increased by around 30 percent and is expected to increase by another 30 percent by year 2020 (Sheau-Ting et al, 2016). A significant part of this global waste relates to construction activities that produce relatively high amounts of construction byproducts. As mentioned by Begum et al (2009), out of the total amount of materials delivered to a construction project site, around 10 to 20 percent ends up being wasted. According to Ulubeyli et al (2017), the construction and demolition waste (CDW) percentage may exceed a quarter of the total solid waste (by weight), for example the percentage of the construction waste from the total solid waste generated in Europe amounts to 30 percent.

Such percentages of construction waste generation impose serious effects on the environment and the economy. The negative environmental impacts are attributed to the disposal of CDW in landfills and the lack of recycling which deprives the construction industry of environmentally friendly resources. High emissions of carbon dioxide during the whole life cycle of construction materials is leading to water, air, and soil pollution (Yuan, 2017). Aside from the environmental hazards, material waste leads to loss of profit for the contractor and an additional cost to be incurred by the owner since the material cost contributes the highest percentage of a project’s direct cost (Azhar, 2011). For example, when 75 percent of the total construction waste are prevented ahead of construction, the total project cost could be reduced up to 15 percent (Azhar, 2011).

The factors contributing to construction waste generation, as shown in Figure 1, can be attributed to errors in procurement (Daoud et al, 2018), packaging material (Pericot et al, 2014), or damage of materials (Pheng et al, 2016) due to improper handling and storage (Najafpoor et al, 2014) or due to external factors such as bad weather conditions (Garas et al, 2001) Other on-site incidents that lead to construction waste generation include construction mistakes (Ikau et al, 2016) resulting from workers' lack of experience (Poon et al, 2004). Other major contributors include in-design factors, e.g. poor documentation of design as engineers fail to carry out proper measurements for waste reduction during the early stages of design (Ajayi et al, 2017). Finally, as indicated by Alwi et al. (2002), poor communication among the project participants could contribute to the generation of construction wastes.



On-site

- Procurement Errors (Daoud et al, 2018)
- Material Damage (Pheng et al, 2016)
- Inadequate Material Handling and Storage (Najafpoor et al, 2014)
- External Factors (Garas et al, 2001)
- Packaging (Pericot et al, 2014)
- Construction Mistakes (Ikau et al, 2016)

In-design

- Poor Documentation of Design (Ajayi et al, 2017)

Communication

- Lack of communication among project participants (Alwi et al, 2002)

Figure 1 Major contributors to CDW

In order to resolve the issue of increasing rates of construction waste generation and the progressive decline of landfill spaces, Madi and Srour. (2019) showed that effective on-site waste management should be adopted. However, the success of such approaches hinges on human/behavioral related factors. As discussed by Bakshan et al.

(2017), behavior towards on-site construction waste management is associated to personal factors, including worker's positive attitude towards waste management and worker's experience in construction waste management practices. Through a Bayesian Network analysis, Bakshan et al. (2017) showed that effective on-site waste management could reach 83 percent when the aforementioned personal factors are dealt with properly.

Other construction waste management techniques deal with recycling wastes into usable portions (Table 1), instead of their disposal in landfills, which could in turn preserve landfill spaces, reduce the costs of disposal (Ibrahim, 2016), and solve the construction waste negative impacts on the environment and economy (Sapuay, 2016). For example, the recycling of construction materials can lead to significant water and energy footprint reductions, in addition to achievable economic benefits (Srour et al, 2013).

Table 1: Construction Waste Management Technique

Construction Waste	**Recycling**
Concrete	to aggregates (Purnell et al, 2010)
Brick and block	to aggregates (Poon et al, 2007)
Ceramic	to aggregates (De Brito el al, 2005)
Plasterboard	to new plaster board (Rivero et al, 2016)

An equally important waste management technique, i.e. source minimization, is effectively achieved by sticking to the design drawings and specifications. However, as discussed earlier, a major contributor of construction waste generation is poor documentation of design, as there are resistance factors, related to personal and organizational attitude (Lee et al, 2017). These factors hinder the use of Building Information Modeling (BIM) early on in the design, which could have aided in providing exact elements dimensions and faster response to changes and errors in design (Wu, 2017). For example, when using BIM during the design of two residential buildings, construction waste was reduced by around 15.2 percent (Won et al, 2016). Consequently, such percentage reduction of construction waste leads to reductions in green-house gases emissions as well as an overall decrease in a project's total cost (Liu et al, 2011; Salgin et al, 2017). Although recycling and source minimization are considered effective techniques for waste management, they are not consistently used in various countries such as Lebanon where the common approach is disposal of construction waste in landfill or in dumpsites (Srour et al, 2012).

Acknowledging the environmental and economic benefits that could be achieved through proper construction waste management techniques such as recycling, this study proposes a methodology to determine the required design capacity of a construction waste recycling plant, an essential parameter for recycling plant design. In order to achieve that, accurate forecasting and quantification of construction waste rates over time is adopted as an initial step. This study proposes a BIM based method to quantify the construction waste generation rates over the entire project duration. The proposed method is applied on a case study site project, where the waste quantities generated over time serve as a baseline for estimating waste from multiple project sites in Beirut. A set of project specific construction waste S-curves are generated visualizing the waste generation rates across the multiple stages of construction. The integration of several sets of S-curves obtained from different types of projects allow for an accurate forecast of waste generation rates, thereby assisting waste management authorities to design the required capacity for recycling plants.

CHAPTER 2

LITERATURE REVIEW

2.1 Waste Estimation Using On-Site Records (Reactive)

As indicated by Shen et al. (2005) and Bossink et al. (1996), contractors have the opportunity to measure waste rates through sorting and weighing of each material waste and comparing them to the amount of materials purchased. Using this technique, waste rates were found to fall in the 1 to 10 percent range.

Similarly, Bakshan et al. (2015) relied on site visits to collect waste generation coefficients or to estimate generation rates for major waste streams during various construction stages. The quantity of waste generated on site was estimated on the basis of purchase records and actual quantities of materials used.

Wu et al. (2014) classified on-site quantification methods of construction waste as requiring either direct or indirect measurements of waste quantities. As approached by Lau et al, (2008), direct measurement of waste on-site requires calculating the amount of construction waste according to the waste layout meaning through understanding the dimensions of waste piles. For example, the waste can have either a pyramidal shape (Figure 2) or a rectangular shape (Figure 3) and its volume is calculated accordingly.

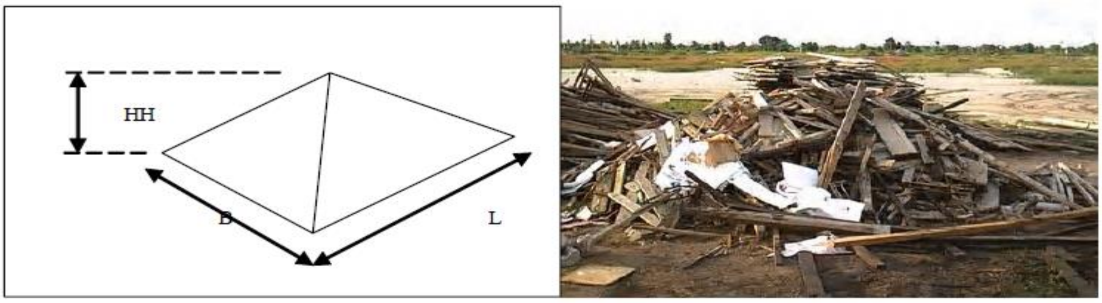


Figure 2 Pyramidal layout of waste

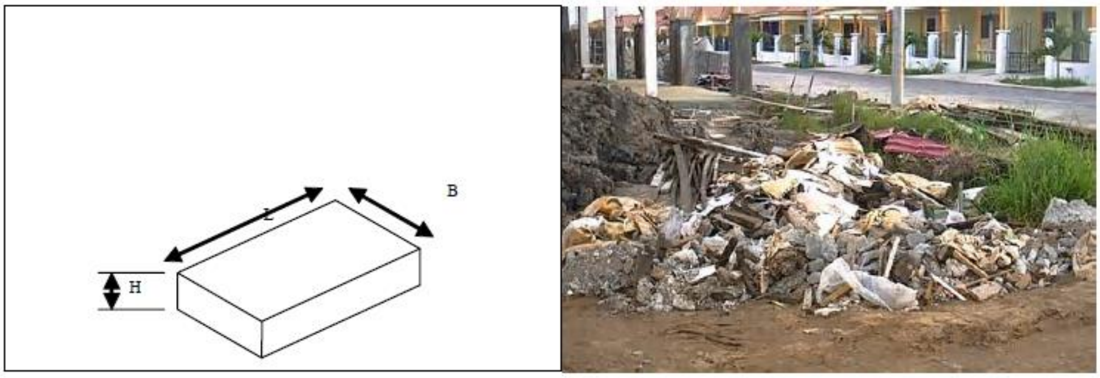


Figure 3 Rectangular layout of waste

Indirect approaches are as well utilized. For instance, Poon et al. (2004) estimated the quantity of construction waste from different construction works of high rise buildings in Hong Kong through truck load records from these sites. Kartam et al. (2004) estimated CDW generation rates in Kuwait by relying on truck records from landfills and on statistical data for the annual waste production. The first method included a statistical analysis of CDW based on the number of trucks approaching landfill sites, and it was found that about 3 million ton were generated annually. The second method explored annual statistics of waste production activities, and it estimated the generated wastes at around 1.6 million tons.

The classification system accumulation method was introduced as it provides a more specific determination of construction waste quantity based on waste classification (Llatas, 2011). According to this method, different stages of the construction process and the elements used in each process are identified. Therefore, the waste can be quantified according to the different stages of the construction project. The different types of waste which comprise of packaging, soil, and remains waste are summed to find an estimate of the total waste. Mahayuddin et al. (2013) proposed a similar approach whereby five similar types of projects were considered and the waste generation for each stage of each project was computed. The waste generation was obtained by weighing the waste generated and dividing it by the project's gross floor area, and finally summing up the results to obtain the total waste generated at each stage. In other words, the method commences with identifying the different stages of construction and the materials used in each stage.

Wimalasena et al, (2010) proposed an even finer method to quantify construction waste based on activity-based waste generation rate. Site observations were conducted to quantify waste, while accounting for factors including activity specific factors, labor, material, equipment factors, site and weather conditions, and company policies (Wimalasena et al, 2010). These factors can be identified as human factors and non-human factors and have thus different quantification techniques. Assessing the contribution of these factors on waste generation is done based on conducting surveys whereby human factors are assessed based on the competency and work satisfaction of labor. As for the non-human factors, they are composed of assessing the work environment and comfort level.

McBean et al. (1993) defined the generation rate calculation method, which involves collecting data about the regional construction waste per year. The total amount of waste is derived by the summation of individual constituent waste. The constituent waste are divided into building constituent waste and industrial constituent waste. Furthermore, taking recycling policies into account, the total amount of waste can be formulated by the amount of waste that isn't recycled of the individual constituent waste.

