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DEAPARTMENT OF CIVIL, CHEMICAL, ENVIRONMENTAL AND MATERIALS ENGINEERING – DICAM

SECOND CYCLE DEGREE IN ENVIRONMENTAL ENGINEERING

MASTER THESIS

BIM-DRIVEN CIRCULARITY ASSESSMENT AND DEMOLITION WASTE MANAGEMENT

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Abstract:

The increasing amount of waste, which may cause severe economic and environmental consequences, needs to be properly managed by communities and governments. Therefore, it is necessary to have master plans aimed at decreasing waste generation and mitigating its impacts.

This thesis deals with construction and demolition waste (CDW) and focuses in particular on circular methods for a proper management of CWD. To deepen the analysis, building information modelling (BIM) is introduced, with a particular focus on a BIM-integrated method employed for measuring the circularity level in buildings.

In this method the circularity is measured in a numeric way through the REVIT software and a case study is presented therein for a better understanding.

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Introduction:

Nowadays, the circularity plays a crucial role in the human's life. This is one of the most important requirements of the sustainability (*Luiz Santos et al., 2022*). For having a better environment to live and a greener future it is needed to behave in a circular way. In fact, the less waste we produce, the more sustainable community we have.

The construction industry is one of the major waste producer in the world. In the US for instance, 600 million tons of C&D (construction and demolition) debris were generated in 2018, which is more than twice the amount of generated municipal solid waste (Environmental protection agency). So, it is necessary to have some wise policies and smart strategies to reduce the amount of C&D waste or at least some reuse/recycling plans.

The circularity has been popular in the construction industry and some research has been done in this field so far. There are some methods to assess and analyze the level of circularity in the projects. Some of these methods focus on green building rating systems (BREEAM, LEED, etc.). The BREEAM (Building Research Establishment Environmental Assessment Methodology) and LEED (Leadership in Energy and Environmental Design) are two rating systems; different projects can be evaluated based on LEED and BREEAM standard. Each of them has some specific criteria to assess different aspects of construction.

A number of frameworks has been stablished for the circularity evaluation that are not numerical and do not consider the material flow; these methods are a little bit overestimated for reusing and recycling aspects and seems to be very optimistic.

In order to achieve an acceptable circular projects, it is needed to have a proper insight to the used material in the construction. Especially in the renovation projects. The experts should consider the circularity even in the design phase.

If there will be a simple numeric circularity assessment tool, then specialists have a quick overview to their project in the renovation in the design stage. It can encourage them to improve their projects in the circularity aspects.

The purpose of this study is to develop a numerical method for circularity assessment with regards to the material flow. It is a BIM-based (Building Information

Modelling). After defining the method, it has been implemented in the REVIT AUTODESK software which is a powerful software in the BIM field. For showing the results in the practical way, the method is applied on a sample project in the REVIT.

Chapter 1: Construction and demolition Waste (CDW)

Nowadays, there are massive building infrastructure in the construction industry and a considerable amount of construction and demolition works which produces an enormous amount of waste each year, the vast majority of which is disposed for landfills. Also, it may increase dust, hazardous substances, and construction and demolition waste (Mingxue Ma et al., 2020). It will definitely cause harmful influences on the environment and society, such as land occupation, groundwater contamination, and air pollution.

Thus, some productive operative actions and waste management policies have been applied. However, huge amount of waste is still a concern for stakeholders and apply pressure on the limited capacity of landfills. (Kai Kang et al., 2022)

According to the Eurostat the total amount of waste generated in Europe in 2020 is around 2154 million tons which is equal to 4815 kg per capita. Some of European countries which produce the most are provided in the table 1.

Table 1 annual waste generation (Source Eurostat)

Country	total waste generated (million tons)	Population (million)	waste per capita (kg)
Germany	401.2	83.2	4822.115385
France	310.4	67.75	4581.549815
Italy	174.9	59.11	2958.890205
Poland	170.2	37.75	4508.609272
Sweden	151.8	10.42	14568.1382
Rominia	141.4	19.12	7395.39749
Netherlands	125.1	17.53	7136.337707
Bulgaria	116.4	6.88	16918.60465
Finland	116.1	5.54	20956.6787

It can be observed that Germany (401 million tons) and France (310 million tons), contributed the most to the annual waste generated in Europe. These two countries are responsible for a third of total waste generated in the whole Europe. Italy is on the third place with nearly 175 million tons waste generation.

As it mentioned before, averagely each person in the Europe produced 4815 tons of waste in the 2020. However, this amount is very different for each country. The most dominant country in the Europe is Finland with around 21 tons per capita. After that, Bulgaria and Sweden are in the second and third place with 16.8 and 14.7 tons respectively. Italy with 2.9 tons per capita is below the average amount (Eurostat).

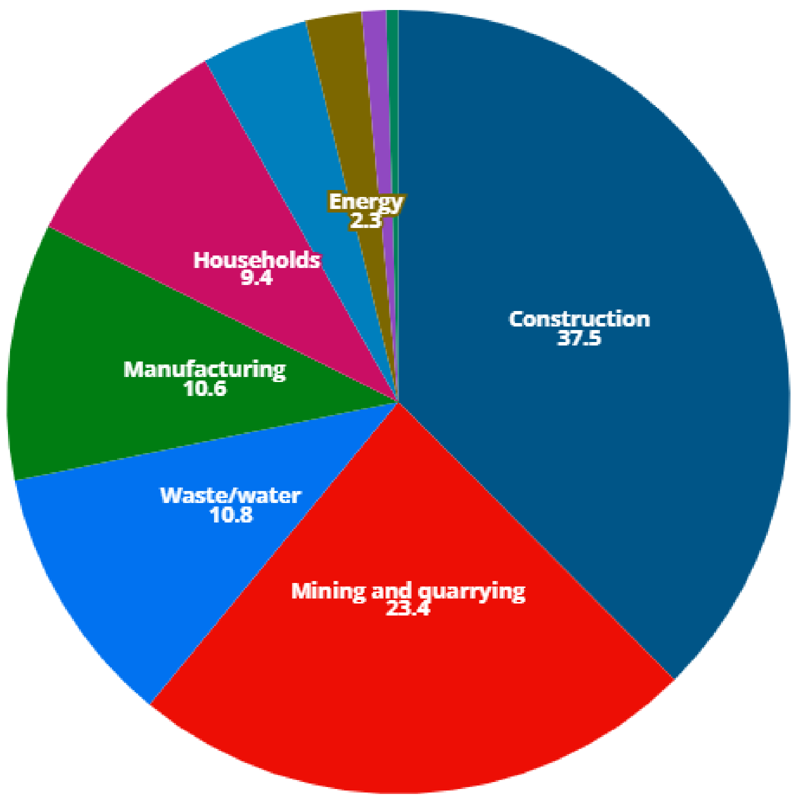

Figure 1.1 waste generation by economic activities (Source [EuroStat])

The figure 1.1 shows that the construction industry has the biggest portion and is responsible for 37.5% of total waste generation.

According to the *Interreg Europe*, which is a key European Union (EU) instruments, about 450 – 500 million tons of construction and demolition waste (CDW) are generated annually in the EU that is more than a third of all waste generated in the EU.

Typically, construction waste products include a big variety of materials; some of them can be recycled and the rest cannot. It is important to mention that there are some waste that are dangerous for the nature and environment. As it mentioned before, the amount of waste demolition materials is increasing annually, therefore, a smart solution should be applied in order to manage this amount of waste. The recycling could be a wise solution. For having an effective recycling, it is necessary to identify different types of waste material. These materials can be classified in following groups:

Hazardous and dangerous materials:

The asbestos is a material can be classified in this group. In general, and simple word, asbestos is a mineral which is resistant to corrosion and heat; as a result of this specific attribute, this mineral is used in several parts of the construction. Some example of asbestos materials are resilient floor tiles, pipe insulations, asphalt roofing, ceiling and wall insulations, floor backing and, etc (Lester levin, 2018). above-mentioned materials that contains asbestos are very hazardous and cause health risk to humans. As it can be observed in the figure 1.2 the asbestos is required to be handled safely otherwise individuals exposed to this materials might encounter with diseases.

Figure 1.2 asbestos

Inert materials:

Inert materials are not originally hazardous, but they can be harmful if they mix with an asbestos material (Shiv Bolan et al., 2017). Concrete and brick form the major portion of waste material which are dumped to the landfills the materials of this group can be recycled by passing off in the small rubbles. Almost all of walls at building can contain these materials. The figure 1.3 shows a wall which has different layers, brick, concrete, and tile.

Figure 1.3 brick, tile, ceramic

Inert materials are originally made of aggregates. Generally, aggregates are made of alluvial deposits and rock crushing with very fine components (William H. Langer. 1988). Aggregates are the most mined material and are used as reinforcement to add strength to the composite material.

Figure 1.4 different types of concrete aggregates

As the figure 1.4 displayed, aggregates are produced in the factory. With different categories. These aggregates could be classified in different sizes from course to fine aggregates (figure 1.5). It contains clay, silt, sand, and gravel. Gravels are widely used as building materials. Aggregates are used as major material under foundations, roads, and railroads, drainage applications, as a stable foundation or road/rail base with predictable, uniform properties. These materials are neither chemically or biologically reactive and will not decompose. (Bamshad Mobasher et al., 2002).

Figure 1.5 different sizes of construction aggregates

Other materials:

These material are used widely in the temporary buildings. Fortunately, these materials can be reused, recycled, or at least disposed easily. These are specifically included lumber, shelves, plywood, and sawdust (Andrew Buchanan, 1999). In addition to the wooden parts, Plastic materials contains, PVC sidings, plumbing system, plastic sheets, and some insulations. Glass materials include lighting systems, glass shelves and decorations; in some cases, glass can be sued as façade materials (figure1.6) making reflective appearance for the façade. Almost all of mentioned materials are not hazardous individually but can be dangerous when mixing with other types (Hamdy Abdel Gawwad, 2021).

Figure 1.6 wood and glass facade

Metallic waste:

This group of waste includes all types of metal that are used in the construction, such as iron and steel skeleton. In addition, other metals like copper, bronze and aluminum could be used as window frames or façade elements (David Doran and Bob Cather 2013). Figure 1.7 shows the aluminum door frames as well as structural steels beams.

Figure 1.7 metal construction waste

Drywall:

Drywalls consist of all masonry walls that typically made of gypsum. These wallboards are used as partition to separate different parts of building. This group of demolition waste normally left over after the demolition of the building (Beatriz Guerra et al., 2019).

Figure 1.8 drywall

Unfortunately, the drywall materials are not treated properly and usually dumped in the landfills (figure 1.8).

Paints, sealants, varnishes, and adhesives:

Paints are used widely in the construction; they could be used for wood cover, metal, or some walls. Varnish may be used as remover. Sealants are a chemical substances that are used for blocking the fluid passages. All of these materials are extremely hazardous and harmful for the nature and humans (Vitalii Ishchenko et al., 2018).

The figure 1.9 shows some chemical sealant and glues that are used in the construction for connecting elements together etc.

Figure 1.9 chemical paints and sealants

Overall, around 90% of above-mentioned construction waste materials are non-hazardous and can be reused, recycled, or reclaimed. The rest of them which is nearly 10% are hazardous and in some cased, non-recyclable, involved, contaminated soils, leftover paints, asbestos and etc.

Chapter 2: Demolition methods

Demolition can be done via several techniques. Rely on the location and the conditions of building, the method can be different. For example, in the urban areas, demolition should be done so carefully, because of the high density while, in the rural areas the devastating blast could be faster and more economical. Demolition has some preoperative actions that are shown in the figure 2.1. These processes are unique for each project but typically are as flow:

1. Building observation: before the demolition, experts should examine several attributes of the construction and the surrounding area such as, method of construction, drainage system, traffic condition, materials, construction age, neighborhood community, etc.
2. In the next stage, hazardous substances should be removed. Flammable materials, radioactive or toxic substances for instance. This step is so sensitive and must be done by expert personnel.
3. Demolition Plan: after all considerations, demolition engineers, can plan the process. This plan should demonstrate in detailed, different phases, equipment that are needed and necessary notes and safety remarks.
4. All individuals involving in the demolition process must follow the guideline related to the safety. Usually, the safety specialist can define these guidelines.

