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CIRCULAR ECONOMY & INFRASTRUCTURE DECONSTRUCTION-CASE STUDY OF OLD CHAMPLAIN BRIDGE

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1. ABSTRACT

This research elaborates the study and economic feasibility of the deconstruction of the Old Champlain Bridge, Montreal by the means of adopting a circular approach. The construction industry generates the highest amount of wastes than any other industry accounting to around 27%. Therefore, there is a need of waste minimization and management to curb the waste generation and reuse the materials in other projects. This research evaluates the economy involved in adopting a non- circular and a circular approach and compares it during the lifecycle of the structure, Champlain Bridge in this case. The social and environmental viability has also been assessed for a better overview. By following the framework identified from the other case studies, the identification part included the approximate estimation, the inflation and the real interest rates and came up with 5 values of inflation to work with. The bridge's economic analysis, consisting of the annual maintenance cost and any rehabilitation costs involved for each year during its life has been calculated by the declining balance method, followed by the cash flow diagram. This made the optimization. The construction materials used have been assumed as Concrete, Asphalt, rebars and structural steel. The loop stage helped us to check whether the resources/ wastes have been put in the circular loop to asses the circularity in terms of investment costs. It was found that around 82% of the materials could be recycled on a whole. The looping in the framework used the recycling rates, quantities. Recyclability, purchasing cost and the carbon emission rates of the construction materials. The costs were deduced and calculated as per the tons of materials used and recycled. The evaluation stage finally analyses the present, annual and future costs through the lifetime of the bridge and the capitalized costs of circular and the non-circular approaches were compared. It was found out that, with the assumption of the average lifecycle of the bridge as 70 years, around $157. million can be saved using the circular approach, which is around 2.5% of the total bridge construction cost in today's date. There is also a reduction of 59% of carbon emissions in this project as compared to the traditional construction method. The analysis of the bridge has been considered as a business case where the cost savings and environmental viability has been weighed. The theoretical evaluation of the bridge found that a circular approach has the potential to save billions of dollars if implemented throughout Canada. Although with limited publicly available data, the theoretical value determined is more that what it would be if determined to on field practice because the cost spent in practice depends on the budget and available historical data on the bridge.

2. INTRODUCTION

Circular economy in the 20th century has been defined as the sustainable approach in the field of economy where the waste materials are considered as a vital resource to manage in a way that does not compromise with the needs of the future generations and events (Olabi, 2019). It is in fact conceptualized as an economic model for closed- loop production and consumption systems, where waste is designated as a valuable resource (Garmulewicz, Holweg, & Veldhuis, 2018). The pattern and consumption of natural resources have always been following a linear model (Arup, 2016). The linear approach in construction where take- make- use model have been implemented has a negative impact on the environment in terms of carbon emission and stands as a barrier to potential cost savings and benefits (Arup, 2016). Circular economics has its origin in industrial ecology and ecological economics, whose concepts have been articulated and the principles are being used in business and economic design which involves reuse, recycling and remanufacturing in the process of material flow (Garmulewicz, Holweg, & Veldhuis, 2018). This aims to decouple economic growth from the resource consumption in any sector (Arup, 2016) and (Garmulewicz, Holweg, & Veldhuis, 2018). In certain studies, agenda of circular economy is defined as a model to develop an alternative to the traditional take-make-waste model that eliminates waste by appropriate resource-efficient methods as a sustainable approach (Akinade & Oyedele, 2019).

Adams et al. 2017 has defined circular economy as an opportunity to address the reduction in the use of primary materials, resources and therefore the carbon footprints. Reducing carbon footprints comes into play as the development of new economic policies are taking place to bring benefits to the environment (EC, 2016). This very concept in the field of construction and deconstruction (not demolition), which can also be considered as a material intensive sector, has the potential of extending the vision of achieving a sustainable construction methodology that is environmentally sound and responsible, efficient in resource consumption and at the same time providing a promising life to the structure (Srour, Tamraz, & Chehab, 2012).

Some journals have even provided information on demolition with reference to deconstruction. (Hamidi, Bulbul, Pearce, & Thabet, 2014) has differentiated demolition and deconstruction. According to them, demolition is a straightforward crushing down of the structure whereas the deconstruction is labour intensive process of dismantling the structural members and using the dismantled fragments in other projects. Demolition leads to generation of a large amount of waste, whereas deconstruction promotes reusing and recycling the dismantled fragments. The demolition and deconstruction depend on the timeframe to complete the project assigned. Deconstruction mainly focuses on diverting waste from landfills. This saves the landfill closure costs and development of new landfill (Deconstruction versus Demolition Website, n.d.). Therefore, it requires careful planning of the project. Deconstruction takes time but it also creates a lot of employment opportunities. “Adopting circular economy principles could significantly enhance global construction industry productivity, saving at least US$100bn a year” (Baller, Dutta, & Lanvin, 2016) This definition clearly draws a line between the linear economic model and circular economic model.