Yost et al. (1996) accounted for the variety of the construction activities with respect to the economy status, and for that, the waste generation (kilograms) was derived by multiplying the waste generation per financial value (kilograms per dollars) by the total financial values (dollars) of construction projects in a specific region. The financial value of construction projects was linked to the amount of waste through the relationship between the financial value of a square feet of construction project, and the amount of construction waste per square feet of construction project.

Later, the area-based calculation method was developed whereby the construction waste generation rate is multiplied by the project area (Lage et al, 2010). The quantity of construction and demolition debris is equivalent to the building related wastes, categorized into waste generated from new construction, demolition, and renovation activities.

Another method, the lifetime analysis method proposed by (Poon, 1997), relies on the assumption that the built structures will eventually be demolished and end up with demolition waste whose weight is equal to the weight of the materials purchased for construction. However, Cochran et al. (2010) argues that not all the materials purchased are used to build the structure. Therefore, the amount of demolition waste is not equal to the amount of material purchased for construction, but to the actual amount of materials used to build the structure; computed through subtracting the amount of material wasted during construction from the total amount of materials that were purchased.

2.2 Waste Estimation Using Predictive Parametric Models

Solis-Guzman et al. (2009) argue that a classification system is to be present in order to effectively manage the waste quantities. The classification system requires identifying items that are used in a construction project along with their corresponding bill of quantities (BOQ) information. By using this approach, Solis-Guzman et al. (2009) quantified the waste generated from a new construction project depending on two types of waste. These types include the wreckage waste (e.g. material breakage and cutting) and packaging waste. Therefore, the amount of waste generated from the aforementioned two types are obtained through multiplying the quantity of items used from the BOQ by their corresponding coefficients obtained from the Andalusian Construction Costs Database.

Ding et al. (2014) proposed two linear equations for the quantification of CDW. The first equation tracks the flow of materials that are purchased for the construction process and those that are used in the construction process. The difference between the two terms is the amount of construction waste. The second equation formulates the total weight of CDW in a region based on the following equation ($CDW = CA*G_C + DA*G_D$) where CA is the total area of the constructed buildings (m^2), DA is the total area of demolished buildings (m^2), G_C is the average waste generation per building area during construction (tons per m^2), G_D is the average waste generation per building area during demolition (tons per m^2).

Miguel et al. (2016) estimated CDW based on three steps starting with data collection using historical records. Such data is obtained for buildings of different types and ages. The buildings are categorized as residential and nonresidential within a range years from 1920 till 2011. Finally, CDW for the whole sub-areas is determined by an extrapolation procedure whereby the generated waste per area for the residential and non-residential buildings, the building area, and the number of buildings are computed so that the total construction and demolition waste is obtained for the specific range of years.

Ghosh et al. (2016) derived a mathematical equation whereby the quantity of CDW was found either by weight or volume. The weight of construction waste was formulated by multiplying the waste generation rate by the selected area of the activity; the waste generation rate being the quantity of one waste material divided the selected area. Another method estimates the construction waste by volume through multiplying the height of the waste by the total built surface.

De Guzmán Báez et al. (2012) proposed a linear equation to estimate the weight and volume of the waste generated from a railway project, whereby certain characteristics of the railway, such as the length of the railway and the number of intersections, are multiplied by their corresponding parameter from BEDEC database, a Catalan abbreviation for Structured Database for Construction Elements.

Two additional linear equations were proposed by Shi et al, (2006) to quantify CDW. The first equation estimates the construction concrete debris by multiplying the total amount of cement used in concrete mixes annually by an assumed percentage of cement waste production during process of construction, and divided by the typical cement percentage from the total amounts of all components in a concrete mix.

On the contrary, Katz et al. (2011) proposed an empirical model which was developed based on data collected monthly over a period of eight months from 10 construction sites undergoing either of the three construction stages including structural frame, early finishing, or late finishing. The data collected showed that during the beginning of the project where structural framework activities are occurring, a small amount of waste is generated. Early finishing work activities that follows the structural frameworks activities generate larger amounts of waste, and finally the late finishing activities result in the largest amount of waste. Based on the aforementioned data collected, the built model showed the accumulation of waste exponentially, revealing the increasing rate of waste generation over time.

Kern et al. (2015) developed several statistical models which were applied them to the case of 18 high-rise buildings. The statistical models involved dependent and independent variables, in which the fittest regression model of the sample data resulted in a value of R^2 of 0.694.

2.3 Waste Estimation Using Predictive Computer-Based Models

A Smart Waste Benchmark Calculator was developed not only to estimate the amount of construction waste for new buildings but also to reduce the environmental impacts by reducing the amount of waste and resources used. While Smart Waste can help in estimating and managing the construction waste, it is limited to projects in certain regions and requires keeping good record for accurate data (BRE, 2008).

Later, DeconRCM, a web-based system linking project information inputs to an algorithmic Excel based model, was proposed to quantify the construction waste rates (Figure 4) (Banias et al, 2011). DeconRCM utilizes two processes, demolition and renovation, in order to estimate accurately the quantity of different waste types. Data regarding project information such as the number of floors, type of building, etc. is inputted in DeconRCM. Moreover, a database regarding the necessary characteristics of disposal sites is used in a web mapping service application within the DeconRCM. The model thus outputs estimates of wastes based on the aforementioned database of a similar type of project. In addition, the system is constructed with mixed integer linear programming (MILP) model which provides the optimal management of the waste produced through taking into account the amount of waste and providing the optimal cost and rate of recycling such waste amount.

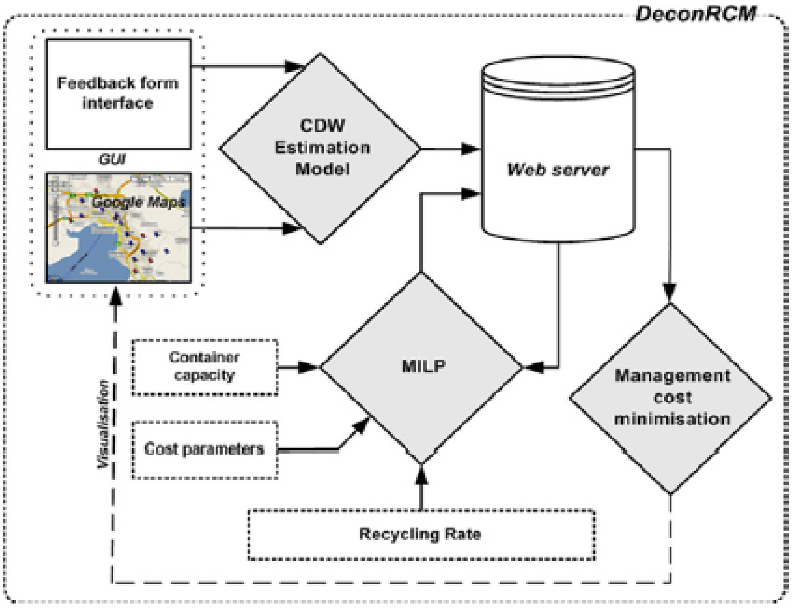


Figure 4 Structure of DeconRCM

Another web-based construction waste estimation system was introduced to provide accurate estimation of construction waste (Figure 5) (Li et al, 2013). This method requires developing a web based system of a construction project, first whereby the project is divided to elements, components, and systems. Second, the quantity for each material used in the delivery work packaging process is computed and converted into a common unit. After that, material quantities are then converted to weights and multiplied by the waste percentage dedicated for each material. Finally, the total construction, which is the summation of the individual waste, is calculated.

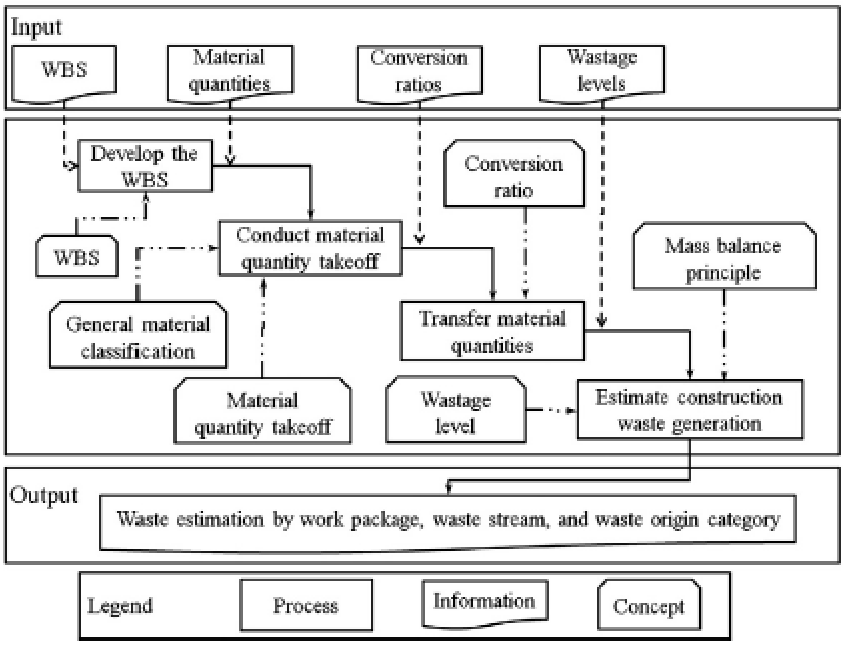


Figure 5 Web-based construction waste estimation system

Cheng et al. (2013) recommends using a BIM-based system to quantify the construction waste material. For that purpose, the BIM model built using Revit allows for the extraction of materials volume information and allows users to manipulate certain parameters such as width and height. The construction waste volume can be therefore computed by multiplying the extracted volumes by waste volume factors obtained from a database and subtracting the volumes reused and/or recycled. The model provides details of the construction waste by category and material. The model also allows the calculation of the waste disposal charging fee which is equal to the weight of the disposal waste multiplied by landfill charging per ton as well as the number of trucks used for hauling which is equal to the volume of total waste divided by the truck capacity.

Finally, Lu et al. (2016) proposes using S-curves to forecast the amount of construction waste generated. The methodology entails collecting landfill disposal records at different time intervals of the project. The disposal records are then entered along with other project parameters to calibrate an artificial neural network (ANN) model. The model identifies the best form for the S-curve using curve-fitting whereby the best form generates the least mean-square error. The model is then used to forecast the quantity of waste for new projects whereby the S-curve for the construction waste generated is then derived. The developed model is case and context specific and requires significant manual effort in collecting landfill records. Table 2 provides a summary of the construction and demolition waste quantification techniques discussed above.