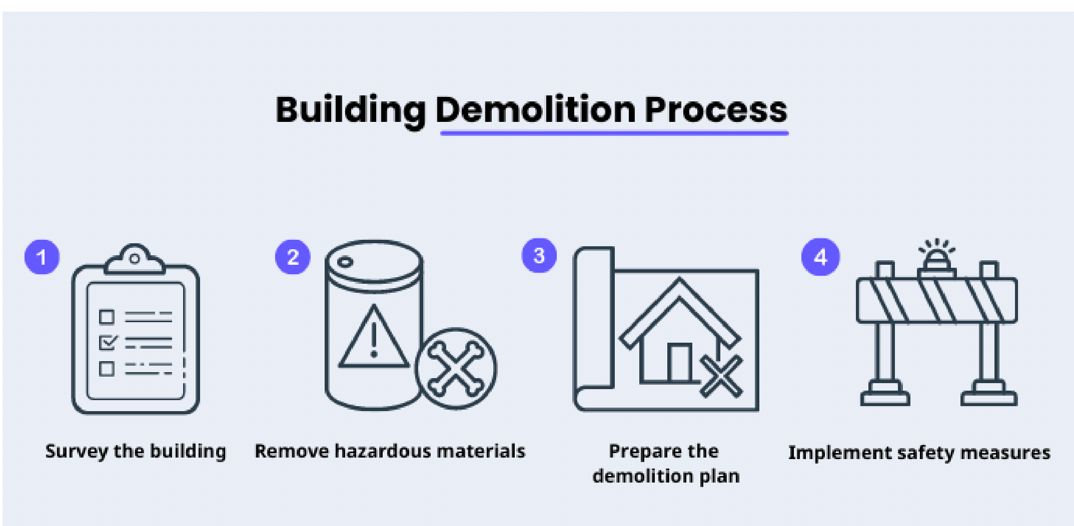

Figure 2.1 demolition processes (source Safety culture, Jaydee Reyes, 2023)

Implosion: the most common method of construction demolition is implosion. In this method explosive substances like dynamite are used in order to destroy the main columns and beams of the structure and it can result in collapse of the whole building. As it can observed in the figure 2.2, the explosives are placed at the bottom of structure to destroy the main columns and the foundation.

To have a safe and successful demolition it is important to locate explosives in the proper space. This method usually used for big structures in the urban areas so building debris can be thrown out after the explosion so the surrounding areas and the other building should be analyzed.

Figure 2.2 implosion demolition

Explosives: in this way of demolition, the explosives are used to break down the structure into smaller pieces, so it is easier to manage the waste material. Referring to the figure 2.3, the explosives are placed in several parts of the structure, in different floors.

Explosion cause blast and vibration in the area so it can damage other building as a result this method has a lot of safety regulations and consideration.

Figure 2.3 explosive demolition

High reach arm: another deconstruction method is with high reach arm; it is a top-down method and in this way a machine, excavator for instance, is used. As the figure 2.4 represents this mechanical machine should be equipped by a long demolition arm. This arm can destroy the building using a hammer, crusher, or shear. This method is convenient for demolition companies because the pieces after demolition are small, and it is easy to remove them.

Figure 2.4 high reach arm demolition

Wrecking ball: this method is an old way of demolition. As the figure 2.5 displayed, a special mechanical equipment is used in this method which consist of a heavy ball that is suspended from a cable. This ball is swung into the building and can break the concrete and masonry walls with repeated kicks. Expert crane operators must perform the demolition because it is important to kick the ball to the right target. Wrecking ball demolition makes big noises and vibration so it is necessary to analyze the surrounding environment and other buildings.

Figure 2.5 wreck and ball demolition

Selective demolition: this method is also called dismantling; selective demolition is popular because reusing and recycling is possible. These materials could be wood, brick, metal and even concrete; they can be reused in the building or in another structures. Dismantling is so labor intensive, time consuming and expensive, therefore, it is required to do cost-benefit analysis before doing the selective demolition.

As the figure 2.6 shows, in this method, the building materials should be separate and sort in each stage; this facilitates the reuse and recycling efficiency.

These materials could be pipes, furniture, window frames, timber components, tiles, etc. selective demolition needs on site sorting; meaning that without implementation, the selective demolition does not work, and all material types will be mixed together.

Figure 2.6 selective demolition

Construction and demolition waste (CDW) contains a substantial portion of the total solid waste stream and represents the 10-30% of total waste generation in Europe, nearly 180 million tons per year, approximated at 480 kg per person.

In which, 28% is recycled, but the rest of 72% is disposed. CDW have a composition very variable according to local building techniques, climate, economic activities, degree of technological development in the area, raw materials available. The production of CDW waste depends on the site and other issues such as design, location.

CDW has some economic and environmental benefits:

- Diminish the volume of used materials
- Reduce the waste generation
- Using the existing buildings in their current form again and again
- Renovate existing buildings for another use
- Deconstruction of buildings to recover components for reuse.
- Recycling and reusing materials from the construction waste flow.

Chapter 3: Global waste management and circularity

According to European union law, the European Union's approach to waste management is based on three principles (Directive 2008/98/EC of the European Parliament). These principals are waste prevention, recycling/reusing, disposal.

There needs to be some indicators and statistics data in order to monitor these policies; the statistics data could be related to the waste generation, recycling and etc. these high-quality data are provided by Eurostat. The Eurostat is a part of the European Union, which is responsible for providing high-quality statistics and data that help us to compare different aspects of European countries [Eurostat - European statistics (europa.eu)].

Referring to the European commission, the European Union's approach to waste management is based on the 'waste hierarchy' that can be observed in figure 3.1. the hierarchy, represents some options for waste management policy in the following priority order, from the prevention, which is the most preferred one, to the disposal that is the least preferred option. In the following, each of these options are discussed.

Figure 3.1 waste hierarchy (Source European commission)

Waste prevention: This is a principal factor in any waste management policy. It means that we should try to stop generating waste; also, we have to decrease the use of hazardous substances in the products, consequently the disposing of it will become easier. Waste prevention is associated with enhancing manufacturing processes and influencing users to demand more eco-friendly products and less packaging.

Recycling and reuse: in the next stage, if waste cannot be prevented, we should try to recover materials as much as possible, preferably by recycling. The European Commission has indicated some specific 'waste streams' for the purpose of reducing their overall environmental effects. This involves packaging waste, obsolete vehicles, batteries, and E-waste. Generally, waste stream is the complete flow of waste from its source to the recovery, recycling, or final disposal (Understanding waste streams Treatment of specific waste, 2015)

Improving final disposal and monitoring: If the first and second option cannot be achieved, the waste should be carefully burned. The burning procedure should be done with special considerations; finally, the last option could be the landfill. These disposal procedures require monitoring and controlling because the emissions caused by incineration might be harmful for the environment (EuroStat).

Nowadays, the EU waste framework directives ask the Member States to present measures on waste recycling, reuse, collection, and disposal. This framework has some basic waste management principals as below (Directive 2008/98/EC of the European Parliament):

- Waste management should be done without threatening human health and damaging the environment.
- Waste management policies must be without risk to water, air, soil plants or animals.
- It is also required to consider disturbance through the noise or smell.
- And, without influencing the countryside or places of special interest.

Several European Union members are already managing to recycle waste. In the figure 3.2 the rate for each country can be observed.

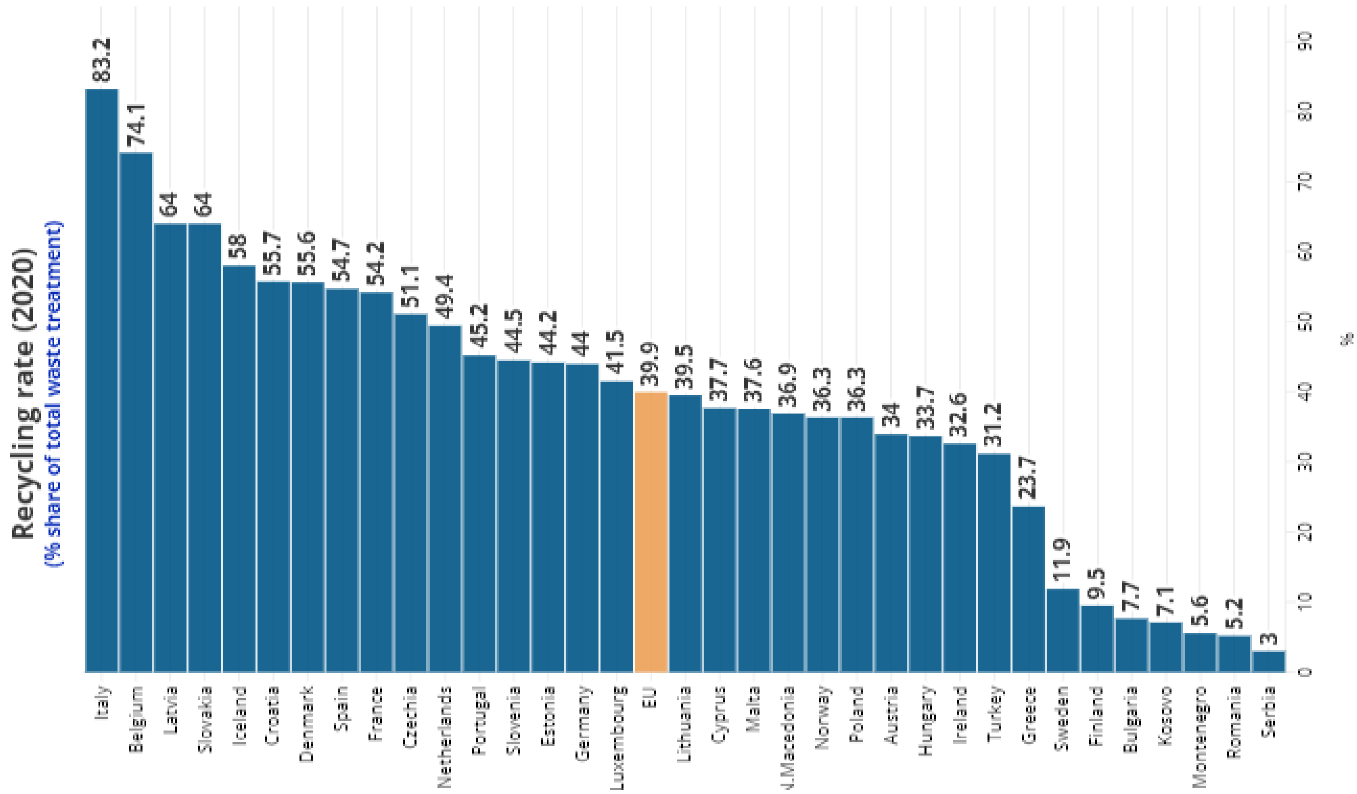

Figure 3.2 recycling rate of European countries (Source Euronews)

As the bar chart in figure 3.2 displays, the average recycling rate is around 40%. However, the rate is dramatically different for each country. It is varied from 83.2% in Italy to just 5.2% in Romania. The Belgium with nearly 74% is on second place and the Latvia and Slovakia are on the third place with 64% recycling rate.

Germany and France are the highest waste producer (were discussed in chapter 1); fortunately, the recycling rate of these countries is above the average rate is 44% and 54.2% respectively.

Linear versus circular

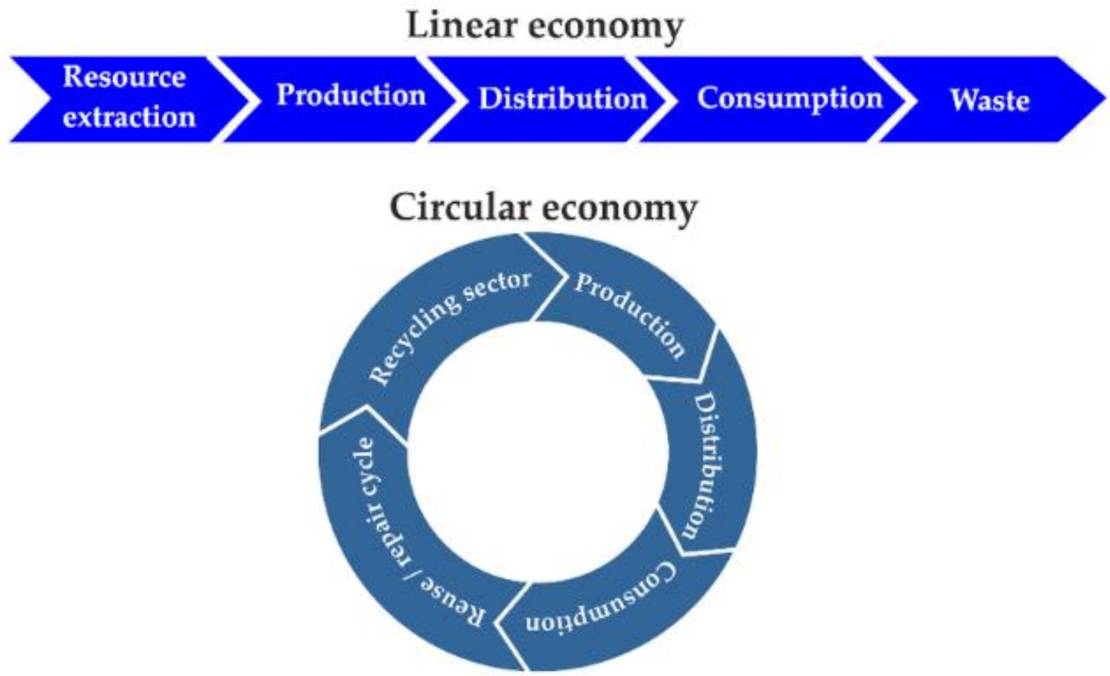

Figure 3.3 linear versus economy (Barbara Fura et al., 2020)

As it can be observed in the figure 3.3, In linear systems, natural resources are extracted from nature then, processing into products. After that products are distributed and after consumption, finally they are wasted. Actually, in this systems we have only three simple steps, take, make, dispose.