It is understood that continuous production of resources is not possible in the world that consists of finite amount of resources in order to prosper in a field. This leads to the rise of Circularity. Linear economy, following a take make waste approach with no space for recycling, is a slow poison for the future generations. Several idealists have been supporting this approach with considering sustainability. If we are to measure use economic growth as a measure of development, it needs to be efficient enough in managing the goods, products, and services, which linear economy is incapable of doing. Circular economy provides that prosperity with growth by providing an entirely new framework without returning the waste to the environment.

Figure 1 Linear Economy (Olabi, 2019)

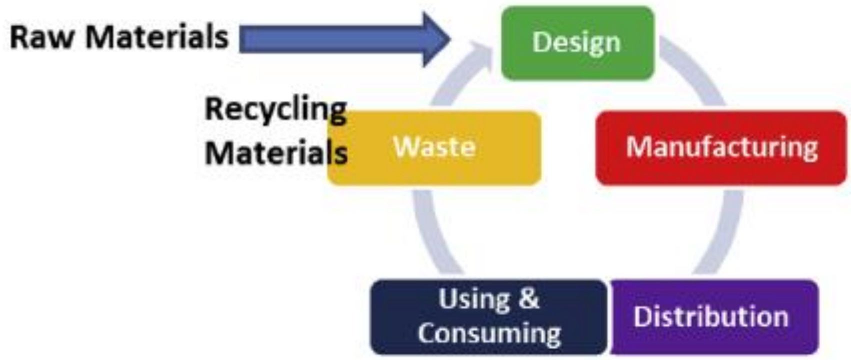

Figure 2 Circular Economy (Olabi, 2019)

There are various possibilities to define circular economy as there is no common definition for it in any of the studies and research papers. It has also been termed as a "theoretical dream" despite great interest taken by the scholars and practitioners in 4R's framework. Michelini et al. (2017) has defined circular economy as an industrial system that is restorative or regenerative by intention and design that enhance natural capital, optimize resource yields by bringing in the idea of circularity in the resource use, replacing the traditional concept of take- make waste model. The linear model has been using excessive amounts of energy in manufacturing new resources, therefore eroding the ecosystem without considering sustainability. It is a concept with so much traction, developed for the stakeholders to assess the movement of money across a given project. A business model is defined by how circular the economy is in terms of profit making. Geissdoerfer et al. (2017) and Schut et al. (2015) has mentioned that one of the widely used definition has been provided by Ellen MacArthur Foundation (2012) which reads:

"[CE] an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models."

It indeed helps create new jobs and develop new business models. It is estimated that by the year 2030,the resource productivity will increase by 30% , creating 2million new jobs, whereas this eco-friendly design which employees the concept of reuse and recycling is expected to bring net saving of around 8% of annual turnover and with an annual benefit of $1.8 trillion considering the entire European Union (European Circular Economy Website, n.d.).

Song et al. (2015) has defined the circular economy in terms of waste hierarchy that if there is no possibility of waste reuse and repairs, they can be recycled and recovered from the waste streams. Geng et al. (2009) believes that the concept of circular economy would bring great social benefits in the society. Although Circular economy is widely spoken about in various industries, there is a need for a strong business model that supports its application and measure longevity.

3. LITERATURE REVIEW

While the terms of Circular economy and sustainability are gaining attention in several industries, let us look at how this concept fits into the Construction Industry. Construction industry is Canada's largest industry that accounts for 6% of the country's GDP. At the same time this industry generates a lot of demolition waste which has been a major concern in almost every developing nation (Srour, Tamraz, & Chehab, 2012). Recycling and reusing construction and demolition wastes in the most efficient way is the agenda where various parameters are to be selected, followed by evaluating the effective measures to reduce material waste.