Table 2: Summary of CDW Quantification Methods

Author/Year	Description
Shen et al, 2005; Bossink et al, 1996	On-site measurement of waste rates through sorting and weighing each material waste and comparing them to the amount of material purchased
Bakshan et al, 2015	Site visits to estimate the quantity of waste generated on site on the basis of purchase records and actual quantities of materials used
Llatas, 2011; Mahayuddin et al, 2013	Waste generation is obtained by weighing the waste generated from a stage of the project and dividing it by the project's gross floor area, and finally summing up the results to obtain the total waste generated at each stage
Poon et al, 2004	Estimating the amount of construction waste by relying on truck load records from sites
Kartam et al, 2004	Estimating construction waste by relying on truck records from landfill
McBean et al, 1993	Estimating waste by summing individual household constituent waste and industrial constituent waste
Yost et al, 1996	Waste generation obtained by multiplying the waste generation per financial value by the total financial values
Lage et al, 2010	Construction waste generation rate is multiplied by the project area
Poon, 1997	Demolition waste whose weight is equal to the weight of the constructed structure
Cochran et al, 2010	Demolition waste is the amount of materials discarded subtracted from the materials purchased

Wimalasena et al, 2010	Quantifying waste with respect to human and non-human factors involved
Lau et al, 2008	Estimation of waste by understanding dimensions of “waste piles”. This is based on the assumption that the waste can have either a pyramidal shape or a rectangular shape and its volume is calculated accordingly
Solis-Guzman et al, 2009	Identifying items from the BOQ and multiplying the quantities by their corresponding coefficients obtained from the Andalusian Construction Costs Database
Ding et al, 2014	Linear equation to calculate the total CDW in a region based on the summation of the area of the constructed or demolished buildings multiplied by average waste generation per building area during construction or demolition
Miguel et al, 2016	Estimating waste through collection of data for buildings of different types and ages
Ghosh et al, 2016	Quantity of construction and demolition waste is found either by weight or volume
De Guzmán Báez et al, 2012	Linear equation to estimate the weight and volume of waste generated from a railway project, where certain characteristics of the railway are multiplied by their corresponding parameter from a database
Shi et al, 2006	Linear equation based on multiplying total amount of cement used in concrete mixes annually by an assumed percentage of cement waste production during process of construction
Katz et al, 2011	Empirical models (exponential functions) derived based on data collected monthly over a period of eight months from 10 construction sites undergoing either of the three construction stages including structural frame, early finishing, or late finishing
Kern et al, 2015	Determining the amount of waste in construction for the case of 18 high-rise buildings
BRE, 2008	Smart Waste Benchmark Calculator to estimate the amount of construction waste for new buildings and to reduce the environmental impacts
Banias et al, 2011	DeconRCM which links project information inputs (e.g., number of floors, type of building) to a built-in web mapping service application (e.g., GIS database of landfills)
Li et al, 2013	Web based system whereby each material weight is multiplied by its corresponding waste percentage
Cheng et al, 2013	BIM model built using Revit which allows for the extraction of materials volume information which are then multiplied by waste volume factors obtained from BAAC cost database
Lu et al, 2016	Artificial neural network (ANN) model whereby landfill disposal records are entered along with other project parameters and the model identifies the best form for the S-curve

CHAPTER 3

RESEARCH OBJECTIVES AND METHODOLOGY

3.1 Problem Statement

Construction waste contributes significantly to global waste. Statistics show that out of the total weight of materials supplied to a construction site, 10 to 20 percent are misspent (Begum et al, 2009), contributing to the growth in global construction waste. This issue is dreadfully depleting the economic and environmental welfare of the concerned countries worldwide. To make things worse, several parts of the world are suffering from a progressive decline in landfill spaces. Lebanon is a good example. To tackle these issues, proper waste management techniques such as recycling of construction waste should be adopted. The first step is to improve the accuracy of estimate waste generation rates.

3.2 Aim of the Study

This study proposes a methodology to determine the required design capacity of a construction waste recycling plant, an essential parameter for recycling plant design, which if implemented could help achieve environmental and economic benefits. In order to achieve that, accurate forecasting and quantification of construction waste rates over time is adopted as an initial step.

3.3 Gap in Literature

As shown in Chapter 2, the construction waste quantification methods mentioned in the literature are context specific and require significant amounts of field data collection. Additionally, they do not leverage advanced design concepts (e.g., BIM), which offer the potential of estimating the amounts of waste on a timely basis (e.g. hourly, daily, monthly).

3.4 Research Methodology

This research proposes a BIM based generic methodology for construction waste forecasting and quantification on a timely basis (e.g. hourly, daily, or monthly). The proposed method is automated and takes into account project specific information. The method adopts the use of BIM tools (e.g., Revit and Navisworks) and the concept of S-curves to estimate and represent waste generation rates.

As such, a BIM 4D model is developed in Navisworks through the interplay of a Revit 3D model and a Primavera schedule. Through an automated process developed by macros in a Microsoft Excel Form, defined as Waste Quantification Excel template, project information are exported from Revit, Primavera, and Navisworks to the Excel template form whereby the user (e.g., contractor) can input estimates of construction waste percentages for different materials and elements. Anylogic is then used to generate random values of waste percentage rates following a triangular distribution. The Excel template is then used to estimate waste quantities over time depicted by cumulative S-curves.

The quantification of construction waste generated over time allows for determining an essential parameter in designing a recycling plant (i.e. nameplate capacity). In other words, the study serves to determine the actual capacity needed for a construction waste recycling plant, which is if implemented, would help achieve environmental and economic benefits.

CHAPTER 4

PROPOSED PROCESS TO GENERATE WASTE S-CURVES

An automated process for the generation of construction waste S-curves presenting time-based waste quantities is developed through the use of a combination of Revit, Dynamo (Revit add-in), Primavera, Macro-Enabled Excel Template, and Navisworks. The aim is to provide contractors with a management tool that would automatically generate the necessary construction waste management data. The proposed process, including all related documents, is presented in a detailed chart (Figure 6). The chart includes three swim lanes (Table 3):

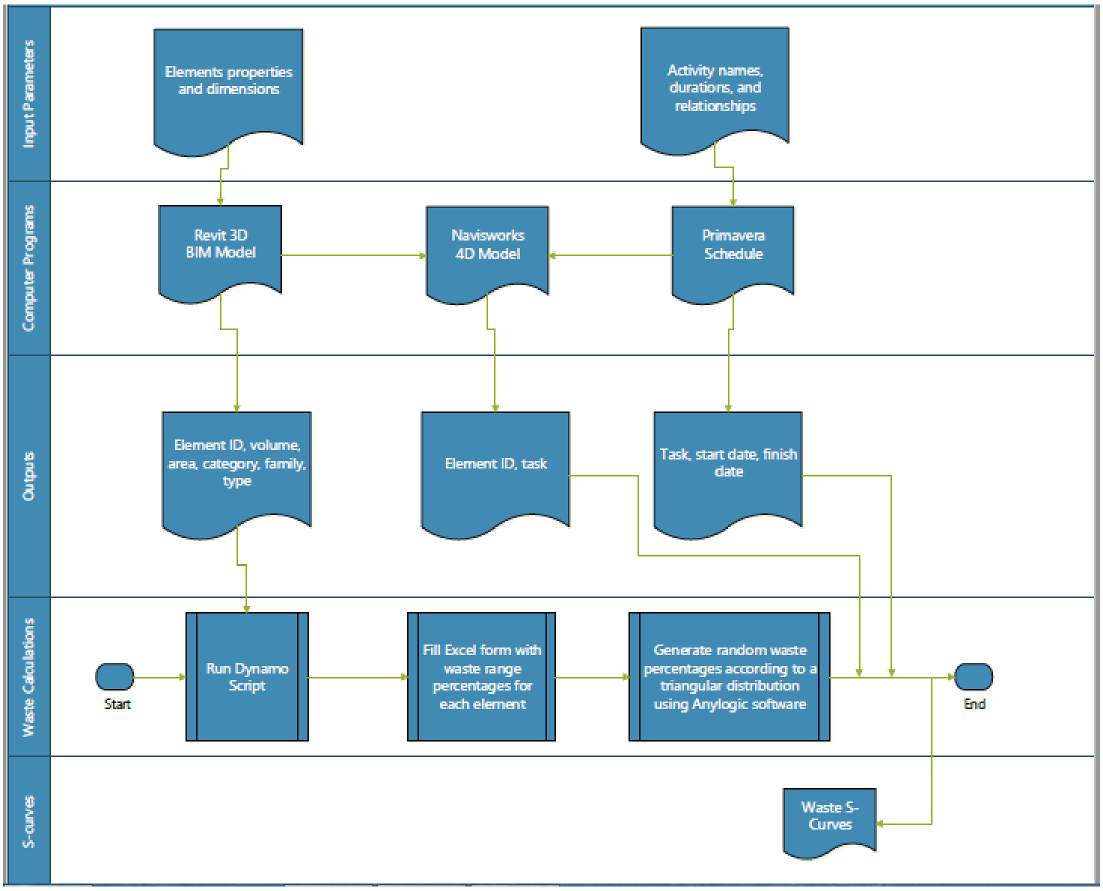


Figure 6 Automated Waste S-Curves Generation Process

Table 3: Description of Process Chart's Swim Lanes

Swim Lane Titles	Description
Computer Programs	Documents that are expected to be developed initially irrespective of the waste management process. In all cases, these are prerequisites to the successful completion of the proposed automated process.
Waste Calculations	Steps to be undertaken to achieve the desired outputs.
S-curves	The end-result (outputs) of the process at completion.

4.1 Input Parameters and Computer Programs

As a first step, a Revit 3D model is to be developed. This document represents the project design and components. The "Automated Waste S-Curves Generation Process" can be applied only to the elements included in the model. Elements that are not modeled will naturally not have any waste data generated. As part of the process, waste range percentages are assigned by model element types. Revit Hierarchy is as follows: *Category (e.g. Wall), Family (e.g. Basic Wall), and Type (e.g. Generic – 200 mm)*. Therefore, this process takes into account the lowest level of Revit's element categorization to provide the contractor with as much flexibility as possible. The implication of this process is that all elements pertaining to the same type will have the same waste range percentages. For example, waste range percentages may vary depending on the construction method *(e.g. concrete pump versus chute).* In such an instance, more than one type will have to be created for the same element to reflect this distinction.

Second, the project schedule has to be available, whether in Primavera P6 or equivalent. The adopted software should allow for exporting the schedule in CSV format with at least the following data: *Activity ID, Activity Name, Start Date, and Finish Date.*

Finally, a Navisworks 4D model is to be developed, which requires that a Revit 3D model is exported to Navisworks and then linked to the project schedule. Each element present in the model is linked to one of the scheduled tasks. The waste S-Curves that will be generated as a result of this process will be as accurate and as precise as the available 4D model. This is why waste S-curves precision will depend on the level to which the schedule is dissected.

4.2 Computer Programs Outputs and Waste Calculations

A list of properties including *Category, Family, Type, Element ID, Volume, and Area* for each element in the Revit 3D model are then exported to the Excel Template, through the use of Dynamo, a Revit add-in. For elements where volume or area is not applicable *(e.g. a window does not have a volume in Revit),* a value of 0 is assigned, therefore not affecting future calculations. The Excel Template is used to centralize the data extracted from Revit, Navisworks, and Primavera. It is the file that will be the interface with the user *(e.g. the contractor).* The Excel Template can be divided into two components: *Visible Components* to the user and *Hidden Components* from the user used for calculation purposes. Figure 7 summarizes the data exchange as part of the process from a platform to another.