Some countries and economies, especially underprivileged ones have been encumbered with the negative effects caused by linear economy. These impacts contains both environmental and health influences. The figure 3.4 shows a landfill in Madrid, the satellites measure a high amount of methane emission from this landfill (European space agency, 2021).

Unfortunately, many landfills and manufacturing facilities are located in the poor communities, provided waste and toxic substances for them. Also, a lot of workers that are dealing with waste processing coming from the low-income communities and these jobs are not safe and healthy for them.

Figure 3.4 landfill

On the other hand, in the circular systems, products are reused or recycled after consumption. In this way they are returned in the cycle each time.

Nowadays, one of the biggest challenges that governments and societies are encountered with, is the climate change. We can take advantage of circular economy, to mitigate the climate change phenomenon.

According to United Nations' International Resource Panel, extraction of natural resources is the reason for 50% of the global greenhouse gases emissions (UN environment program, 2019). So, it is necessary to develop some strategies to decrease the impacts of these material consumption.

The circular economy is really functional and has the high possibility to protect the environment. In addition, the economies can take advantage of it, economies can enhance through the circular way. In the point of sustainability view, circular economy can help us to achieve a sustainable society because, one of the requirements for a sustainable community is social equality, and CE can improve the social justice (U.S. Environmental Protection Agency).

Linear versus Circular constructions

In the linear constructions, natural resources are extracted from nature, then, the materials are processed, after that components are manufactured, in the next stage the building is assembled and after the production phase of building the construction is finally demolished and the wasted materials are dumped to the waste plants. Whereas, in the circular constructions, materials are taken back to the cycle through reusing, relocating, recycling, and reprocessing. The concept of circular economy (CE) has appeared aimed at dissociating the economic growth from raw material extraction. It can be done through resource reusing continuously in the closed loop. We can take advantage of CE to create a more sustainable future. Although, moving from linear economy to the circular economy brings very complex challenges that needs some theoretic insights and technical tools (van den berg, 2020). The CE can be beneficial when an assessment framework is available in order to monitoring the operation on the way of CE (Saindani, 2019).

CE assessment in buildings:

A lot of different circularity evaluation methods at the building, component, or product-level have been stablished. Among them, material efficiency is usually considered as an essential dimension. It highlights a system in which virgin resources and unrecoverable waste are minimized or eliminated (Coenen et al., 2021).

But, a lot of these circularity methods, heavily depend on lifecycle information of material, building and products so it relies on statistic data and could be very optimistic.

One of the most popular methods is Material Circularity Indicator (MCI) which contains a lot of uncertainties in the investigating of the end-of-life material treatment. As a result, above-mentioned methods are not suitable to measure the material efficiency properly and accordingly, designers and other players in the construction have bounded perception into the performance of their project from the circularity point of view. However, nowadays, circularity gradually plays an increasingly important role in tenders and decision-making during design/construction projects, where stakeholders need timely, relevant, and accurate information to make agreements and reduce uncertainty (Tushman and Nadler, 1978).

Overall, there is lack of a practical method with actual circularity intuition in construction projects, to facilitate material efficiency in a practical numeric way.

To sum up, there is an urgent need for insight into circular material efficiency in the construction project; regarding the crucial role of BIM in the construction projects and its potential, a BIM -based circularity assessment method can be suggested.

In the traditional methods, the estimation must be done over the whole building lifespan; however, in this project-based method we try to emphasize on the material flow, meaning that actual material and resources which are coming in and out of project site.

Green building is the implementation of constructing houses with process which are environmentally friendly in all building lifespan including design, construction, operation and etc. the green building paradigm has four main components, material, energy, health, and water. According to this definition, the circularity is the backbone of green building.

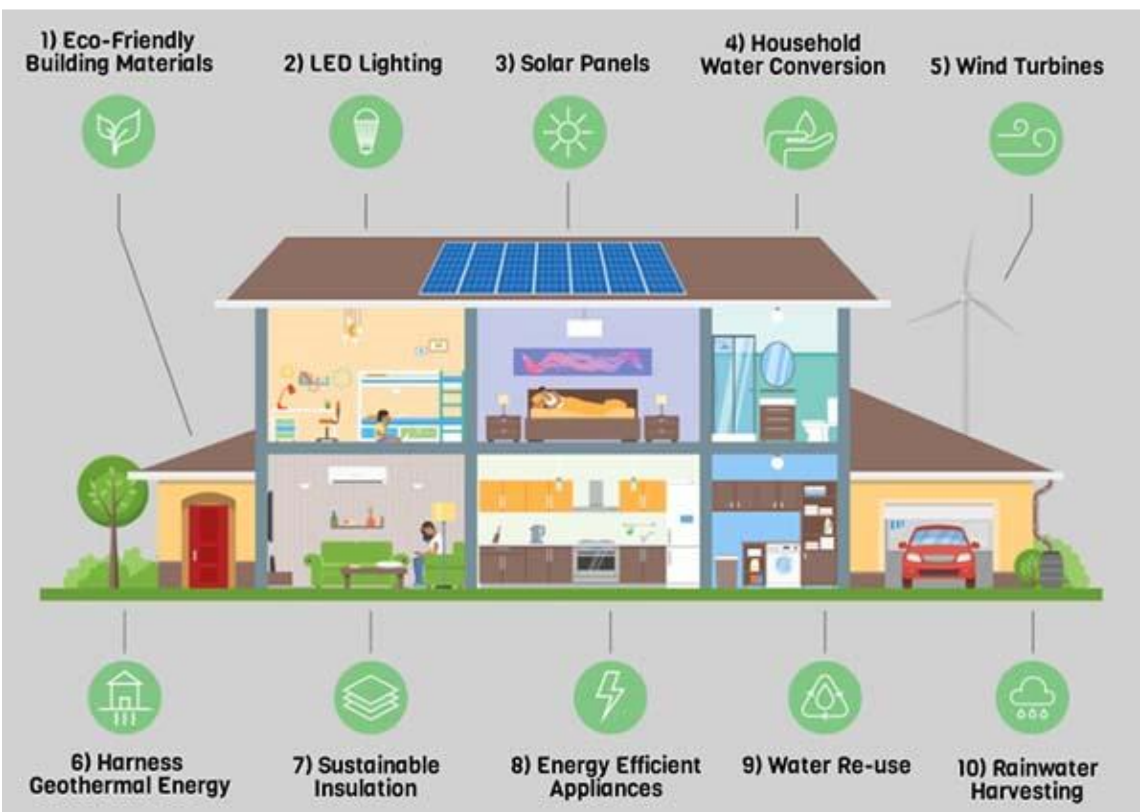

Figure 3.5 green house parameters (Source CadPro-Net-Zero home design)

In the figure 3.5, the principals of green building are shown. There are also some green building rating systems which evaluate the constructions and rate them based on the different parameters. Referring to the green building parameters, if a construction can be built in a circular way, it can gain the high score from the green building rating systems.

These rating systems have a manual; each of them may have different evaluation methodology. In these manuals the rating procedure and the point dedication for each part is indicated. In the following the circularity assessment with some of these manuals are provided.

LEED: it stands for Leadership in Energy and Environmental Design. The LEED is an American green building certification and is the most widely used green building rating system in the world (US green building council).

Figure 3.6 LEED certification requirements (Source civilseek)

As the figure 3.6 represents the LEED contains a material and resources category, which has credits to reward projects. This certification system, consider a longtime evaluation period for materials involved in the projects. LEED indicated 2 up to 2 points for projects fulfilled construction and demolition criteria. It considers two options (US green building council):

1. Diversion: go along with the Waste Management Policies and divert at least half of the total CDW from landfills and incineration amenities; 1 point is dedicated to the diversion.
2. Alternatively, it considers the waste prevention. Reclaim or recycle at least half of CDW and implementing waste reduction design techniques and construction strategies for new construction elements. It can have 1 or 2 point.

BREEAM: BREEAM (Building Research Establishment Environmental Assessment Method) is the world's leading science-based suite of validation and certification systems for sustainable built environment (BREEAM official website). The BREEAM always encourages sectors to circular economy and resilience.

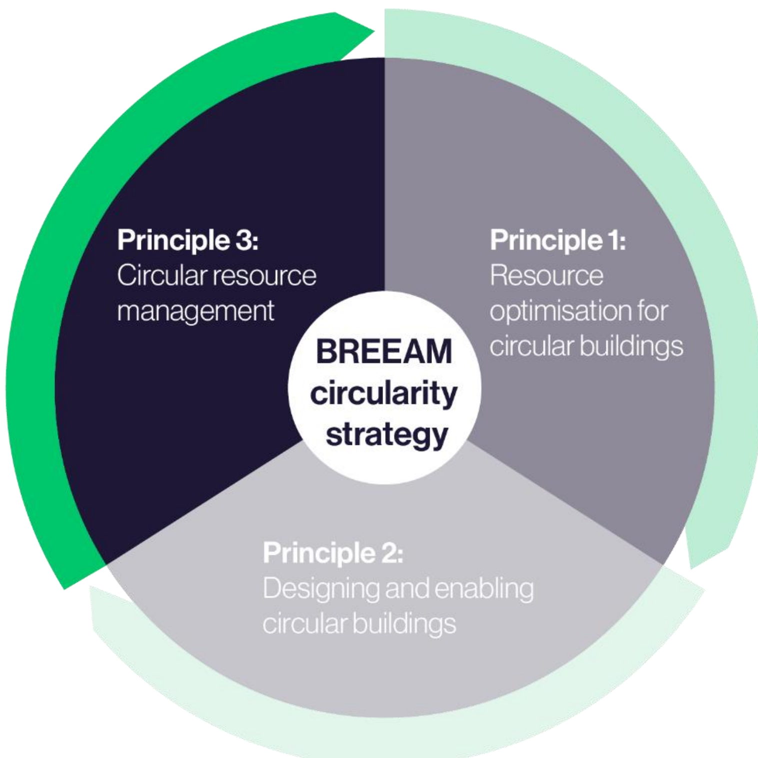

Figure 3.7 BREEAM circularity principals (Source BREEAM)

As the figure 3.7 shows, the circular economy has 3 principals in the BREEAM framework. The principles are:

1. Resource optimization for circular buildings: the purpose of this principals is acknowledging the reduction of virgin resources consumption and preserving the quality of used materials at the same time.
2. Designing and enabling circular buildings: this factor focuses on implementing the circularity in the entire project lifespan. From the phase zero to the end.
3. Circular resources management: this principal is aimed at facilitating material flow management and highest amount of material reusing and lowest value of waste.

ESTIDAMA: the ESTIDAMA is based in Abu Dhabi and is a building design methodology for constructing more sustainable buildings.

It also devotes a part to the circular economy. The Estidama rating system is intended to divert a minimum of 30% of construction and demolition waste through recycling/salvaging (Swain, 2018).

Chapter 4: Construction and demolition waste treatment techniques

In the previous chapters, it is mentioned that there is huge volume of CDW generating every year and it has posed a dramatic dangerous to the environment. As a result, it is needed to have some policies to reduce the amount of waste disposal. There are some advantages to waste disposal reduction, for example:

- As the figure4.1 represents, the recycling process is a job intensive industry, and it needs a lot of workers and specialists to work. So, it can create a lot of job opportunities which is very beneficial especially for poor communities.

Figure 4.1 construction recycling factory

- The reusing of recycled materials may decrease the total construction expenses. Because it is cheaper to buy recycled or secondhand material instead of new one. Also, after the demolition it can makes profit for the owners because they can sell their waste debris to the recycling factories. In addition, it can diminish the transportation costs. In fact, it is a bit expensive to move debris to the landfill but, some of recycling factories have free transporting services and can remove the waste from the construction sites.