Construction industry has been on a boom for the past three decades. With this boom, the industry has also seen an increase in the number of construction and demolition waste that are generated (Srour, Tamraz, & Chehab, 2012). With the increase in globalization, the consumption of resources has been increasing proportionately (Behrens, et.al 2007 & Richard, et.al 2011). The waste generation is indeed an integral part of the process but also it is considered necessary to manage the waste in a way that it is efficiently utilized after recycling. The concept of circular economy with one of its definitions focusing on avoiding waste and closed loop recycling as its key features for cleaner environment as of date has been implemented on consumer goods and products that come from food and clothing industries. This initiation has pushed to adopt a multidirectional approach that provides a sustainable base, acting as an alternative to the traditional method in the construction industry as well (Despeisse, et al., 2017). Circular economy in the field of construction is not a new concept. It has been practiced in European countries for some time, proving to be a very effective and efficient way of construction and its finances (European-Commission, 2014) It has been seen that in the developing nations, recycling of the waste materials is a challenge as they are not properly documented, and the flow is not recorded with the pace of construction activities (Srour, Tamraz, & Chehab, 2012). The reason being the linear approach in construction where take- make- use model have been implemented that has a negative impact on the environment in terms of carbon emission and stands as a barrier to potential cost savings and benefits (Arup, 2016). In the very need to get a breakthrough in this issue of reducing the use of primary materials, researches have been inclined on the database that projects the waste generated from construction and demolition (EMF and MCK 2014 and Pratt & Lenaghan 2015). This very concept of circular economy aims to decouple the amount of resource consumed from the economic growth which in turn, helps in the production of more durable resources that can be reused and disassembled, thereby, minimizing the resource waste.

New innovative practices in the Construction industry contributes to boosting the economy of the country. Professor Carl Haas in his speech at CSCE addressed how circular economy is pushing the adaptive reuse market to effectively approach new building techniques. The similar depth in his thinking has also been expressed by (Doan & Chinda, 2016). According to their research in construction and demolition waste recycling program in Bangkok, they found that construction and demolition waste that contains around 95% recycling waste are disposed as landfills without any waste separation. Thailand generated around one-fourth of the total of 1.5 million tons of C&D waste. Stating that the construction contractors in Thailand have least interest in the concept of recycling the waste building materials, Doan and Chinda (2016) emphasize on the need of educating the importance of recycling the waste. Their study aimed at developing a system dynamic model with the supplemental data on 5 types of construction and demolition waste namely concrete, brick, metal, wood, and ceramics to determine the feasibility of construction and demolition waste. The homogeneity of wastes can not be assured as the demolitions is a haphazard process. The segregation of the components is done at a later stage depending on the fate of the waste. The benefit elements such as noise pollution savings, landfill charges, sand, aggregate and carbon tax savings have been identified by expertise advice, and cost elements such as labour wages, truck and fuel costs, maintenance costs were determined and using the supplemental data modelling. World Bank (2014) says that Thailand is the only country imposing carbon tax of an average of 450 Baht per ton of CO_2. It is an initiative to reduce the use of virgin materials and promote reusing and recycling of C&D waste.

The net present value has been determined keeping the IRR at 12% followed by a sensitivity analysis (Doan & Chinda, 2016). The simulation results show that it takes 14 years for the recycling program to break even. This is different for different sectors considered in this paper.

Circular economy is at its infancy stage in the construction industry due to lack of knowledge regarding the process. Therefore, in order to achieve cost efficient and environment friendly construction this concept needs to be blend right from the root of the construction processes and training. This can be achieved by designing structures in a way that disassembling (not demolishing) and reusing the components after the useful life of the structure for other construction activity may reduce the cost of construction and gives rise to sustainable construction activity. It is understandable that 100% deconstruction is highly unlikely to achieve but even a minimal utilization creates a very big impact when performed on a larger scale. Srour, Tamraz, & Chehab (2012) has even explained through an equation where the selling price of Recycled material, RCp, should be greater than the difference between recycling cost and the gate & landfill tipping costs.

$$RC_p \geq R_c - C_r$$

The results in Doan and Chinda (2016) have concluded that initially the costs would be higher, but with the increase in the amount of investments by the companies would prove it to be a successful one.

Mining and other energy harnessing activities and been showing their inclination towards adopting circular economy in their approach. The resources such as metals that are considered crucial for the modern society has been a topic of discussion, to utilize them in a sustainable manner. Kinnunen and Kaksonen (2019) have found a sustainable factor in mine tailings for the rocks after the extraction of minerals. A huge amount of waste is generated from the tailings produced on a daily basis. Although, the study is in progress and companies are still figuring out the efficiency and profitability. The mine life cycle also plays a major role in handling mine side-stream. The valorization potential needs to be considered in order to make a stronger statement when it comes to the need for a circular economy in Mining industry. There is clearly a lack of definition of circular economy in Mining industry, but the situation is expected to change when looking at a longer term.

In order to dig a bit deeper, we need to learn about the indicators of circular economy and what the indicators measure. Indicators can be ratio, index, result of a simulation (Gallopin, 1996). (Moraga, et al., 2019) explains the familiarity of Circular Economy in the European union. Circular Economy at a macro scale level is useful in Energy analysis, analysing the material flow (Kalmykova, Sadagopan, & Rosado, 2018). It also shows that indicators might lead to different conclusions and cause ambiguity. According to (Pauliuk, 2018) the British Standard Institute has assessed five characteristics using the indicators which are restore, regenerate, maintain utility, maintain financial value, and maintain nonfinancial value. Finding what indicators measure Circular Economy and what do the indicators measure in circular economy are the important things to understand. The focus is mainly on the R – framework that strategizes the need of Circular Economy. Various business models are supported by such strategies. These are the strategies that are needed to be measured with the help of the indicators. There is a need for a framework that monitors what to measure and how to measure the indicators through different approaches. Different models like Raw material scoreboard, waste framework directive and Efficiency of resource have been identified direct and indirect indicators. The framework used is mostly focussed on preservation of the material resources using the recycling methods. In other terms, the approach is termed as the Life Cycle Thinking approach.