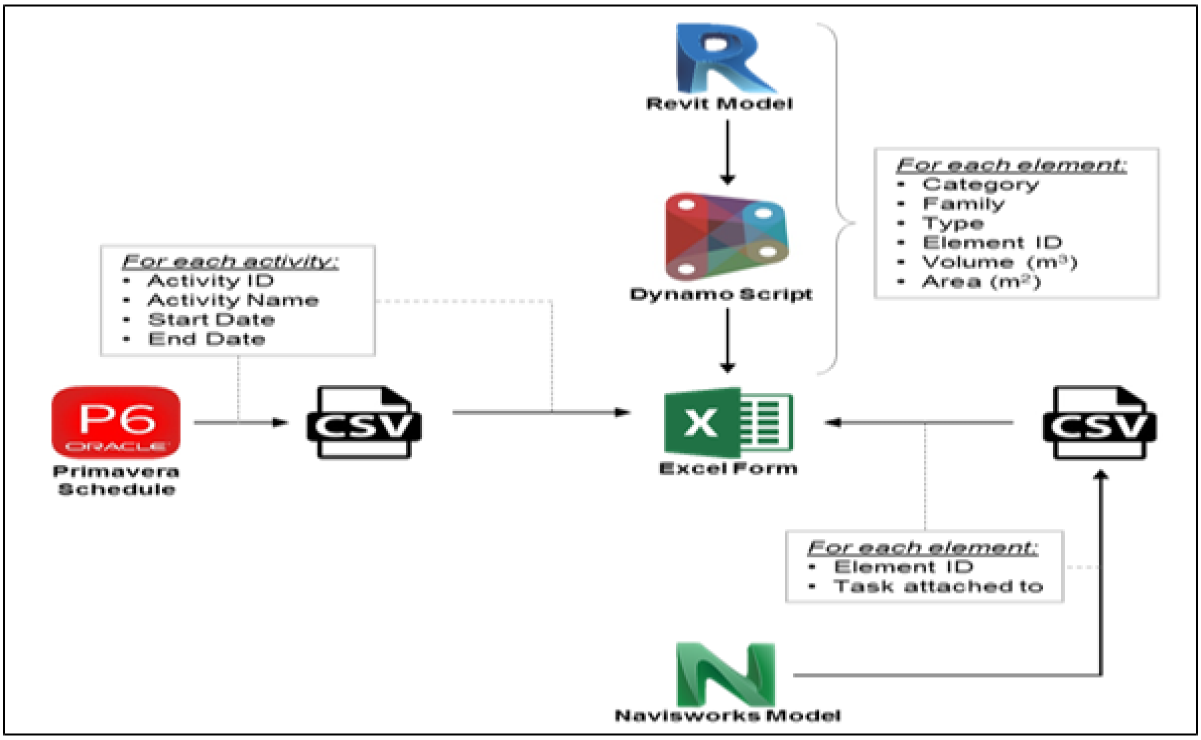
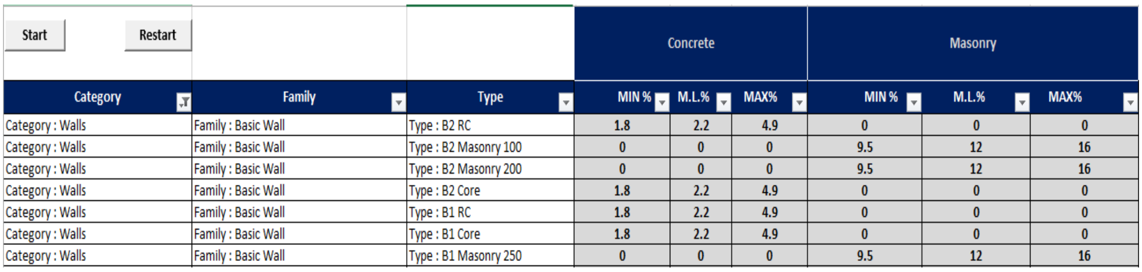


Figure 7 Platforms for Data Exchange

4.2.1 Visible Components

Once the Dynamo script is run, the Excel Template is automatically opened resulting in an empty table with column headers and two macro-enabled buttons. In fact, the table is not empty, as it includes as many rows as there are elements in the Revit model. However, these rows are hidden. Once the user clicks on the first button labeled *"Start"*, the macro behind this button results in revealing to the user the unique element types. In order to keep the process flexible, the materials and waste range percentages will have to be filled by the user. All duplicates are filtered out, meaning if multiple elements have the exact same properties (category, family, type), the properties will appear once to the user thus optimizing the process by allowing the user to fill in the waste range percentages once instead of filling these values for each single element.

In the case where an element is made of only one material *(e.g. concrete)*, the user will simply input 0 as the waste percentage for the other materials for that same element. Figure 8 illustrates the table view after clicking on the *"Start"* button and after it was filled.



Category	Family	Type	Concrete			Masonry		
			MIN %	M.L.%	MAX%	MIN %	M.L.%	MAX%
Category : Walls	Family : Basic Wall	Type : B2 RC	1.8	2.2	4.9	0	0	0
Category : Walls	Family : Basic Wall	Type : B2 Masonry 100	0	0	0	9.5	12	16
Category : Walls	Family : Basic Wall	Type : B2 Masonry 200	0	0	0	9.5	12	16
Category : Walls	Family : Basic Wall	Type : B2 Core	1.8	2.2	4.9	0	0	0
Category : Walls	Family : Basic Wall	Type : B1 RC	1.8	2.2	4.9	0	0	0
Category : Walls	Family : Basic Wall	Type : B1 Core	1.8	2.2	4.9	0	0	0
Category : Walls	Family : Basic Wall	Type : B1 Masonry 250	0	0	0	9.5	12	16

Figure 8 Excel Template content after "Start" button click and filled by user

The waste range percentages are then simulated in Anylogic to account for the variability associated with material waste quantities on construction sites. Moreover, simulation allows for the consideration of a wide array of scenarios rather than a single point estimate. The overall framework for the simulation is shown in Figure 9. The developed simulation tool connects to the waste quantification Excel template, and acquires three waste point estimates for every element included in the Revit Model. For the purpose of this tool, we focused on concrete, masonry, plaster, and ceramic materials which are the major contributors to waste generation on construction. Once acquired, the developed simulation tool uses these estimates to build triangular distributions for the different materials. Each of these distributions is then used to generate 30 random observations, which in their turn are sent to the Excel waste template. This particular number of random number generations is selected in order to maintain normality of the variables, and in order to diminish any possible impact of outliers.

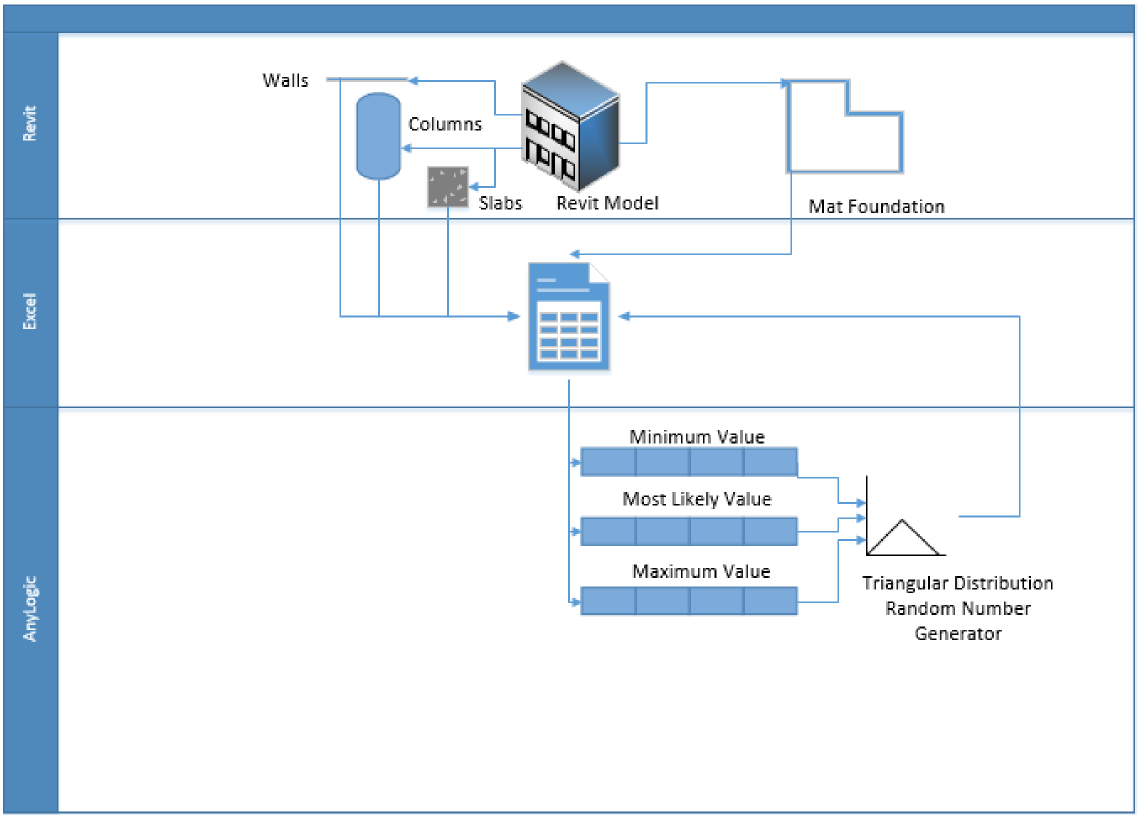


Figure 9 Overall Framework for the simulation

Once the 30 random waste percentages are generated and sent to the Excel template, the minimum, most likely, and maximum waste percentage for each element can then be computed through the following equations:

$$Wmin\,\% = \frac{1}{n} * \sum_{i=1}^{n} a_i - (2 * \sigma) \qquad (1)$$

$$Wmost\ likely\,\% = \frac{1}{n} * \sum_{i=1}^{n} a_i \qquad (2)$$

$$Wmax\,\% = \frac{1}{n} * \sum_{i=1}^{n} a_i + (2 * \sigma) \qquad (3)$$

Where: W_{min} % = minimum waste percentage (%), $W_{most\ likely}$ % = most likely waste percentage (%), W_{max} % = maximum waste percentage (%), n = number of values generated from the probabilistic distribution, $\sum_{i=1}^{n} a_i$ = the sum of the n values generated from the probabilistic distribution, σ = standard deviation, and $\frac{1}{n} * \sum_{i=1}^{n} a_i$ = the average of the n values generated from the probabilistic distribution.

Finally, in case where the model is updated and running the Dynamo script needs to be repeated, a macro behind the *"Restart"* button is simply used to erase all extracted data.