- The recycling can significantly lower the amount of disposal facilities, like landfills. These landfills are very dangerous for the environment, also for humans and animals; because some of them contains hazardous substances that can be mixed with the soil or water. The figure 4.2 shows a lake in Serbia mixed with a huge amount of plastic waste caused environmental problems for the lake and animal living there.

Figure 4.2 construction landfill in the lake

- In each city there are some landfills that occupy a large space. With reducing the waste disposal and reusing materials we can save this substantial space for other usage.

- Nowadays, several industries extract a lot of raw materials from the resources. which has a lot of negative impacts. With recycling we can counterpart resources consumption and reduce its effects.

Almost all of building material can be recycled and there are three methods for that:

Site-separated: As it is visible in figure4.3, in this method, some boxes are used. Each box is dedicated to a type of CDW. In fact, the waste will be separated immediately after the demolition. It can be done by demolition workers. It could be very useful because everyone can be sure that the recycling targets are met, and their job is effective; so, it can encourage them to continue the separation task carefully and do it also in the other projects.

This method has some requirements though. It needs an enough space for boxes also it requires recycling specialists to monitor the separation task.

Figure 4.3 site separation

By separating construction waste, it would be easier to recycle great amounts of waste materials. This method seems to be very expensive and demanding but if we do it correctly, it would lower the cost of project in total. The separation operation includes some steps as below:

1. In order to have a beneficial segregation process, it is necessary to have an insight to the waste types that we have in the site. In this way we can manage and monitor that more effectively. It is also required for the next stages.
2. As the name of method says, the waste should be separated. For that purpose, we need sufficient containers, instead of large dumpster. At least, there should be enough containers for woods, hazardous substances, and inert materials. before providing the containers, we should ensure that we have enough space in the site to place them.
3. In the next stage, we need to train the team who are doing the separation task; the waste management plans are created in the offices, but the works should do them in the site, so they need to be educated to follow the guidelines and it is really crucial.

Commingled recycling: is some projects there is not enough space in the site for placing containers, so it is not possible to separate waste. In these cases, we can use commingled recycling; as the figure 4.4 shows, a big dumper is needed in this method; actually, all types of debris will be mixed together and dumped in a big container. After that the waste will be sorted off-site. It is easier to do and does not need specific controlling.

Figure 4.4 dumper

Hybrid recycling: this method is a mixture of first two methods. In the hybrid recycling, we try to separate some types of waste and discard to segregate them specifically. We can only devote some boxes to metal, glass, and non-recyclable materials.

In this way we can reduce the amount containers, moreover, the space could be saved and the workload for separating might be reduced. Actually, in the hybrid recycling we can take advantage of both methods.

Overall, for each single project, the recycling expert should analyze some criteria an choose the best and suitable method. Some factors that could be useful are the number of available staff, the amount boxes, the location, and the condition of the site.

After the CDW collection, finally it is time for waste treatment. The recycling process is different for each materials. Some of them are so simple and easy, while the other are complex and expensive.

In this chapter the recycling and recovering process for some of construction materials are discussed; some materials are widely used in the construction and renovation sites, such as concrete, brick, wood, plastic, metals, and asbestos. In the following, the recovering operation of each of them are debated.

Concrete:

Concrete is broadly used in the construction projects; it can be used in the structural part of building as beam, column, and the foundation. Furthermore, in the sidewalks, roadways and, etc. so after the demolition of each project, the contractor encounters with a huge volume of concrete that are so heavy and dense. Luckily, the concrete can be recycled and divert into a usable material again.

Generally, the process includes crushing the concrete in the smaller sizes. In fact, the large concrete parts will be reduced to smaller particles or even powder. This operation can be used near the construction site because it is quite difficult to carry heavy concrete parts so they will be converted to smaller parts.

Recycled concrete has two benefits, firstly, the wasted concrete is not taken to the landfills, secondly it can also replace with other aggregates that should be mined.

Figure 4.5 concrete crushing

As it discussed, the concrete is grinded; this process requires some equipment. The most important one is the crusher (figure 4.5). also, an excavator in needed to dump the concrete to the crusher; after the crushing, it is necessary to remove the specific elements such as steel; it can be done by an electromagnet or water flotation.

The figure 4.6 represents one of the usage of crushed concrete; recycled concrete can be used for permeable paving in sidewalks, this pavement increases the water infiltration so the water runoff will reduce, and the groundwater will increase. Moreover, the broken concrete can be used as pavement layer in the base part of the asphalt ways.

Figure 4.6 permeable pavement

Another valuable utilization of broken concrete is the production of new concrete mixture; actually, the smaller particles of concrete, can be used as aggregate in the concrete. It can prevent the extraction and production of raw mineral and reducing the virgin resources consumption.

In addition, another role of recycled concrete is controlling streambank erosion; the larger parts of concrete can be placed in the bank of river or even the seacoast to prevent the outburst in the flood situations.

There are also more usages for recycled concrete such as landscaping; in the figure 4.8 the usage of crushed concrete in the yard can be observed. Furthermore, these concrete particles can be used for wire gabions. These cabins that are filled concrete particles could make decoration and as a wall for private territories. In the figure 4.7 a wire cage is shown, this cage can be used instead of wall or fence around the yard.

Figure 4.7 wire cage

Figure 4.8 crushed concrete landscaping

Wood and Timber: the wood is very flexible and has low density. This material is suitable for earthquake shakes so it can decrease the volume of foundation; the heat insulation of wood is also high, and it is 15 times more that concrete for instance. All of these characteristics has caused wood used in many structured. As the figure 4.9 shows, the wood is widely used in buildings in different parts such as:

- Structural parts, as the beam, column, and shuttering
- As the stud and frame in the walls and prefabricated houses
- Door, windows, and frames
- Decoration and cabinets
- Floorboards, chipboards, and interior design

Figure 4.9 wood in construction

So, the high range of wood consumption in the building caused the huge volume of wood in every demolition operation. Wood in biodegradable and it can be debased in the nature, nevertheless it is better to reuse the timbers because it reduces the number of trees being cut down and decrease the deforestation.

The wood recycling has some steps; firstly, the wood should be cleaned and all of contaminations may be removed; then wood waste needs to be sorted into different groups. The classification is based on the type of wood and the size of that. In the next stage, the wood will be shredded; according to the figure 4.10 it needs a powerful shredding tool. After that the small metal particles should be removed using the magnet. Finally, the shredded wood divided into groups and each group will be processed to use as a specific purpose such as, biomass fuel, panel board, furniture and etc.

Figure 4.10 wood shredding

The recycled wood can be used for several purposes; the major utilization of that is the carbon neutral biomass fuel. In addition, the wasted timbers can be converted to the panels to be used in construction again. There are other usages for wood waste out of building environment, such as animal bedding, crates, pallets, and landscaping.

The wood recycling is really labor intensive but, it can help us to protect the environment by cutting less trees. In this way we can preserve the nature and it is crucial for our sustainable goals.

Brick: the brick has been founded in the very ancient structures; the usage of it is back to thousands years ago (Sadek Deboucha and Roslan Hashim, 2010). The brick commonly considered as the first material that human has manufactured by his hands. The figure 4.11 shows a dome, made of brick, built in 16th century. It is one of the dominant components using in the construction industry; as a result, we are coming up against a huge volume of waste brick in each construction and demolition operation. So there need to be some techniques to bring back this amount of wasted brick to the cycle again.

Figure 4.11 wasted brick

Hopefully the brick is recyclable; the benefit of brick is recycling is preserving the mines; the less soil we extract for brick production, the more we protect the environment. The brick can be reused in two ways.

The first method is the easy and simple one. In this method, after the demolition operation, the brick should be cleaned and reused in another project directly. In the renovation projects, contractors prefer to reuse the brick again in the same project (in the next chapters it will be discussed that it has the highest circularity factor).

The process of second way of recycling is almost concrete; as the figure 4.12 shows, in this method the bricks would be crushed and converted into brick chips.

Figure 4.12 brick recycling

This recycled bricked can be used is artistic ways such as landscape material, patio designing and etc. moreover, the finer particles are suitable for base layer of roadways because almost all of bricks are made of clay.

The brick particles have low density; because of this characteristic, traditionally, the crushed bricks can be used as sloping material at the top of the roof (figure 4.13). the crushed bricks do not apply considerable load to the roof, and it is efficient to use them for this purpose.

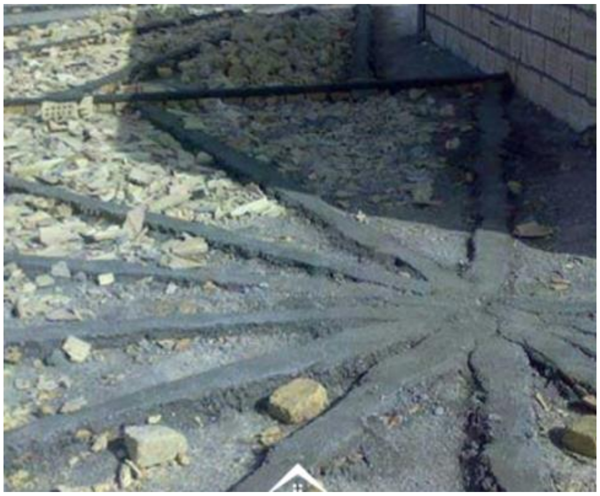

Figure 4.13 sloping with crushed brick

In addition to previous recycled brick utilization, to reduce resource wastage, recycled clay brick was considered as an aggregate substitute in concrete. (Lihua zhu, 2020).

Steel: steel is very common in the tall building. As the figure 4.14 shows the steel is used in the structural part of the buildings. The steel has very high strength and is not brittle, so it is proper to use in the construction that are in the danger of earthquake or other natural disasters. The steel is one of the most durable materials in the construction. Fortunately, another good point of steel is that it is recyclable. In fact, a great percentage of a steel can be recycled and reused for another project (Mark D. Webster 2012).

Figure 4.14 steel structure

The process of steel recycling is really simple. After the demolition sorting (on-site or at the recycling site). The steel will be removed from the whole debris volume; as the figure 4.15 displays, it can be done by big magnets. After that the steel should be transferred to the steel production steel production factories; in these factories the waste steel would be melted and converted to the other type of product. The product can be a structural product or even something else.

Figure 4.15 steel recycling

The main issue for steel recycling is to separate different types of steel during the sorting and demolition phase. Referring to the scrap recycling industries there are 316 different types of steel.

The steel can be recycled several times, without any degradation in terms of attributes or its performance; nowadays, 93% of steel used in the constructions is recycled because it has many benefits for demolition companies; in fact, it is very economically advantageous to send their waste to the steel production companies. on the other hand, it is also beneficial for the steel producers to use these wasted steel and produce new product.

The steel is made of the iron and some other substances; these components are obtained through the mineral extraction. So, the more steel we produce the more iron ore we should mine; it is so dangerous for the environment. However, with the high rate of steel recycling, we have minimized the virgin resources extraction.

Asbestos: Asbestos is a highly heat-resistant fibrous mineral that are generally used for insulation (Robert L. Virta, 2002). Because of these characteristic, asbestos is used as insulation and fireproofing in the construction. Specifically, the roof plates cover is made of asbestos.

This material is hazardous and should be removed carefully before the demolition operation. As the figure 4.16 represents, the asbestos should be removed through special substances and expert individuals.

Figure 4.16 asbestos

After the asbestos removal, it needs a special treatment process. The method of asbestos recycling requires high temperature; with the temperature, it will be converted to glass or ceramic so it can be used for another purpose.

Because of high risk of asbestos and dangerous recycling process, the recycling operation should be done by eligible companies which are approved by environmental protection agency (EPA).

At this process the asbestos-involved materials will be washed with hot solution; the solution contains the sodium hydroxide acid which can dissolve the fiber. Next, the solution should be heat extremely until 1250 degree centigrade. The high temperature causes the asbestos to be changed structurally and be converted to the glass. Finally, the glass will be recycled.

Figure 4.17 asbestos recycling process

The glass and ceramic obtained by asbestos recycling can be used in road and construction project. In spite of asbestos, these produced materials are not toxic and can be used by humans.

There is another innovative recycling method for asbestos. In this method the heating application is changed to some chemical and physical process. The product of this method is an asbestos-free material called Calmag that can be used as a sustainable aggregate. This aggregate can be a suitable replacement of the cement. The figure 4.17 shows the special equipment using for asbestos recycling.