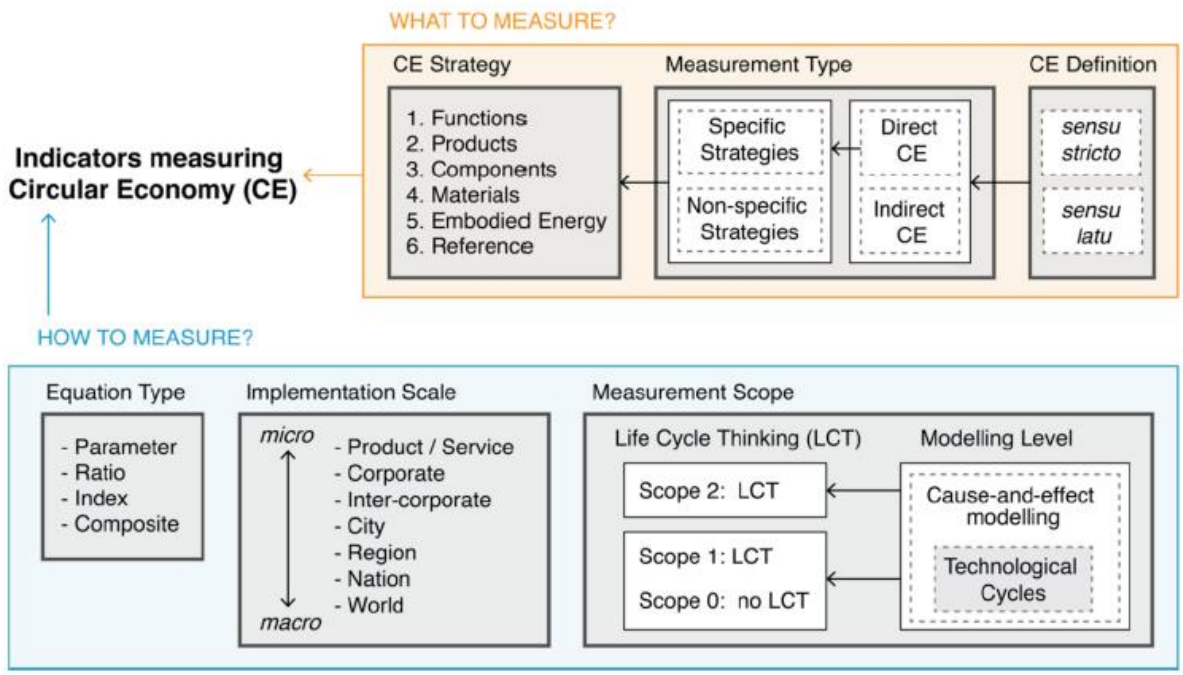

Figure 3 Classification Framework for CE indicators (Moraga, et al., 2019)

García-Barragán, Eyckmans, & Rousseau (2019) states that the recycling and circular economy are pretty much similar, but the metrics of recycling can not be used to measure the circular economy of a project. Circular economy focuses on maximizing the value of a resource, whose metrics are compatible with the recyclables. Therefore, a mathematical approach has been taken in order to define the working of a circular system to check the efficiency of circular activity and linear activity.

Tingley & Allwood, (2015) has discussed some case studies of the structures ranging from temporary to permanent buildings within the United Kingdom. The main aim is to study the reduction of embodied CO2 emissions. Reusable materials drastically reduce the CO2 emissions. This reduction happens without stopping the economic growth of a nation. (Teigiero, Solar-Pelletier, Bernard, Joanis, & Normandin, 2018). European countries which have adopted this has been able to reduce around 29 million tonnes of CO_2, saving around 23 billion sterling pounds (Teigiero, Solar-Pelletier, Bernard, Joanis, & Normandin, 2018). They have suggested the use of materials in construction which can be reused after the useful life of the structure, such as lime mortar steel structures with no signs of deformations, structural timber. In short there is a need to design structures for possible deconstruction. The London Olympic Park 2012 was designed for structures with possible deconstruction. Although portal steel frames were retrieved for possible reuse, the usage was not tracked. Now in order to lease the stadium for Soccer Tournaments, certain changes to be adapted will cost around £190 million with the steel frames not being reused. A 7200 square metre temporary Water Polo & Shooting Arena seating facility constructed from Truss system with PVC covering costed them around £1.2 million to design it for deconstruction. The components were effectively deconstructed and were expected to be used for the Rio Olympics 2016. Chobham Manor, a temporary marketing suite with full deconstructed steel frame, can be removed from the site without a trace. Around 80 % of the joints are used as a pin joint system. Since it is foundation less, the structure has a lower embodied carbon. Vulcan house is another case study where the there is a potential of reusing 950 tonnes of structural steel but due to composite metal deck floor, removing the beams without damage seems to be a difficult task. Although the structural members can be reused, the potential is limited to columns for this case. The journal suggests that the trend in designing demountable steel structures are proving efficient which increases the useful life of the building and making it energy efficient.