4.2.2 Hidden Components

The first hidden component is a sheet that is connected to *"External Data"* which means that the sheet content would change as the external data source changes. The *"External Data"* source in this study is the exported CSV file from Navisworks. It consists of *"Element ID"* and *"Contained in Task"* for each element. The *"Contained in Task"* column presents for each element the task to which it is assigned. Each element can be assigned to more than one task, and more than one element can be assigned to the same task. Accordingly, the waste quantities for a specific task is the sum of waste quantities for all the elements assigned to that task.

The second hidden component is a sheet including sixteen columns (Table 4). *"Element ID", "Volume (m^3)" and "Area (m^2)"* are filled when the Dynamo Script is run, as data extracted directly from the Revit model. Moreover, the materials waste quantities are filled based on the following equations:

$$Wmin = (Wmin\,\% \; * Q)/100 \qquad (4)$$

$$Wmost\ likely = (Wmost\ likely\,\% * Q)/100 \qquad (5)$$

$$Wmax = (Wmax\,\% * Q)/100 \qquad (6)$$

Where: W_{min} = minimum waste (m^3 or m^2 as applicable), $W_{most\ likely}$ = most likely waste (m^3 or m^2 as applicable), W_{max} = maximum waste (m^3 or m^2 as applicable), W_{min} % = minimum waste percentage (%), $W_{most\ likely}$ % = most likely waste percentage (%), W_{max} % = maximum waste percentage (%), Q = quantity as extracted from Revit using Dynamo (m^3 or m^2 as applicable).

Later, the *VLOOKUP* function is used in order to look for the waste quantities of each *"Element ID"* and assign each "*Activity Name"* to its corresponding waste quantities.

Table 4: Hidden Waste Quantities

				Concrete Waste (m^3)			**Masonry Waste (m^2)**			**Plaster Waste (m^2)**			**Ceramic Waste (m^2)**		
Element ID	**Volume (m^3)**	**Area (m^2)**	**Min**	**M.L.**	**Max**	**Min**	**M.L.**	**Max**	**Min**	**M.L.**	**Max**	**Min**	**M.L.**	**Max**	**Activity Name**
288423	1.732	6.929	1.0	1.06	1.11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	B2 RC Walls
288563	3.209	12.836	4.6	9.4	14.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	B2 RC Walls
288680	5.138	20.553	9.9	15.5	21.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	B2 RC Walls

The third hidden component is another sheet connected to another external data source. The *"External Data"* source is the exported CSV file from Primavera. In addition to the data source, additional columns are added with formulas. The purpose of these columns is to calculate the waste quantities for each activity as shown in Table 5. The column labeled *"Duration (days)"* is simply the difference between the start date and end date columns. The remaining columns, which are the waste quantities, are calculated based on the following formula:

$$TW_{Ax} = \sum_{E1_{Ax}}^{En_{Ax}} W\, En_{Ax} \quad (7)$$

Where: TW_{Ax} = total waste generated by activity x (m^3 or m^2 as applicable), $E1_{Ax}$ to En_{Ax} = all n elements assigned to activity x, WEn_{Ax} = waste for element n pertaining to activity x (m^3 or m^2 as applicable).

This is accomplished through the use of the SUMIF function in Excel: *"=SUMIF ([Activity Name Column from Table 4], [Activity Name], [Waste Quantity Column from Table 4])".*

Table 5: Summary of the waste quantities for each activity

Activity	**Duration (days)**	**Concrete Waste (m^3)**			**Masonry Waste (m^2)**			**Plaster Waste (m^2)**			**Ceramic Waste (m^2)**		
		Min	**M.L.**	**Max**	**Min**	**M.L.**	**Max**	**Min**	**M.L.**	**Max**	**Min**	**M.L.**	**Max**
Mat Foundation	16	6.34	9.89	13.54	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
B2 Columns	12	0.34	0.62	0.91	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
B2 RC Walls	16	1.39	2.65	3.92	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Etc.	…	…	…	…	…	…	…	…	…	…	…	…	…

4.3 S-curves

The Waste S-Curves are part of the automated process outputs. As shown in the process chart, at the end of this process, a new sheet appears in the Excel template which consists of graphs presenting the Waste S-Curves for the different materials.

CHAPTER 5

CASE STUDY

5.1 Description

In order to check how the proposed waste quantification tool is used in practice, and to calibrate mathematical S-curve function depicting waste generation rates over project duration, the methodology discussed in the previous section was tested on a construction project situated in Beirut, Lebanon. The project consists of a six-floor residential building with two basements and four above ground floors, and with a total built up area of 2,300 m^2.

Through the use of BIM based and schedule planning software, an automated construction waste quantification process is proposed which aims at quantifying the amount of construction waste generated over time. The process, therefore, results in S-curves for construction material waste, including concrete, masonry, plaster, and ceramic wastes. In that regard, the approach consists of developing a 3D model and schedule for the project. Through the assembly of the 3D model and the project schedule, a 4D model is developed in order to quantify the construction materials over time. The aforementioned steps provide the major inputs for the automated construction waste quantification process which results in the generation of construction material waste S-curves.

5.2 3D Model and Project Schedule

The structural and architectural AutoCAD drawings prepared by the project's contractor are retrieved and used as a reference to develop the 3D model using

Autodesk Revit (Figure 10). The AutoCAD drawings provide the used construction elements with their corresponding dimensions and constituent materials. These construction materials were defined in Autodesk Revit in accordance to their corresponding structural and architectural elements. Moreover, the project schedule was developed using Oracle Primavera and data obtained from the project's contractor. This data includes the actual work breakdown structure of the project resulting in a number of construction activities. The data also foresees the duration for each construction activity and the relationship between these construction activities.

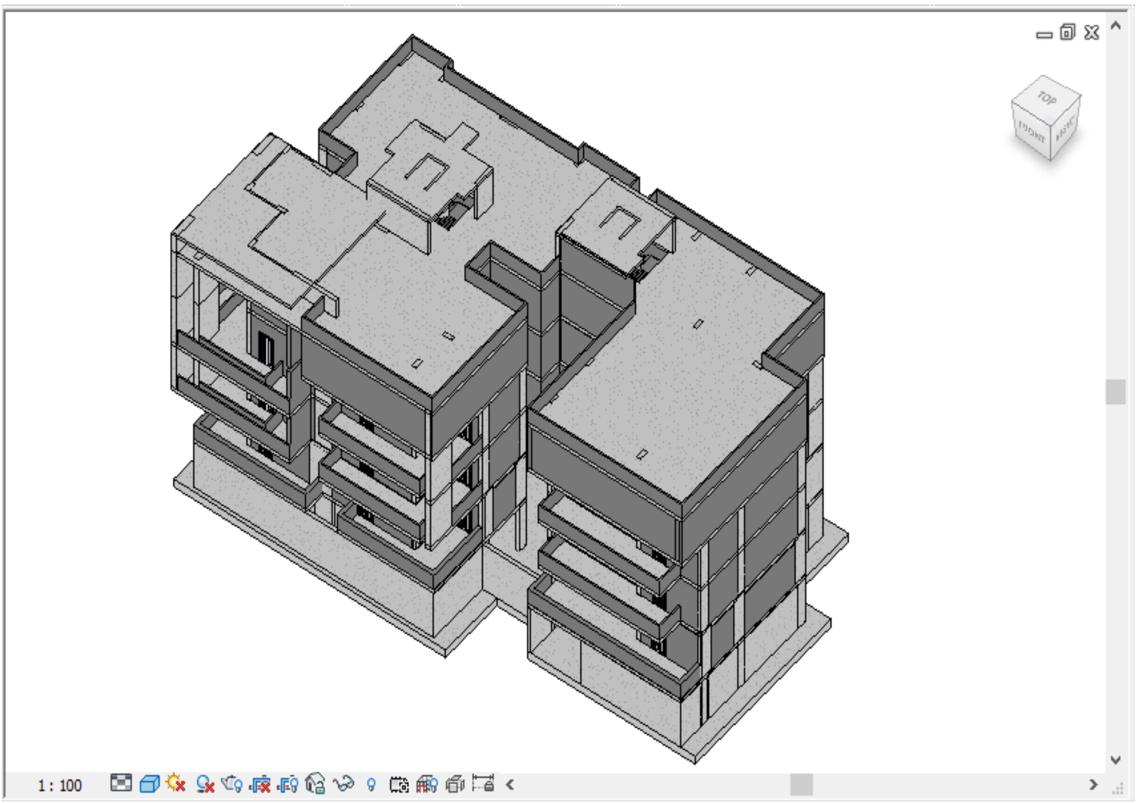
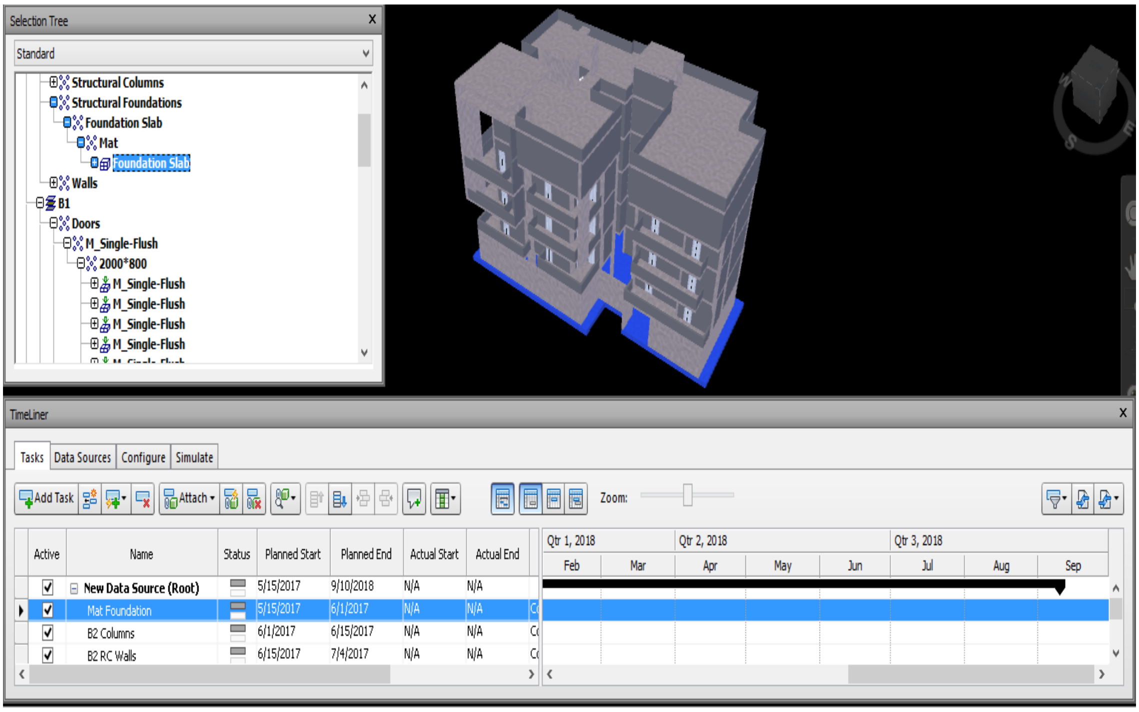


Figure 10 Revit 3D Model of the Construction Project

5.3 4D Model and BOQ

The 4D model was developed using Autodesk Navisworks after the project’s 3D model and schedule were exported to Navisworks and each element in the 3D model was assigned to its corresponding activity in the project’s schedule. The quantification option in Navisworks aided in quantifying the elements included in each activity. Therefore, the resulting material quantities represents the amount of material required over the duration set for each activity. For example, the volume of the mat foundation obtained from Navisworks represents the volume of concrete required over the defined duration for the mat foundation activity in the project’s schedule (Figure 11). Finally, the total material quantities, including the total quantity of each of concrete, masonry, plaster, and ceramic were compared to the total amounts presented in the bill of quantity.