Plastic: plastic is used in various parts of construction. In the structural parts, the hinges and screws would be plastic. Also, wall covering, waterproofing parts and flooring can be plastic. This material is widely used in electrical fixtures of building, the electric wiring cover, the plugs, and tec. Are all plastic. In some building the door and window frames are plastic as well.

Moreover, in the plumbing system, almost all of pipes and other parts are made of plastic because it is so flexible and is waterproof, also it is very resistant to acid insulations. In the figure 4.18 some usages of plastic in the building can be observed.

Figure 4.18 plastic utilization in construction (Nafisa Nazneen Choudhury, 2022)

The plastic materials are so cheap that why they are so popular and are used a lot in the construction industry. unfortunately, the plastic is not biodegradable and can last a long time in the environment. If we discard the plastic materials without any recovering process, they will remain in the nature and can damage the ecosystem as a result it is highly needed to have some considerations for plastic recycling.

Fortunately, the plastic recycling is so common these days and there are a lot of agencies and companies that encourage people to recycle the plastic. The process of plastic recycling is not complex; the figure 4.19 shows a plastic recycling factory. This recycling process has some steps as below (Vannessa Goodship et al., 2006):

Step 1: Collection of Waste Plastic.

Step 2: Sorting of Plastics into Categories.

Step 3: Washing to Remove Impurities.

Step 4: Shredding and Resizing.

Step 5: Identification and Separation of Plastics.

Step 6: Compounding.

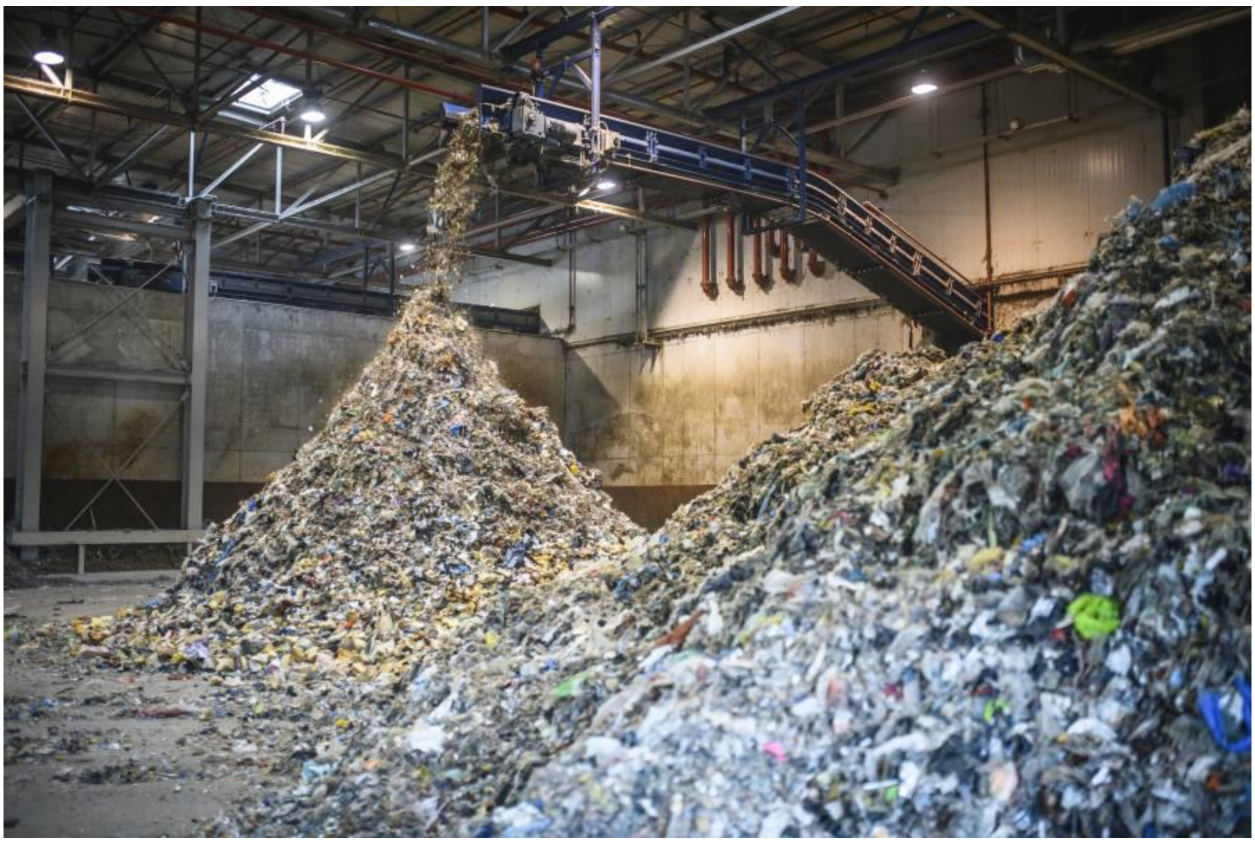

Figure 4.19 plastic recycling factory

The recycles plastic can be used again in the construction industry a lot. The recycled plastic materials provide the high quality and economical choice. In the following some usages of recycled plastic in construction are provided:

- This product can be used as roofing tiles. It is easier to use and so lighter that other ceramics that previously used in construction.
- The plastic is so durable and has high thermal capacity, so it is a proper choice for insulation. Recently, some companies are using plastic insulation in their projects.
- Plastic can play a role in the structural part as structural lumber. it can be used instead of wood or steel and have some positive points. It is so cheaper that steel. Comparing with the wood, it has less toxic effect; because the wood requires some covering substances that are toxic and can be harmful for humans. The figure 4.20 shows a bridge made of plastic lumbers.

Figure 4.20 structural lumber

The flooring and carpeting can be made of recycled plastic. This plastic carpet is so durable and waterproof; In addition, it can be proved cheaper another positive point of that is the appearance. These flooring type is so light reflector and has better color variety.

- It can also be used in concrete mixture, to improve the strength of concrete and reduce the density of that.
- Another important part of each property is the yard or the backyard. The fence of the yard can be made of recycled plastic. This fence is resistant to weather conditions.

- The plastic can be used for the plastic brick production. The plastic bricks are cheaper and lighter. It is a Lego-based material and can accelerate the project. Because working with these bricks is quicker than it would be with traditional bricks.

Figure 4.21 plastic bricks

In the figure 4.21 the plastic bricks are shown; these interesting bricks are so resistant and can stay unchanged a long time; furthermore, these are not brittle at all so can be a suitable material for the building with the high risk of earthquake.

- PVC window is another product of recycled plastic. This type of window is cheaper and has better insulation. Also, this is more durable than wooden frames. Nowadays PVC windows are so popular in the residential houses.

Chapter 5: The concept of BIM

BIM (Building Information Modelling) is the process of making and controlling information on a construction project all around the whole life cycle of it. In fact, BIM can play a role in the design phase, construction phase and even operation phase. A major aspect of the BIM is developing and digitalizing the data of every parts of the project. So, the BIM specialist always is dealing with huge amount of data, and it is necessary to handle his/her work with appropriate technology.

In the traditional way of design, there was only a symbolic drawing that only contains lines and dots that can be known by human observer only. But BIM is a new paradigm in the construction industry. In this object-oriented environment, we define set of standards, so computer can understand what is that object it also can assist human to human communication. In addition, this semantic model can facilitate computer to computer communication.

One of the most important principles of BIM is working on same file, it meant that all of parties in the construction industry are working on single unique file and each specialist is responsible for a part of the project. In fact, in the BIM we try to shift from a paradigm with multi representation to a single model-based platform which using the concept of Lego that everyone works together.

According to the figure 5.1 BIM can play role in all different phases of each project. From the programming and designing to the demolition and renovation. In addition, the BIM could be used for the facility management during the operation phase of the building. The time and cost analysis are also possible with the BIM these are called 4D and 5D modelling respectively.

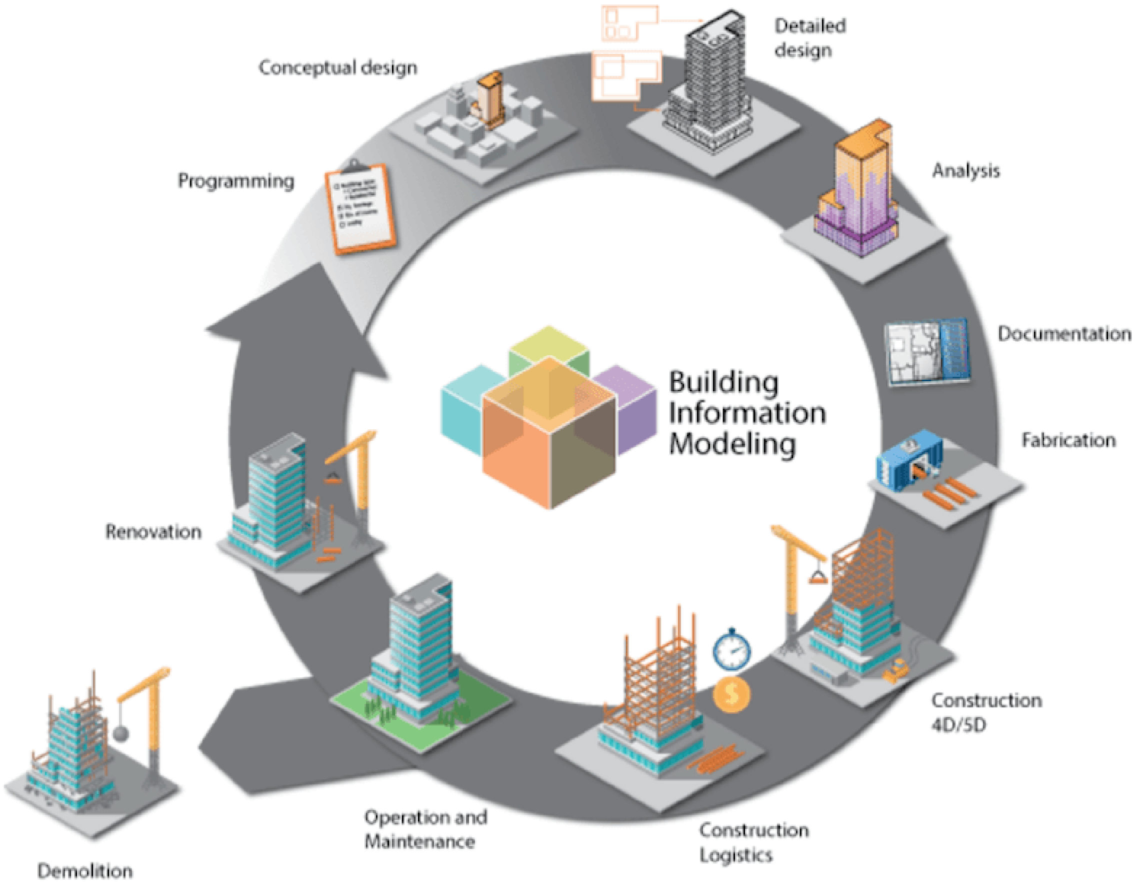

Figure 5.1 BIM (Source BIMmda)

As it mentioned before, BIM is a semantic modelling, which means that all of objects involve in the model have meaning both for humans and computers. Each component has some **attributes**, some **operation**, and some **relation** to other components.

As the figure 5.2 shows, each engineer in the construction industry can add some properties to the elements in the model; for example, for a wall, the architect can place the wall in the proper position, with suitable thickness and color. The structural engineer on the other hand, can add the material of the wall, the amount of concrete or brick that are needed for that wall and etc. also the mechanical engineer, can add some properties related to the thermal resistance and insulation part of the wall. Actually, each party can have his own definition of an object, but the point is that they are working on the same file.