Garmulewicz, et al. (2018) has also designated waste as a valuable resource in their economic model. It is not only limited to the economic model, but the principles can also be developed to design a business model in maintaining and recycling the resources. Some journals have even provided information on demolition with reference to deconstruction. Hamidi, Bulbul, Pearce, & Thabet, (2014) has mentioned about the application of building Information modelling as a useful tool in determining the end of life operations and cost- benefit analysis of demolition waste management. With the inputs from the hierarchy of Environmental Protection Agency, the cost and benefits have been structured. The potential application of BIM in shaping the circular economy in construction to develop a waste management tool is determined from the data acquired from the literature and on-site survey. A cost- benefit analysis is performed by selecting the 5 major components of the building which can be retrieved from the Revit Architecture model evolved during the designing phase. Like any other literature, the limitations exist and are with the reference sites. The data collected at one site could not be used as a reference for another site due to the nature of work and unit of materials. Thus, making it suitable only for an individual project-based level (Hamidi, Bulbul, Pearce, & Thabet, 2014).

With the integration of the Adaptive Neuro-Fuzzy Inference System (ANFIS) with BIM have even widened the scope of predicting the construction waste (Akinade & Oyedele, 2019). There is a need to design the waste out of the site efficiently. The construction supply chain is needed to predict the construction wastes from the building design (Akinade & Oyedele, 2019). The concept of combining different AI techniques into a single hybrid system which includes all the strengths and limitations resulted in ANFIS. It is constructed with several layers of different parameters that generally have 2 inputs and one output. With the step by step process for accessing documents from the BIM has been implemented in Waste analytical system (WAS) for ANFIS. The limitations have been identified as their reliance on the national waste generation rates. Also, it can be used only once after the building design has been completed. Supply chain plays a vital role in supplying resources according to the construction needs (Akinade & Oyedele, 2019). Therefore, the integration of this technique has a huge implication for the circular economy in order to quantify waste at every stage which would minimize the accumulation and timely waste process and disposal.

Circular economy essentially promotes the reuse of materials thus minimizing the wastes to be landfilled. Simulation approach by Lu, et al. (2009) in a case study on Hong Kong's Kai Tak Airport demolition also focuses on investigating the cost efficiency of waste handling practices. Around 115400 cubic metre of broken concrete was sieved. The CYCLONE model and been contrasted with the SDESA model. In the Cyclone model the state of the resource is identified in the resource- driven workflows with the help of certain nodes that enable linkages between different workflows. Whereas, SDESA model gets into the depth of each workflow and the entities associated with it (Lu, 2003). The SDESA uses activity blocks, which further breaks down into tasks which clearly maps the flow of waste in the process. The utilization rates achieved from simulation were high (up to 99%) which would in turn cut the project duration by half and the direct costs could be curtailed. Recycling the construction waste is a challenging task without a theoretical framework. The framework according to Srour, Tamraz, & Chehab (2012) uses information to determine various parameters right from the origin of the waste. This helps to monitor the path of waste disposal, categorization of wastes and appropriate techniques of waste utilization, costs involved and selling the recycled materials.

4. SUGGESTED FRAMEWORK

Moraga, et al. (2019) had suggested that Indicators can measure according to Circular Economy Definitions and Circular Economy Strategies. There are two definitions representing Circular Economy that have been given by Moraga, et al. (2019). Sensu Stricto and Sensu Latu.

Sensu Stricto has a narrow focus on CE about its characteristics that is slowing, which means extending the life of the structure/ product and the other one is the closing resource loops, where the resources are converted into their secondary usage resulting in a circular flow.
Sensu Latu has a broader focus (Murray, Skene, & Haynes, 2017)where the processes like planning, designing, procurement follow, shifting the focus to sustainability and the environmental effects of CE strategies implemented.

This study has come up with the steps that define the framework of the case studies.