Active	Name	Status	Planned Start	Planned End	Actual Start	Actual End
☑	**New Data Source (Root)**		5/15/2017	9/10/2018	N/A	N/A
☑	Mat Foundation		5/15/2017	6/1/2017	N/A	N/A
☑	B2 Columns		6/1/2017	6/15/2017	N/A	N/A
☑	B2 RC Walls		6/15/2017	7/4/2017	N/A	N/A

Figure 11 Selected mat foundation and its corresponding activity (Navisworks)

5.4 Quantities from Navisworks versus Quantities from BOQ

The total material quantity, obtained through Navisworks, was compared to that in the BOQ on the basis of percentage difference between the aforementioned two quantities. A resulting range of 0.9 to 12.1 percentage difference was observed to be normal. The amounts presented in the BIQ are not exact and are rather the contractor's estimates based on a previous experience of a similar type project. Moreover, in a contract of a lump sum nature, the contractor tends to increase the materials quantities that are of a higher price, and while maintaining a balance to bid with the lowest cost, the contractor decreases the material quantities that are of a relatively lower cost. As shown in Table 6, the total amount of concrete, and ceramic-tiles presented in the BOQ were higher than those that are actually required, whereas the total quantities of masonry and plaster were found to be less in the BOQ than the actual quantities required.

Table 6: Actual quantities versus educated estimates

Tasks	Autodesk Navisworks	Bill of Quantity	% Difference
Concrete Works	1105	1200	7.9
Masonry Works	2631	2416	8.2
Plastering Works	7815	7748	0.9
Tiling Works	2637	3000	12.1

5.5 Quantify Construction Waste

After developing the 4D model in Navisworks, each construction *"Element ID"* and *"Activity Name"* was exported to the hidden sheet in the Excel template described in the previous section. The Primavera schedule was as well exported to the hidden sheet in this Excel Template. It contains the *"Activity Name"* and the *"Start Date"* and *"Finish Date"* for each activity. Moreover, data consisting of list of properties for each construction element in the 3D model was extracted from Revit after running the dynamo script in Revit and pressing start button on the Excel Template. The aforementioned list of properties include each element's *"Category", "Family", "Type", "Element ID", "Volume",* and *"Area".* Duplicates of the list of properties were filtered out - this is just to make it easier for the user to fill his/her estimates of waste range percentages.

After that, the waste range percentage (minimum, most likely, maximum) for each material and for each category were filled. The percentages used in this study are the 25th percentile (Q1), median, 75th percentile (Q3) of the waste percentages retrieved from previous studies (Table 7). Figure 12 presents the distribution of the waste percentages for each waste stream graphically.

Table 7 Material Waste Percentages

Material Waste	Waste Percentage Distribution					References
	MIN	Q1	MEDIAN	Q3	MAX	
Concrete Waste	1	1.8	2.2	4.9	12	Pinto, 1989 Soibelman et al, 1994 Pinto et al, 1994 Poon et al, 2004 Rameezdeen et al, 2004 Bergsdal et al, 2007 Zhao et al, 2010 Coelho et al, 2011 Coelho et al, 2013 Mercader-Moyano et al, 2013 Alireza Asgari, 2017
Masonry Waste	2.9	9.5	12	16	23	
Plaster Waste	1.01	3.25	4.3	4.6	6.25	
Ceramic Waste	0.32	1.1	5	10.1	16	

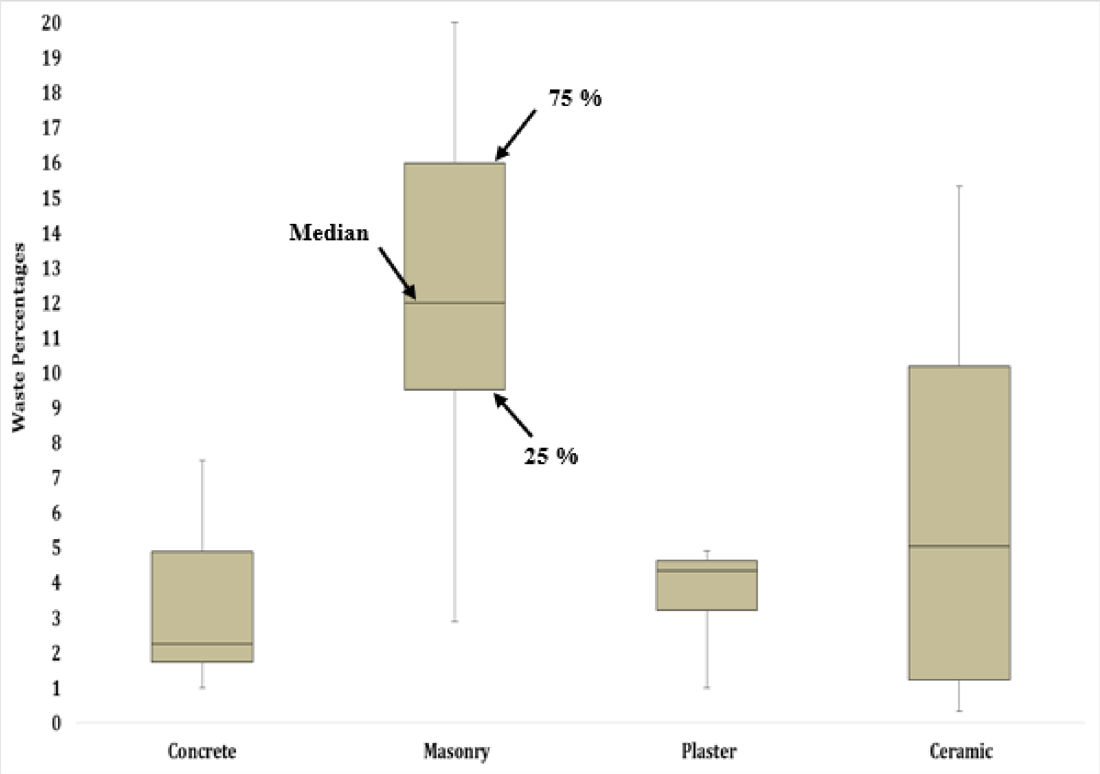


Figure 12 Box and whisker for material waste percentages

The waste range percentages were then simulated in Anylogic generating a triangular distribution of waste percentages for each element and material. Later, the construction waste quantification was done for each *"Element ID"* through the use of the equations discussed earlier. Each *"Activity Name"*, for which *"Duration (days)"* was defined, was then assigned to its corresponding *"Element ID"* through the use of *VLOOKUP* function and the waste quantities corresponding to the same *"Activity Name"* were summed up using the *SUMIF* function.

Finally, three waste S-curves for each material, representing the cumulative quantities of each waste material is plotted versus time, were then obtained (Figures 13, 14, 15, and 16). The project's construction schedule lasted approximately 18 months. However, the vast majority of concrete, masonry, plaster, and ceramic waste was generated in the first year of construction.