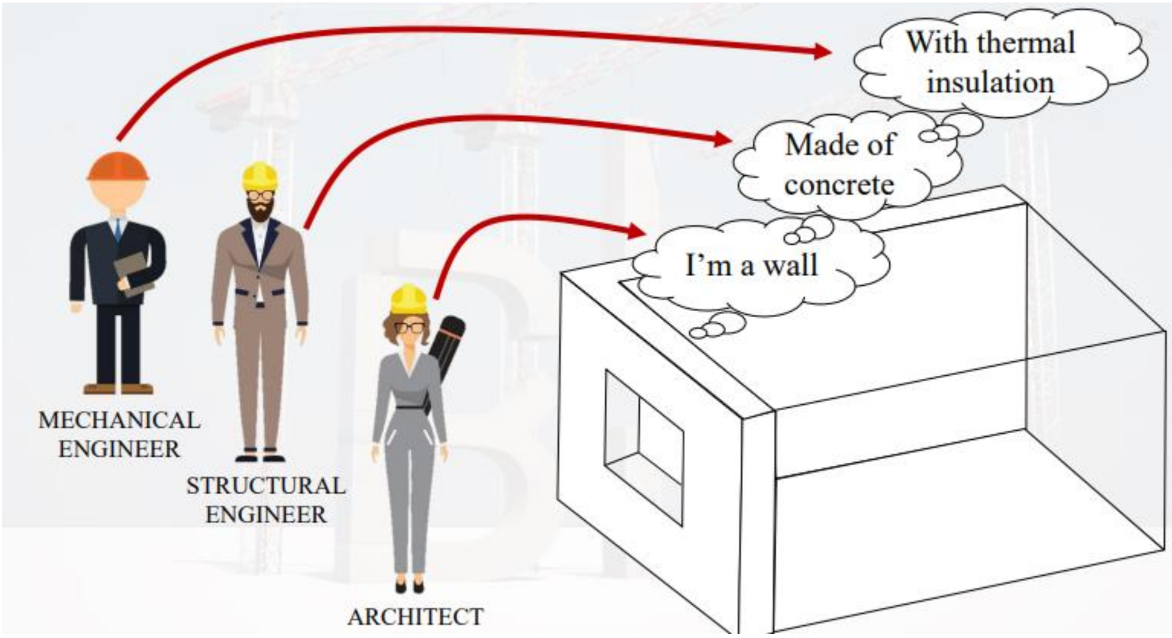

Figure 5.2 BIM data (Source BIMcorner, Konrad Fugas, 2022)

The role of BIM in demolition phase:

Increasing urbanization has caused in a considerable amount of building demolition, generating huge amount of construction and demolition waste (CDW) in many countries. But adaptations and deterioration to existing buildings are poorly documented, providing a data gap before the demolition task. Moreover, the whole demolition operation depends heavily on on-site process, pre-demolition audit and efficient construction and demolition waste management (CDWM). To improve the efficiency and informatization of building demolition and CDWM, a smart framework based on BIM technique can be a solution. By utilizing BIM, a building works as a database or information management system, providing the possibilities for incorporating various analysis (Di Biccari, 2019).

BIM allows interdisciplinary information to be laid over one single digital building model (Jack C.P, 2013). this system can extract material and volume information and all other quantity take off through the BIM model and integrate the data for detailed waste estimation and planning. Actually, recycling and reusing are also taken into account in this system, meaning that, BIM specialists think about demolition phase even in the design step.

These Extracted material data can be delivered to recycling specialists before demolition or renovation to make recycling stage more effective. The recycler can also estimate requirements for the project, such as Pick-up trucks, workers, and all other waste facilities. Furthermore, time and cost analysis are possible through BIM, because the specialist have access to model and can predict some tasks ahead of time.

The approach of this research is based on design science. Design science is a form of research that supports the discipline-oriented creation of successful artefacts (Peffers et al., 2007). In fact, beside the scientific knowledge to civil projects, this thesis emphasized on the designing pragmatic tools or specifically, a BIM-driven approach.

For attaining a higher level of efficiency, it is assumed that all of parties involved in the project, are working based on an agreed framework. Meaning that, designing, document sharing and etc. are standardized and based on specific protocols.

Above-mentioned point is necessary, because of the interoperability between different software. In fact, all software and files should be supported with a standard platform. Almost all of BIM-based software are readable and understandable in the IFC platform. Each player in the project can import the IFC file from the software and hand it over to the next party. Overall, as the figure 6.1 shows, the IFC is like a bridge that connect different formats together.

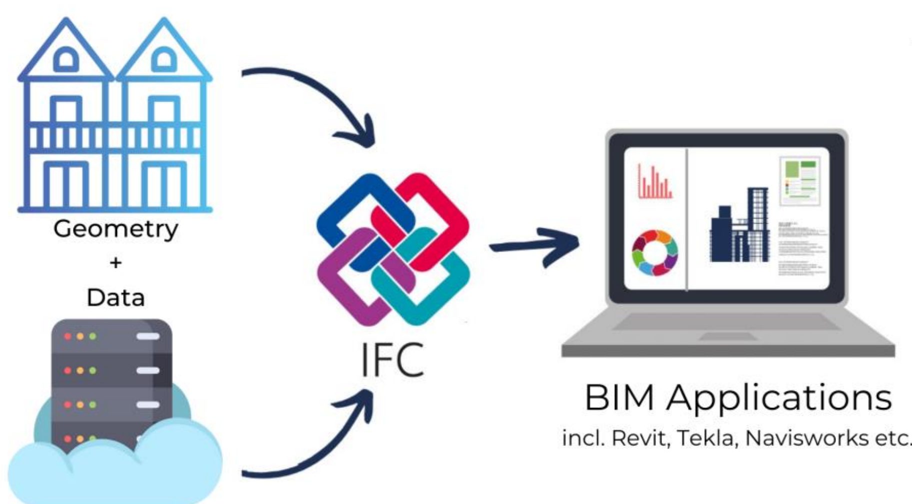

Figure 6.1 IFC format (Source [Prototech Sloutions](#))

In this study, the analysis, calculations, and the whole approach is done with Revit Autodesk. Revit is a powerful software in the construction field and the BIM world. Except from the designing and 3D modelling, it is easily possible to extract quantity schedule, data, different attributes and etc. In this study one of the Revit example projects has been chosen as the case study. In the figure 6.2, the 3D view of the building can be observed.

Figure 6.2 case study_3D view

In these views, details are set on fine level and the type of view is realistic. It is assumed that this old residential building will be destroyed and replaced with a new renovated project.

For having a better mindset of the interior part of house, a plan view of the first level is provided in the figure 6.3.

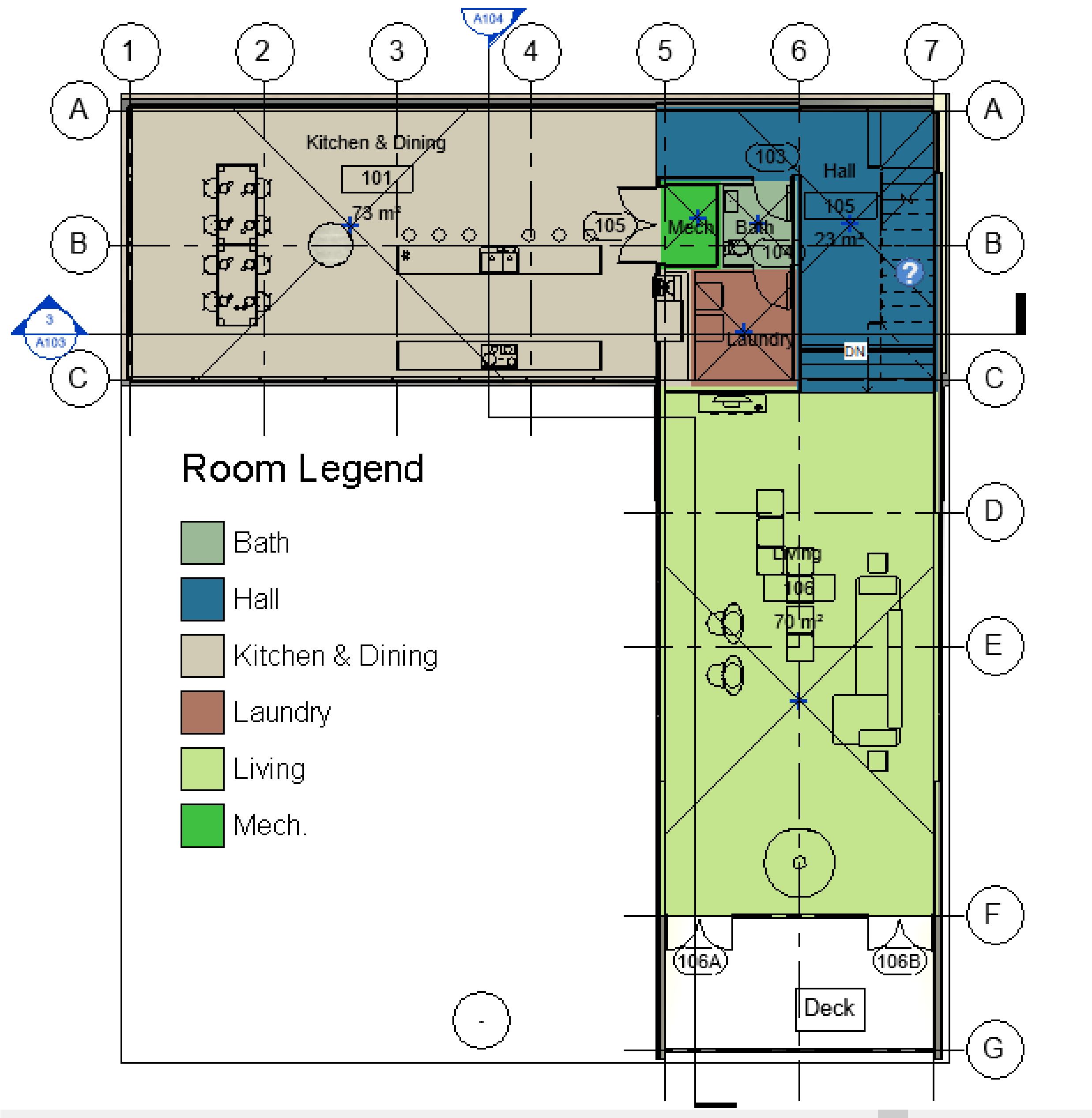

Figure 6.3 plan view

Referring to the plan view, the house contains some area that are separated with different colors. The area of each part is written on the plan, but for better understanding these are provided in the schedule below:

<Room Schedule>		
A	B	C
Name	Area	Level
Kitchen & Dining	73 m^2	Level 1
Laundry	5 m^2	Level 1
Bath	3 m^2	Level 1
Hall	23 m^2	Level 1
Living	70 m^2	Level 1
Mech.	2 m^2	Level 1

Figure 6.4 room schedule

The figure 6.4 is created in the Revit software and is exported. As it has discussed before, it is very convenient to extract quantity data through BIM. The schedule displays different parts of level 1 with name and the area. According to the schedule the total area of first level is 176 m^3.

The purpose of the study is to provide a platform in which the stakeholders are able to monitor and analyze their projects regarding the circularity performance. For this target, it is required to have a new assessment tool to measure and visualize the degree of circularity.

A circular project model, developed by (Van den Berg et al.,2019) is considered. This simple model makes a distinction between new materials, waste and recovered materials (Van den Berg et al.,2020). After modelling the materials flow, it is possible to develop an indicator of material efficiency. Based on the equation 1.

$$circularity\ value = \sum_{i=1}^{5} F_i * R_i \quad (1)$$

In equation 1, F_i is the mass percentage of each material in the project and the R_i is the weighting factor. R_i is indicated based on the circularity level of the material. For example, in the project, the preference is to reuse or recover the material so it may have the highest level of circularity or the highest value of R_i. The figure 6.5 illustrates the R_i values based on the circularity levels:

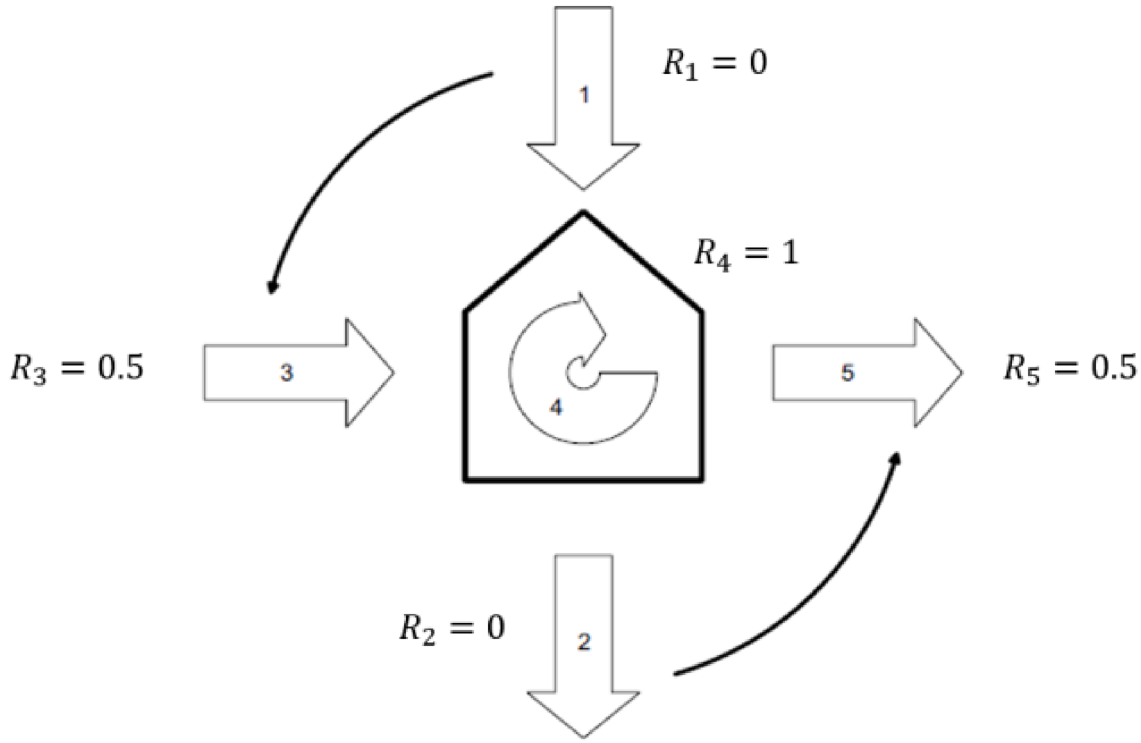

Figure 6.5 circular project model (Marc Van den Berg et al., 2022)

The flowchart in the figure 6.5 distinguishes materials in 5 groups:

- The first group represents the new materials entering to the construction site. So, the circularity level for these materials is zero.
- The second group shows the waste materials. These materials are directly delivered to the landfill without any reuse or recover process. For this reason, the R_i value for that is zero.
- The third group indicates the reusing of recovered materials. Meaning that, a material is recovered before and is reusing in the current construction site. The circularity value for this group is 0.5.