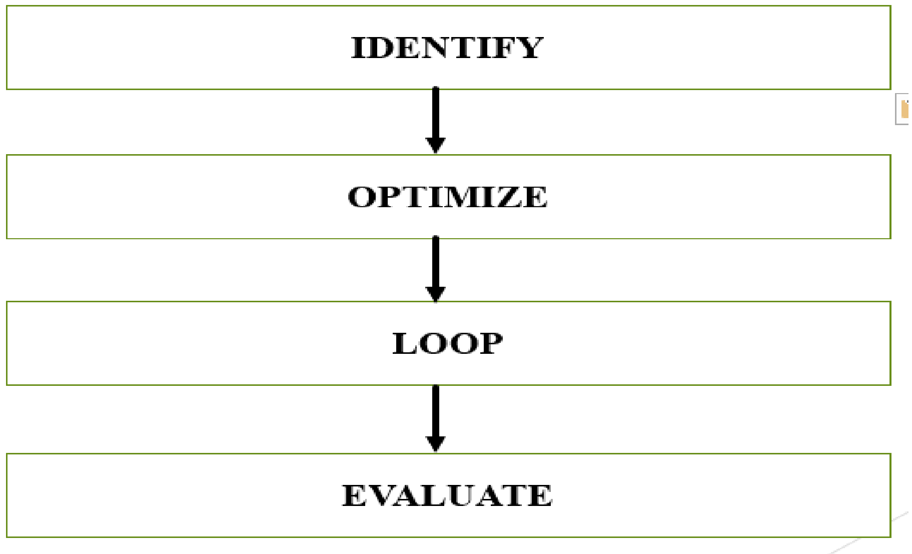

Figure 4 Framework of the case studies

1. Identify: This is a demonstration process of the problem. The problem will be analysed, the limitations will be addressed, all the lacking parameters will be brought forward and mention the efficiency of the technology being incorporated in resolving the issue.
2. Optimization: Design a system or arriving with a solution or technology that suggests efficient sustainability methods to reuse, recycle, increase the lifespan of the structure, cost saving, and any other beneficial parameters involved in decreasing the usage of primary resources.
3. Loop: This is the check stage. Where the resources/ wastes that have been efficiently retrieved are put in a circular utilization loop to check their behaviour in the construction project in terms of time, cost, recycling rates, environmental friendliness.
4. Evaluate: The final stage for showing the results obtained by adopting a circular approach and determining if there is a necessity to go with a better technology or better resources.

In order to strengthen the framework, we analyze what the indicators are in Circular Economy, what to measure and how to measure, there need to be developed strategies in order to assess the implementation status of CE in the construction Industry. Moraga, et al. (2019) has suggested 6 strategies:

4.1 WHAT TO MEASURE

Strategy 1: To increase the lifetime of the structure such as durability, reuse or restore.
Strategy 2: To preserve the essential components of the structure through reuse and recovery and rehabilitation.
Strategy 3: Recycling the materials
Strategy 4: Energy recovery by avoiding incineration facilities and landfills
Strategy 5: Measure the progress of CE keeping linear economy as a reference model.

There are different types of indicators that outline the strategies.

1. Direct indicators with specific strategies: That focus on one or more identifiable strategies, e.g., Reusing rate. (Graedel, et al., 2011)
2. Direct indicators with non-specific strategies: That focus on one or more strategies which are non- identifiable explicitly. (Graedel, et al., 2011)
3. Indirect Indicators: Indicators that evaluate CE with the help of reference indexes. (EC, 2016)

4.2 HOW TO MEASURE

This is where the Life Cycle Thinking (LCT) approach comes into play. "LCT is the capacity to look at products or services over the cycles of design, production, consumption, use, and disposal including interactions with sustainability" (De Haes & Van Rooijen, 2005)

Three measurement scopes are provided considering the LCT approach.

A. Scope 0: the indicators usually measure physical properties from the technological cycles without considering the LCT approach, *e.g.* Recycling Rate (Graedel, et al., 2011)
B. Scope 1: the indicators measure physical properties from the technological cycles considering full or partial LCT approach, *e.g.* Recyclability (Ardente & Mathieux, 2014)
C. Scope 2: the indicators measure the effects from the cause of technological cycles regarding environmental, economic, and/or social aspects with the RRR considerations. (Huysman, et al., 2015)

The implementation scale can vary from Micro to Macro levels and the equation type of the indicator can be ratios, indexes, parameters, and composites.

5. CASE STUDIES

Some case studies have been referred in context with the impact of circular economy in construction and deconstruction. The results and conclusions of these case studies have been analysed and categorized according to the scope they fall under.