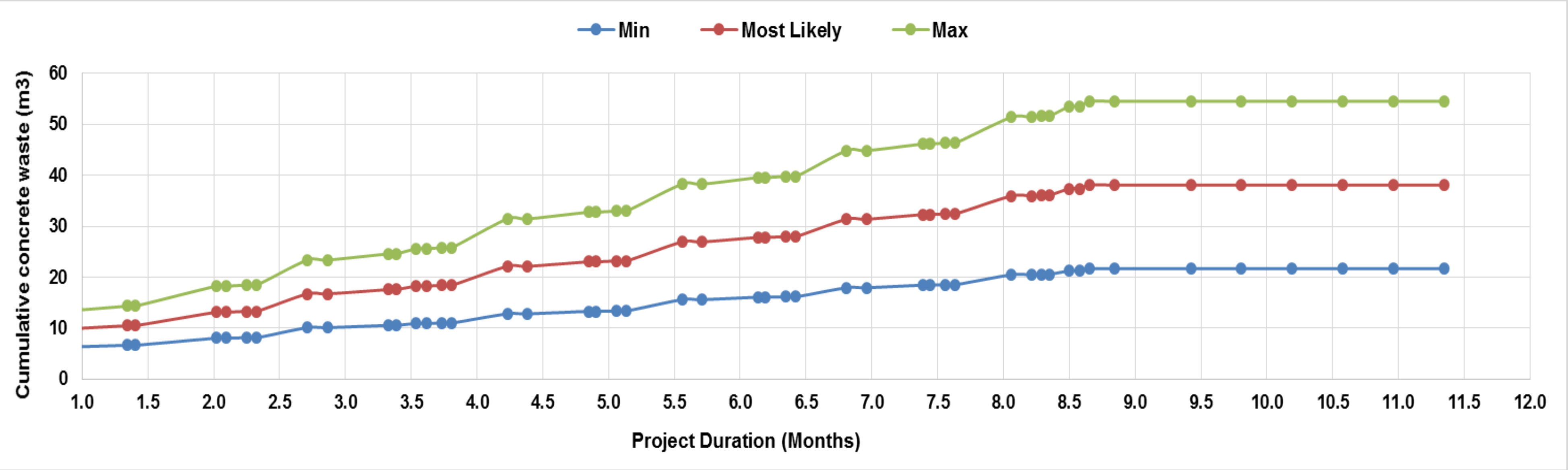


Figure 13. Cumulative concrete waste quantities (m^3) versus Months

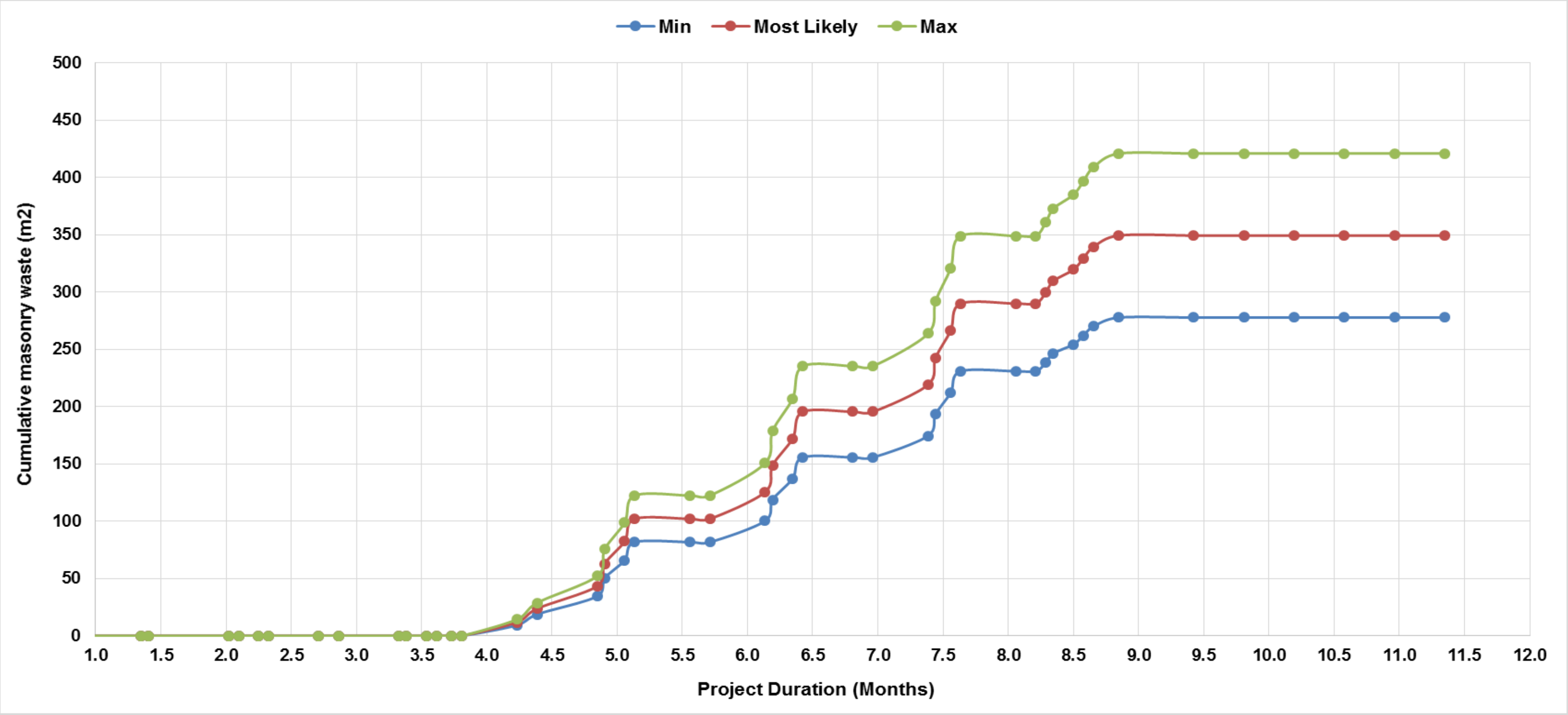


Figure 14 Cumulative masonry waste (m^2) versus Months

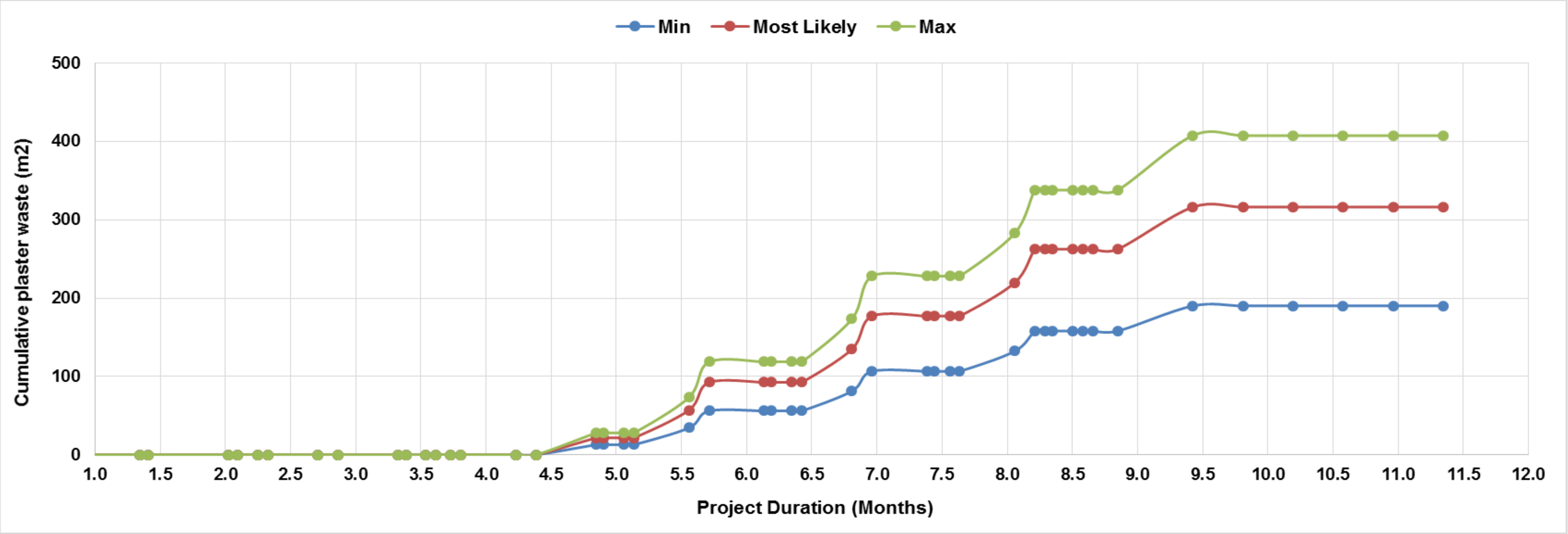


Figure 15 Cumulative plaster waste (m^2) versus Months

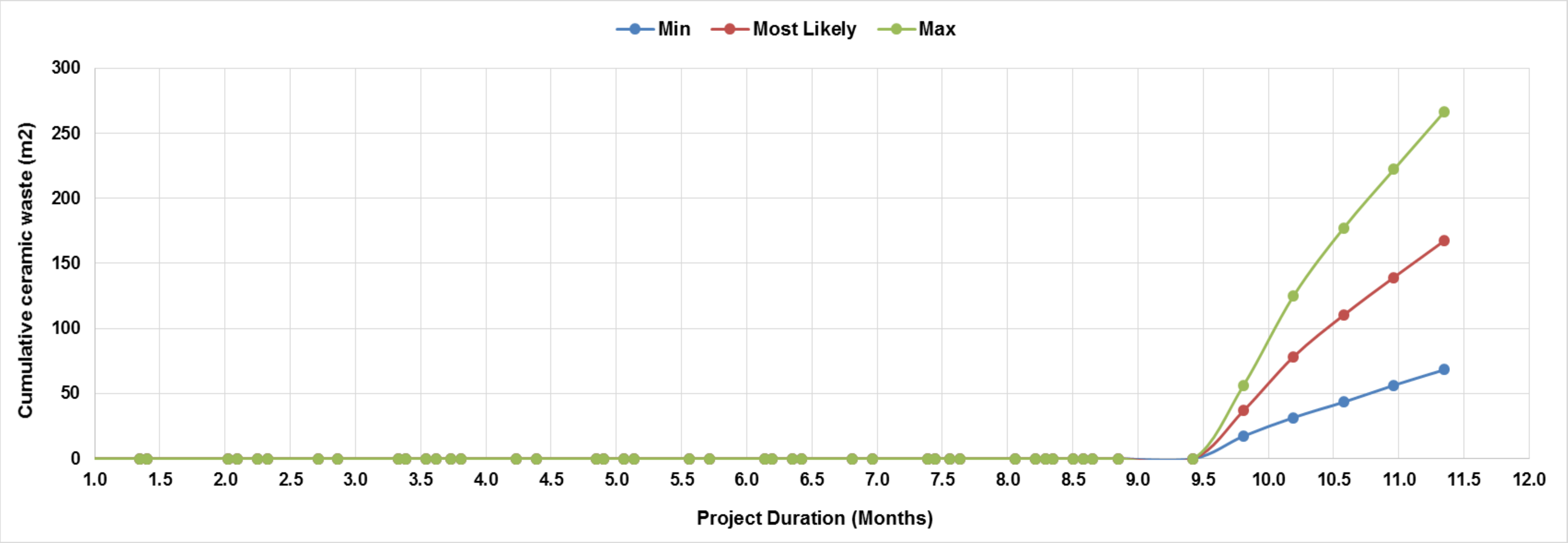


Figure 16 Cumulative ceramic waste (m^2) versus Months

5.6 Design Recycling Plant Required Capacity

The quantification of construction waste rates over time served as a baseline for estimating waste from three types of construction projects (low rise building, middle rise building, high rise building) in Beirut. Therefore, a set of project specific construction waste S-curves were generated visualizing the waste generation rates across the multiple stages of construction. Using the case study's project duration (t) and cumulative quantities of waste (y), best fit curves were developed. The cumulative quantities of each material waste were at first normalized. For example, the cumulative concrete waste during each month was divided by the total amount of concrete waste. Moreover, knowing that the S-curve is of a sigmoidal function, the normalized curve fit waste quantities can be computed through the following equation:

$$y_{ncf} = \frac{1}{1+exp^{-(a)*(t-c)}} \quad (8)$$

Where: y_{ncf} = normalized curve fit waste quantities, t = case study duration presented per month, a and c = parameters defined such as the average error between normalized curve fit waste quantities and case study normalized waste quantities is minimal.

The parameters a and c are obtained through the solver function in Excel which minimizes the error representing the difference between the normalized curve fit waste quantities and the case study normalized waste quantities. The normalized curve fit waste quantities were then multiplied the cumulative quantity of waste, originally used to normalize the case study waste quantities, in order to obtain the actual curve fit waste quantities ($\hat{y}$).

Moreover, the mean squared error (M.S.E) was computed through the following equation in order to check how close the curve fit is to the data points:

$$\text{M.S.E} = \left(\sum \frac{|(y-\hat{y})|}{y} \right)\text{\^{}}2 \quad (9)$$

Where: y = case study cumulative waste quantities, ŷ = actual curve fit waste quantities.

The closer the M.S.E value is to 0, the closer the actual curve fit waste quantities are to the case study cumulative waste quantities. Table 8 presents the values obtained for mean squared error, as well as the parameters *a* and *c* for each material including concrete, masonry, plaster, and ceramic.

Table 8: Curve fit resulting values

Material Parameters	Concrete	Masonry	Plaster	Ceramic
M.S.E	5.00	11.90	7.67	0.01
a	0.43	1.24	1.22	2.49
c	3.63	6.43	7.05	10.32

The parameters *a* and *c* are then used as inputs to generate cumulative waste quantities over project duration for three types of projects including low rise, middle rise, and high rise buildings. Data regarding the three types of buildings (Table 9) were collected from a contractor in Lebanon and includes information about the total project duration, and total built up area. The data presents as well the total quantities for each of concrete, masonry, plaster, and ceramic from which the total waste quantity for each material was computed by multiplying the total material quantity by its corresponding most likely waste percentage used earlier in this study.