- The fourth group designates reusing of recovered materials. Despite of previous group, this material is recovered and is reused again in the same construction site. The circularity value for this group is 1.
- The fifth group specifies the recovering of a material for reusing in another project. The circularity value for this group is 0.5.

According to the classification, the R value is a number between 0 and 1. The $R_i = 0$ shows a poorly linear procedure while $R_i = 1$ is fully circular procedure.

Some assumptions are considered in this model, firstly it does not distinguish materials in each group, for example, recovering the brick or wood is same. Also, in this study the cost or energy, used for recovering of each material is not considered. For example, it is easy to recover the glass, but this process is complex for the concrete. This difference is not considered.

After defining the circularity parameters, it is time to implement them in the software. The final target is to define these parameters as an attribute in the Revit software. Then the software can calculate the overall circularity level of the project.

Revit implementation:

For applying the method in the Revit Autodesk, it is decided to use the type of schedule called material take off which is visible in figure 6.6:

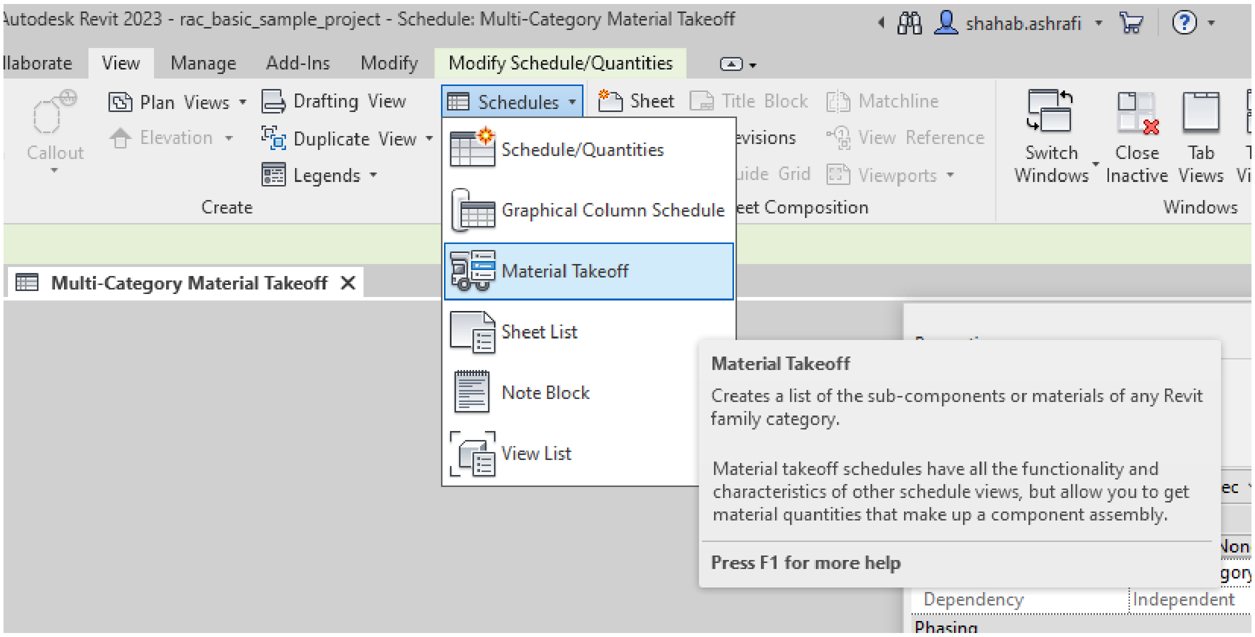

Figure 6.6 material take off schedule

This take-off list can have several fields. But we only select parameters that are needed for the circularity assessment purpose. Referring to equation 1, the component weight and the R value (factor of circularity) are required. Among these two parameters, the first one can be calculated by the Revit based on equation 2:

$$weight = volume * density \text{ (Equation 2)}$$

The volume and the density (unit weight) of each material is available in the attribute part of each component and can be selected same as figure 6.7:

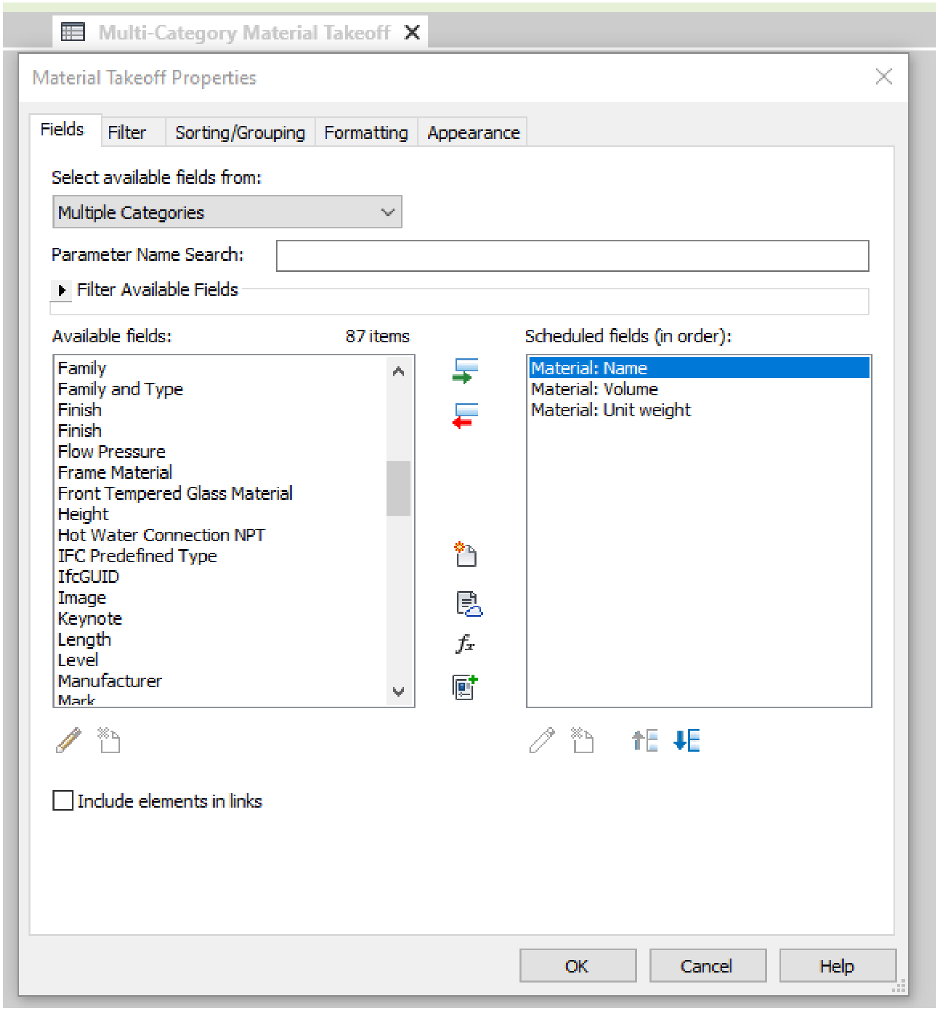

Figure 6.7 field selection for schedule

The weight can be easily calculated with one simple formula (equation 2). The implementation of formula in the Revit is provided in the figure 6.8:

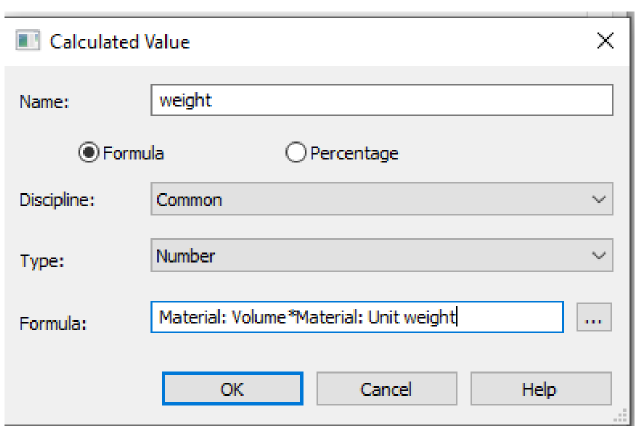

Figure 6.8 weight calculation

The final result is a schedule with name, volume, density, and the weight of each component in the project. This schedule is provided in the figure 6.9.

<Multi-Category Material Takeoff 2>			
A	B	C	D
Material: Name	Material: Volume	Material: Unit weight	weight (kN)
Default Light Source	381.39 m³	0.1 kN/m³	29.356537
Default Light Source	381.39 m³	0.1 kN/m³	29.356577
Default Light Source	381.39 m³	0.1 kN/m³	29.356537
Default Light Source	381.39 m³	0.1 kN/m³	29.356553
Default Light Source	381.39 m³	0.1 kN/m³	29.35655
Default Light Source	381.39 m³	0.1 kN/m³	29.356537
Default Light Source	381.39 m³	0.1 kN/m³	29.35661
Default Light Source	381.39 m³	0.1 kN/m³	29.356598
SH_resin Floor	30.15 m³	0.0 kN/m³	0
CL Concrete_ panels	20.83 m³	17.3 kN/m³	359.990605
Concrete, Cast In Situ	18.51 m³	23.6 kN/m³	436.797917
Softwood, Lumber	17.31 m³	5.5 kN/m³	94.920734
Structure - Timber Joist/Rafter	16.70 m³	0.1 kN/m³	1.285418
SH_resin Floor	15.89 m³	0.0 kN/m³	0
CL Concrete_ panels	15.45 m³	17.3 kN/m³	266.994353
Structure - Timber Joist/Rafter	14.16 m³	0.1 kN/m³	1.089751
Concrete - Cast In Situ	13.98 m³	0.0 kN/m³	0.001076
Concrete, Cast In Situ	12.26 m³	23.6 kN/m³	289.419445
CL Concrete_ panels	10.25 m³	17.3 kN/m³	177.154127
Concrete, Cast In Situ	9.06 m³	23.6 kN/m³	213.856102
Wood - Furring	8.66 m³	0.0 kN/m³	0.000666
Concrete - Cast In Situ	7.99 m³	0.0 kN/m³	0.000615
CL Concrete_ panels	7.73 m³	17.3 kN/m³	133.609483
Concrete - Cast In Situ	7.60 m³	0.0 kN/m³	0.000585
Roofing - Metal Standing Sea	6.93 m³	0.0 kN/m³	0.000533
Structure - Timber Insulated P	6.84 m³	0.1 kN/m³	0.526791
CL Concrete_ panels	6.80 m³	17.3 kN/m³	117.52341
Concrete, Cast In Situ	6.73 m³	23.6 kN/m³	158.834747
Concrete - Cast In Situ	5.99 m³	0.0 kN/m³	0.000461

Figure 6.9 muti material take off list

The density is defined in the kN/m^3 unit so the calculated weight is in kN unit. This schedule is sorted by the volume with descending order. The list contains 696 items but some of them are very small and can be neglected. For this purpose, we filter the schedule with weight greater than 0.05 KN (nearly 5 kg). the process of filtering is shown in the figure 6.10:

Figure 6.10 schedule filtering

After applying the filter, the total items decrease to 184.