5.1 CASE STUDY 1: Simulation Approach for evaluation Demolition in Hong Kong's Kai Tak Airport

The aim of the project was to minimize the cost of waste handling practices by using a simulation model. The loads of broken concrete of mixed sizes were to be sieved namely Small Broken Concrete (SBC) and Large Broken Concrete (LBC), transported in the trucks and stockpiled. The workflows were defined, and CYCLONE simulation was considered at first. But due to the limitation that the model could not specify the resource transit information and detailed logical relationship between the workflows, SDESA model was preferred. This model gave the information on the quantity take off of the resources, defining resource requirements and resource availability at each activity, weather conditions suitable for working, number of working hours amount of concrete to be loaded in the truck, tracking and analysing waste flow (Ming, Lau, & Poon, 2019).

The simulation results were determined by 100 Monte Carlo Simulation runs and further assessment on waste handling and moving patterns resembled with the actual site location. A total of 23653 t. of broken concrete was produced (Ming, Lau, & Poon, 2019).The Actual daily production was calculated to be 454.8 cu m/day and compared to the value determined from Simulation production of 460.8 cu m/day. A Standard deviation of 1.6 cu m. / day was determined. The animation could show the waste handling process similar to the site operations.

Keeping this precision in mind and the actual units produced & transported as reference, simulation was done for different cases in order to check the cost efficiency (Ming, Lau, & Poon, 2019).

Reference – Base Resource produced and transported: The base resource are the actual resources that were initially produced and transported initially so that the data can be fed into the simulation Model to test the following.

1. Resource (+1 unit) → Adding 1 unit of resources to each activity and comparing the time and cost.
2. 1.5 * Resource → 1.5 times the resources produced and transported.
3. 2.0 * Resources→ 2 times the resources produced and transported.
4. 2.5* Resources→ 2.5 times the resources produced and transported.

It was seen that doubling the production and stockpiling of resources per day saves $163 per day and reduces the project time to half (Ming, Lau, & Poon, 2019). Sample calculation has been shown below

C/ -(change in Time) $_{\text{(Original -2R)}}$
= (Total cost of Alt 2R − Total cost of Base)/ (Total duration of Base − Total duration of Alt 2R)

= $((7.33 − 7.35) * (10^6))/ ((9.67 − 4.95) month* (26 day/1 month))

=− $ 20,000/122.72 day
= − $ 163/day

In this case study, there is a motive of reusing the broken concrete obtained from demolishing the Airport components. Also, the simulation intends to minimize the cost and time of the project by managing the utilization of resources such as backhoe and trucks efficiently.

5.2 <u>CASE STUDY 2</u>: Cost- Benefit Analysis in Modelling construction and Demolition Waste Recycling Program in the city of Bangkok. (System Dynamic Modelling)

SD modelling is a technique used on the behaviour of real-world systems for a long- term analysis. To strengthen the decision-making process, the interrelationships have been determined. SD modelling techniques have been used in various fields in construction to assess waste levels, landfill costs and economic impacts in a construction cycle. This study was focusing on developing a model to perform a cost benefit analysis for the Construction and demolition waste program for policy making (Doan & Chinda, 2016)

- There have been a lot of changes taking place in the construction industry, SD modelling helps deal with all these dynamic changes by determining the interrelationships between the activities.
- SD also provides alternatives to select the best recycling program available to be implemented.

Developing a model in the city of Bangkok was a challenging task as the waste disposal was not efficiently tracked. The people in the industry had very little idea about the concept of construction waste recycling (Doan & Chinda, 2016). Therefore around 95% of the waste that could be recycled, were disposed as trash. This study focussed on the cost and benefit elements, based on the types of C&D waste generated, employing Gross Regional Production (GRP) of construction activity.

Five main types of C&D waste were identified: Concrete, Bricks, Metals, Ceramic and Wood. After in-depth interviews and expert advice from the experienced engineers, primary data was obtained and with further studies in various construction projects in and around the world, secondary data was obtained (Doan & Chinda, 2016).

Various cost and benefit elements have been identified from the project's perspective.

Table 1 Benefit Elements (Doan & Chinda, 2016)

Benefit Element	Savings	Unit
Landfill Charges	464	Baht/t
Sand	262.36	Baht/cu.m
Aggregate	555.88	Baht/t
Carbon Tax Rate	450	Baht/t CO2
Air and noise Pollution	34.20%	Landfill space charge

Table 2 Cost Elements (Doan & Chinda, 2016)

Benefit Element	Cost	Unit
Labour Wage	300	Baht/person
Training Cost	12200	Baht/person
Fuel Cost (NPV)	12.5	Baht/kg
Buy/ Rent Ratio	75/25	-
New Truck	2450000	Baht/truck
Truck Rental	95000	Baht/truck/Month
NGV Installation	425000	Baht/truck
Truck Insurance	50000	Baht/truck
Drivers	22500	Baht/truck/Month
Route	2500	Baht/truck/5 years
Tires	2	Baht/truck/km
Regular Maintenance	2	Baht/truck/km
Big Maintenance	100000	Baht/truck/5 years

Based on the above two tables, Total costs and total benefits have been identified using the following equations.