Table 9: Data regarding three types of buildings

Data	**Low Rise Building**	**Middle Rise Building**	**High Rise Building**
Total Concrete Quantity (m^3)	440	2200	4500
Total Masonry Quantity (m^2)	400	3000	5500
Total Plaster Quantity (m^2)	800	6000	11000
Total Ceramic Quantity (m^2)	990	4000	9000
Total Project Duration (months)	12	24	36
Total Built Up Area (m^2)	900	2500	7500

The estimated cumulative waste quantity for each material was then computed during each month towards the end of the specified total number of months for the project using the following equation:

$$z = \frac{1}{1+exp^{-(a)*(t-c)}} * twq \quad (10)$$

Where: z = estimated cumulative waste quantity for a specific material during each month, twq = total waste quantity for a specific material.

Later, in order to estimate the amount of construction waste in Beirut region, data regarding the number of new construction during year 2018 was obtained from "Order of Engineers and Architects" website (Order of Engineers and Architects, 2019). An assumption was taken such that the total number of newly constructed buildings during that year was divided by three, each portion representing the number of low rise buildings, middle rise buildings, and high rise buildings, where such number was then multiplied by the obtained waste quantities (z).

Furthermore, the total waste quantity of each material generated in year 2018 was computed as the summation of the cumulative waste produced from the number of newly constructed low, mid, and high rise buildings

Finally, the total waste quantity of all the materials were converted into a common unit (m^3), and then into tons based on multiplying the total waste quantity of each material by its corresponding density (Table 10). The total waste quantity for all the materials were then summed up and divided by the total number of working hours per year in order to obtain the required recycling plant capacity which was found out to be 204 tons/hour (Table 10). This value assumes 8 working hours per day, 5 working days per week, and 52 weeks per year.

Table 10: Recycling Plant Required Capacity

Material	**Total Material Waste (m^3)**	**Density (tons per m^3)**	**Total Material Waste (tons)**	**Total Waste (tons)**	**Recycling Plant Required Capacity (tons per hour)**
Concrete	91,028	2.5	227,570	$\sum of\ total\ material\ waste\ (tons)$ $= 424, 260$	$424{,}260/\ (8 * 5 * 52)$ = 204
Masonry	93,946	1.5	140,919		
Plaster	3,589	1.9	6,819		
Ceramic	12,238	4	48,952		

Environmental benefits were assessed on the basis of water and energy savings, as well as greenhouse gas emissions reduction. USGS 2011 standards, EPA 2016c, and EPA 2003 were used to provide baseline values for water, energy, and greenhouse gas emissions reductions associated with recycling per ton of construction waste including concrete, masonry, plaster, and ceramic. For example, recycling 1 ton of these wastes could save around 1,360 gallons of water (USGS 2011), 0.11 million BTU (EPA 2016c), and 0.0021 MTCE (EPA 2003).

Moreover, economic benefits were quantified with respect to employment, wages, and tax revenue. For that, the Recycling Economic Information report (EPA 2016a) was used as it specifies the attributes for jobs, and tax revenue for every short ton of waste recycled. For example, 1,000 short ton (i.e. 907.185 tons) of recycled material attributes 1.57 jobs, and $14,101 in tax revenues (EPA 2016a).

Assuming that the total amount of waste is sent to the recycling plant, the environmental benefits in terms of total water, energy, and greenhouse gases that would be saved and the contribution of these wastes to the economic benefits were calculated (Table 11).

Table 11: Environmental and economic benefits of recycling CDW

Total Waste Quantity (TONS)	Total Water Saved (GAL)	Total Energy Saved (million BTU)	Total GHG Reduced (MTCE)	Total Attributes to Jobs	Total Attributes to Tax Revenues ($)
424, 260	$5.8 * 10^8$	$4.7 * 10^4$	891	734	$6.6 * 10^6$

Later, the total amount of benefits were compared to the Lebanese Gross Domestic Product (GDP) in order to assess the economic contribution of these benefits in the locality. For that purpose, each of the total amounts of water savings, energy savings, reductions in greenhouse gases, and attributes to jobs were converted to US Dollars. Table 12 presents the necessary parameters for the conversion of each of the aforementioned benefits to a monetary value.

Table 12 Units Conversion to U.S.D. values

Units	Cost per Unit	References
1 cubic meter or 264.172 gallons	1 USD	(Water supply and sanitation in Lebanon, 2019)
>500 K.W.H	200 LBP/KWH or 0.132 USD/KWH	(Energy and Water Solutions, 2019)
1,500 MTCE	320 million USD	(Economic Costs to Lebanon from Climate Change: A First Look, 2015)
average annual income per person	10,000 U.S.D	(Republic of Lebanon, 2019)

Table 13 shows the economic benefits yielded from water savings, energy savings, reduction in greenhouse gases, expressed in terms of jobs, and tax revenues. Also shown are the economic benefits relative to the Lebanese GDP averaging 52 billion U.S.D (Lebanese Gross National Product, 2019). The calculations performed are presented in details in Appendix A.

Table 13 Economic Contibution of CDW Recycling to GDP

Total Water Saving contribution (USD)	Total Energy Saving contribution (USD)	Total GHG reduction contribution (USD)	Total job contribution (USD)	Total tax revenues contribution (USD)	Total Economic Contribution to GDP (%)
$2.2 * 10^6$	$1.8 * 10^6$	$190 * 10^6$	$7.3 * 10^6$	$6.6 * 10^6$	0.40

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The increase in the rate of construction waste imposes a serious environmental and economic dilemma. The amount of solid waste generated from various construction activities has increased drastically reflecting an increase in construction work. As a result of these trends, several environmental challenges are faced including rapid depletion of natural resources and increased pressure on the dwindling landfilling capacity. In order to resolve such socio-economic and ecological challenges, a proper waste management technique such as recycling should be adopted on site to reduce and reuse certain waste elements.

This thesis proposes a methodology to determine the required design capacity of a construction waste recycling plant, an essential parameter for recycling plant design. Through the collection of proper data from completed projects within Lebanon and with the help of simulation programs such as Anylogic and modelling programs such as Revit, Primavera, and Navisworks, accurate quantities of construction material waste generated over time were obtained.

Three sets of project specific construction waste S-curves were generated visualizing the waste generation rates across the multiple stages of construction. The three sets correspond to three scenarios of waste generation rates (low, medium, high). The integration of several sets allowed for designing the required capacity for recycling plants, which if implemented could help achieve environmental and economic benefits.

6.1 Summary of methodology

This study proposes a BIM based generic methodology for construction waste forecasting and quantification on a timely basis (e.g. hourly, daily, or monthly). The proposed method is automated, and allows for any project specific information. The proposed method adopts the use of BIM tools (e.g., Revit and Navisworks) and the concept of S-curves to estimate and visualize waste generation rates. For this purpose, a BIM 4D model is developed in Navisworks through the interplay of a Revit 3D model and a Primavera schedule. Through an automated process developed by macros, project information are exported from Revit, Primavera, and Navisworks to Microsoft Excel whereby the user (e.g., contractor) can input construction waste range percentages estimates for different materials and elements. The waste range percentages are then fed to Anylogic where random waste rates are generated following a triangular distribution. These rates are then fed to an Excel template which computes the quantities of CDW generated over time and depicted by S-curves.

6.2 Summary of results

Following the above summarized methodology, three waste S-curves for each material, representing the cumulative quantity of each waste material versus each month towards the end of the project, were then obtained. Each plots resulted in multiple S-curves showing a gradual increase of material waste at the beginning of each activity then a plateau indicating no further increase in material waste as the activity approached to its end. The quantification of construction waste rates over time served as a baseline for estimating waste from three construction projects of different types (low rise building, middle rise building, high rise building) in Beirut. The integration of these sets of wastes allowed for an accurate forecast of waste generation rates (on a monthly basis), allowing waste management authorities to design the required capacity for recycling plants.

6.3 Key findings of the study

The maximum total waste quantity obtained from three types of construction projects in Beirut at the end of year 2018 was found out to be 424,260 tons. Diverting these materials (concrete, masonry, plaster, and ceramic wastes) from landfills through recycling yields significant environmental and economic benefits. The environmental benefits that could be achieved include water savings of $5.8 * 10^8$ gallons, energy savings of $4.7 * 10^4$ million BTU, and a total reduction of greenhouse gases of 891 MTCE. The economic benefits include the creation of 734 jobs, and $6.6 * 10^6$ \$ tax revenues. The aforementioned benefits would lead to a total economic contribution to the Lebanese gross domestic product of 0.40 percent.

6.4 Limitations and future work

The application of the proposed methodology required two assumptions, governed by the case study taken into consideration. First, the material waste accounted for in this study includes concrete, masonry, plaster, and ceramic. However, the proposed method is flexible to account for other choices of material waste that the user would wish to quantify according to another project specific information. Second, the four categories of elements that were present in the developed Revit model constitute of walls, structural foundation, structural columns, and floors. Similarly, this depends on the project’s specific information. Last, when computing the waste quantity for an activity of a certain defined duration, the waste production was assumed to be linear across the activity’s duration; however, in reality the waste production may vary from one day to another during the specified activity’s duration, and that could be targeted in future research.

APPENDIX A

Water Saving Contribution

1 cubic meter ⟶ 1 U.S.D

1 cubic meter = 264.172 gallons

264.172 gallons ⟶ 1 U.S.D

$5.8 * 10^{8}$ gallons ⟶ $2.2* 10^{6}$ U.S.D

Energy Saving Contribution

1 BTU = 0.000293 K.W.H

$4.7 * 10^{4}$ million BTU = 13,771,000 K.W.H (>500 K.W.H)

>500 K.W.H

1 K.W.H ⟶ 200 L.B.P

13,771,000 K.W.H ⟶ 2,754,200,000 L.B.P

1 L.B.P = 0.00066 U.S.D

2,754,200,000 L.B.P ⟶ $1.8* 10^{6}$ U.S.D

Green House Gas Reduction Contribution

At year 2020, the expected greenhouse gas emissions is 95,000 M.T.C.E

At year 2010, the greenhouse gas emissions was 80,000 M.T.C.E

So, during a period of 10 years (2010-2020), the GHG emissions are 15,000 M.T.C.E

10 years ⟶ 15,000 M.T.C.E

1 year ⟶ 1,500 M.T.C.E

This GHG damage per year would impose costs on Lebanon of about 320 million U.S.D. In other words, a reduction of 1,500 M.T.C.E per year would save 320 million U.S.D savings per year.

1,500 M.T.C.E ⟶ 320 million U.S.D

891 M.T.C.E ⟶ 190 million U.S.D

Jobs Contribution

According to World Bank, the average annual income per person is 10,000 U.S.D.

1 job ⟶ 10,000 U.S.D

734 jobs ⟶ $7.3 * 10^{6}$ U.S.D

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