The last but not least, it is time to implement the R value in the equation 1. This is a number between 0 and 1. And represent the circularity level of each item. This number should be applied to the software manually by the specialist (normally the demolition expert). So, this parameter is defined as a number parameter that can be filled with the user. This value can be inserted in the column C of the schedule provide in the figure 6.11:

<Multi-Category Material Takeoff>				
A	B	C	D	E
Material: Name	Material: Volume	Material: R value	Material: Unit weight	weight (kN)
Default Light Source	381.39 m^3		0.1 kN/m^3	29.356537
Default Light Source	381.39 m^3		0.1 kN/m^3	29.356577
Default Light Source	381.39 m^3		0.1 kN/m^3	29.356537
Default Light Source	381.39 m^3		0.1 kN/m^3	29.356553
Default Light Source	381.39 m^3		0.1 kN/m^3	29.35655
Default Light Source	381.39 m^3		0.1 kN/m^3	29.356537
Default Light Source	381.39 m^3		0.1 kN/m^3	29.35661
Default Light Source	381.39 m^3		0.1 kN/m^3	29.356598
CL Concrete_ panels	20.83 m^3		17.3 kN/m^3	359.990605
Concrete, Cast In Situ	18.51 m^3		23.6 kN/m^3	436.797917
Softwood, Lumber	17.31 m^3		5.5 kN/m^3	94.920734
Structure - Timber Joist/Rafter Lay	16.70 m^3		0.1 kN/m^3	1.285418
CL Concrete_ panels	15.45 m^3		17.3 kN/m^3	266.994353
Structure - Timber Joist/Rafter Lay	14.16 m^3		0.1 kN/m^3	1.089751
Concrete, Cast In Situ	12.26 m^3		23.6 kN/m^3	289.419445
CL Concrete_ panels	10.25 m^3		17.3 kN/m^3	177.154127
Concrete, Cast In Situ	9.06 m^3		23.6 kN/m^3	213.856102
CL Concrete_ panels	7.73 m^3		17.3 kN/m^3	133.609483
Structure - Timber Insulated Panel	6.84 m^3		0.1 kN/m^3	0.526791
CL Concrete_ panels	6.80 m^3		17.3 kN/m^3	117.52341
Concrete, Cast In Situ	6.73 m^3		23.6 kN/m^3	158.834747
Concrete, Cast In Situ	4.95 m^3		23.6 kN/m^3	116.922025
Structure - Timber Insulated Panel	4.79 m^3		0.1 kN/m^3	0.368562
Concrete, Cast In Situ	4.58 m^3		23.6 kN/m^3	108.074532
Structure - Timber Insulated Panel	4.50 m^3		0.1 kN/m^3	0.34671
Structure - Timber Insulated Panel	4.47 m^3		0.1 kN/m^3	0.344316
Wood - Stud Layer	3.72 m^3		0.1 kN/m^3	0.286604
Concrete, Sand/Cement Screed	3.50 m^3		23.6 kN/m^3	82.720754
Concrete, Cast In Situ	3.49 m^3		23.6 kN/m^3	82.33778
CL Concrete_ panels	2.69 m^3		17.3 kN/m^3	46.42847
Acetal Resin, Black	2.66 m^3		14.0 kN/m^3	37.143407
Structure - Timber Insulated Panel	2.50 m^3		0.1 kN/m^3	0.192721
Wood - Stud Layer	2.48 m^3		0.1 kN/m^3	0.190932
Structure - Timber Insulated Panel	2.41 m^3		0.1 kN/m^3	0.185131
Acetal Resin, Black	[illegible]		[illegible]	[illegible]

Figure 6.11 the final take-off schedule

The following assumption are made:

Group 1: some chemical substances, that cannot be reused or recycled. Like resin, some roof panel boards. The R value of these materials are considered as 0.

Group 2: these are the group are materials that become waste without any recovery process. Like some concretes (except from cast in situ) and panels. The R factor of this group is also 0.

Group 3 and 5: these groups contain a huge range of materials such as concrete, bricks, gypsum, glass, aluminum parts, metal studs and etc. so the R value is 0.5 for them

Group 4: wood studs can be used again in the new project, without considerable recovery process. So, the R value is equal to 1 for them.

After dedicating the R value, in the next step it is possible to calculate R*F (in the equation 1). For that purpose, another field with a formula is define for the schedule (figure 6.12).

<Multi-Category Material Takeoff>

A	B	C	D	E	F
Material: Name	Material: Volume	Material: R value	Material: Unit weight	weight (kN)	R*weight
Default Light Source	381.39 m³	1	0.1 kN/m³	29.356613	29.356613
Default Light Source	381.39 m³	1	0.1 kN/m³	29.356603	29.356603
Default Light Source	381.39 m³	1	0.1 kN/m³	29.356613	29.356613
Default Light Source	381.39 m³	1	0.1 kN/m³	29.356613	29.356613
Default Light Source	381.39 m³	1	0.1 kN/m³	29.356545	29.356545
Default Light Source	381.39 m³	1	0.1 kN/m³	29.356613	29.356613
Default Light Source	381.39 m³	1	0.1 kN/m³	29.35661	29.35661
Default Light Source	381.39 m³	1	0.1 kN/m³	29.356535	29.356535
CL Concrete_ panels	20.83 m³	0.5	17.3 kN/m³	359.990605	179.995302
Concrete, Cast In Situ	18.51 m³	0	23.6 kN/m³	436.797917	0
Softwood, Lumber	17.31 m³	1	5.5 kN/m³	94.920734	94.920734
Structure - Timber Joist/Rafter Layer	16.70 m³	0.5	0.1 kN/m³	1.285418	0.642709
CL Concrete_ panels	15.45 m³	0.5	17.3 kN/m³	266.994353	133.497177
Structure - Timber Joist/Rafter Layer	14.16 m³	0.5	0.1 kN/m³	1.089751	0.544875
Concrete, Cast In Situ	12.26 m³	0	23.6 kN/m³	289.419445	0
CL Concrete_ panels	10.25 m³	0.5	17.3 kN/m³	177.154127	88.577063
Concrete, Cast In Situ	9.06 m³	0	23.6 kN/m³	213.856102	0
CL Concrete_ panels	7.73 m³	0.5	17.3 kN/m³	133.609483	66.804741
Structure - Timber Insulated Panel - Insulation	6.84 m³	1	0.1 kN/m³	0.526791	0.526791
CL Concrete_ panels	6.80 m³	0.5	17.3 kN/m³	117.52341	58.761705
Concrete, Cast In Situ	6.73 m³	0	23.6 kN/m³	158.834747	0

Figure 6.12 new column in the take-off schedule

Now, in the formatting section of the schedule properties we can calculate the total of the columns. For average circularity value, only the sum of weight and R*weight are needed. These two sum values are 3815 kN and 1509 kN respectively (figure 6.13).

Glass	0.01 m³	0.5	23.7 kN/m³	0.179996	0.089998
Glass	0.01 m³	0.5	23.7 kN/m³	0.179996	0.089998
Metal - Steel - 345 MPa	0.01 m³	1	77.0 kN/m³	1.064161	1.064161
Metal - Steel - 345 MPa	0.01 m³	1	77.0 kN/m³	0.53208	0.53208
SH_Aluminum, Anodized Black	0.00 m³	0.5	26.6 kN/m³	0.11736	0.05868
SH_Aluminum, Anodized Black	0.00 m³	0.5	26.6 kN/m³	0.11736	0.05868
Glass, White, High Luminance	0.00 m³	0.5	23.7 kN/m³	0.066751	0.033376
Glass, White, High Luminance	0.00 m³	0.5	23.7 kN/m³	0.066751	0.033376
				3815.776871	1509.059783

Figure 6.13 the sum values

So, the total circularity value is 1509/3815 which is almost 0.4.

This level of circularity is acceptable.

Chapter 7: Conclusion

As it discussed in this study the CDW (construction and demolition waste) is accounts for a high portion of total waste generated each year; the CDW contains an extensive variety of materials. This amount of waste requires some management policies otherwise it will be dumped to the landfills.

In the first chapter of this research, it is talked over building materials. We realized that some of building materials should be dangerous and require special treatments.

In the chapter 2 it is talked over demolition methods. To sum up, the demolition method is unique for each project and should be chosen by demolition specialists; however, the most effective one is the selective demolition.

In the chapter 3 the importance of waste management, specially in the European countries, is debated. Also, some recent recycling-related statistics of some EU members are provided. In the chapter 3 the directives and policies of European union is discussed, and it is found that the directive is simplified in the waste hierarchy.

As the hierarchy shows, the most preference actions that should be done for the waste management is the prevention of waste generation. The second option is reusing and recycling; and finally, the last one is the waste disposal; this research study, is focused on the recycling.

Furthermore, in the chapter 3 it is talked over the circularity; nowadays the circularity is executed in several aspects of human life, and it is growing gradually. It is also necessary to bring the circularity in the construction industry. one of the principals of circular economy is reusing and recycling, that we can take advantage of them in the constructions.

In the chapter 4 some recycling methods are provided. the requirements and equipment needed for each of them were discussed. To conclude, the best method for recycling is site separated but it needs some special requirements. Overall, the recycling specialist should evaluate the project condition and suggest the best option.

Moreover, in the chapter 4 the recycling process of each construction materials is discusses also some usages of recycled materials are provided. it can be obtained from the chapter 4 that, the recycling process is different for each material; the process could be very simple, for example wood or brick, while it would be very complex the asbestos for instance.

To conclude, it is found from the chapter 4 that almost all of CDW can be recycled and reused again. There are a lot of utilization for all types of CDW in different industries.

The recycling process of each CDW is discussed. The recycled CDW can be used again and again, so it seems to be a suitable option for CDW management. In the chapter 4 the recycling process for each material is debated. The recycling operation is easy and simple for some materials while it would be complex for the other ones.

In order to have a proper insight to the level of circularity in the construction, it is needed to assess and analyze the circularity performance of the project. There are some methods to analyze the circularity of construction; some of these techniques are talked about in the chapter 3. As it mentioned before almost all of methods provided so far, are qualitative; it means that, they do not suggest any numerical way to evaluate the circularity level.

It is also talked about the green building rating systems such as LEED and BREEAM. These systems have a unique manual and assess several aspects of projects and rate the projects based on some rules. These frameworks are able to evaluate the circularity level in the project but none of them provide a numerical value for the circularity level.

There is a method developed by *Marc van den Berg* which has a simple formula to measure the circularity level of a project. It considers the materials flow coming in and leaving the construction site. The method is extensively discussed in chapter 6. This method is a BIM-based procedure and assesses the circularity method based on BIM aspects.

The purpose of this study is to implement the method of van den berg to the software. There is a few BIM-related software. For the purpose of this study, the Autodesk Revit is considered. The method, offered by *Van den Berg*, is applied in the Revit so the software can automatically calculate the circularity level of each project and display the result in a schedule. It can facilitate the circularity assessment procedure because it is a user-friendly tool, and the results can be observed very quickly.

The implementation procedure is completely explained in the chapter 6. And the output of the Revit software is a schedule provides the circularity level in the percentage form.

For having a better understanding of the process. It is assumed that we have a renovation project. A sample project is considered as the case study which is residential and is going to the be renovated and reused for another purpose. The calculated circularity level for this sample project is around 40% which is acceptable.

To conclude, the major purpose of this research was providing a numeric method for circularity assessment in construction. As a result, some key aspects are analyzed as below:

1. Building materials and demolition methods.
2. Waste management policies and importance of circularity in the constructions
3. Recycling methods and the recycling procedure for each building material
4. Circularity assessment tools and the lack of a numeric way to analyze the level of circularity
5. The concept of BIM and its role in the circularity evaluation technique
6. Implementing a BIM-integrated circularity evaluation method in the Revit software

In this research a developed BIM-integrated solution for circularity evaluation in constructions is considered and is implemented in the Revit software. The stakeholders can take advantage of this method to have an immediate insight to the circularity performance of their projects which can help them to have a circular design. The Revit shows the circularity level in a schedule and this schedule can be used as template for several projects.

Overall, the main goal of this study which was providing a numeric evaluation method for circularity is satisfied. However, this methodology has some limitation though. For example, the recycling factor; The recycling procedure is extremely different for each material, and it would be good to add some other factors to consider this difference. It is highly recommended to improve this method in the future studies.

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