Total Benefits = Saving in fuel cost to landfill + Saving in landfill charges +Saving in levelling cost + Saving in Virgin Material+ Green Image (Equation 1)

Total Costs= Training cost + Labor Cost + Fuel Cost + Truck Cost +Processing Cost (Equation 2)

The most important thing is the Green Image**.** Thailand is one of the nations that imposes taxes based on carbon emissions. The amount of waste generated has some amount of CO2 emissions for which the government has set a taxation slab for each sector depending on the carbon emissions. It is estimated that there will be a 20% reduction in CO2 emissions in Thailand by 2030. An SD model has been developed for the labour cost and the interrelationship between multiple factors have been determined and indicated through arrow signs.

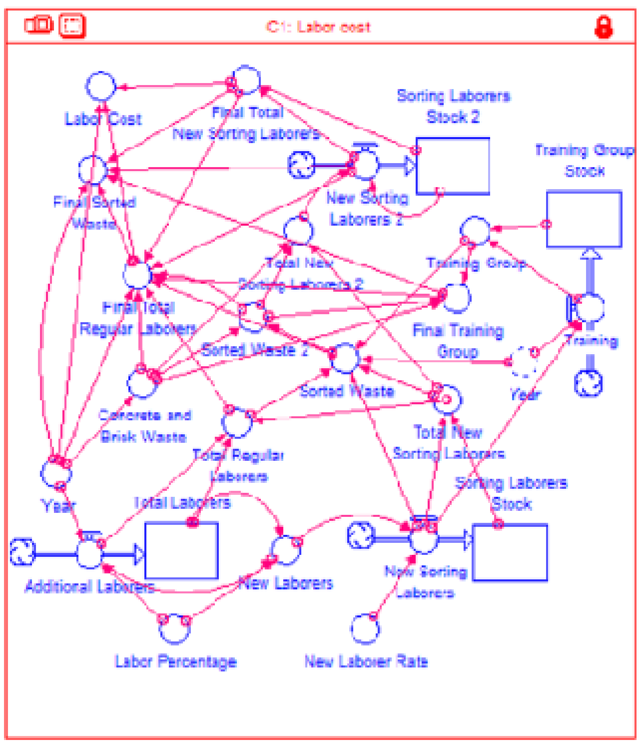

Figure 5 SD Modelling (Doan & Chinda, 2016)

Since the investment's profitability is defined by the IRR, it was found that the project was feasible for an IRR = 12% (government projects Sensitivity analysis was performed, considering 2 cost (Buying rate and Labour cost) and 2 benefit elements (Recycling rate and Green Image rate) (Doan & Chinda, 2016).
Simulation was run and it was observed that though it took 10 years to start making profits, the breakeven point (where the NPV>0) is achieved at 14th year. There has been a tremendous effect

of landfilling charges and green image rates on the recycling process. On site sorting plays a vital role in cost cutting (Doan & Chinda, 2016).

In this case study, there is reusing construction and deconstruction waste which is interlinked with other cost and benefit elements such as landfilling, truck costs, fuel costs. Also, the simulation by setting the apt interest rate in the dynamic model, further shows the parameters that are sensitive and determines the feasibility and possible timeframe to benefit from the scenario, economically as well as environmentally.

5.3 CASE STUDY 3: Queen Elizabeth's Olympic Park.

The case study is about the London's 2012 Olympic Park which was aimed at construction lasting a very short life span and then reuse the materials for a different construction purpose (CE100, 2016). The two distinctive levels it was designed were

1. To host the games
2. To reuse the structures in a different construction location.

The aim was to reuse around 50% of the resources used in the construction of the stands. The seating capacity and other factors were considered before the construction was started. Since the stadium was designed for a potential deconstruction, there were certain deliberations in the areas where waste generation was reduced are:

1. Shallow foundations were used instead of deep foundations which reduced the excavation by 275 mm.
2. Precast concrete piles were used instead of steel piles to reduce waste generation.
3. BIM was used to check performances that reduce rework and onsite waste generation.

The stadium was designed for partial deconstruction using light resources and about 90% less steel than the 2008 Beijing Olympics. A 7200 square metre temporary Water Polo & Shooting Arena seating facility constructed from Truss system with PVC covering cost them around £1.2 million to design it for deconstruction. The components were effectively deconstructed and was expected to be used for Rio Olympics 2016 (CE100, 2016).

1. Due to the reuse of gas pipeline, 2500 tonnes of steel were saved and a cost savings of around £ 500,000.
2. Blockwork technique reduced the amount of steel required which further saved £40,000.
3. 104,000 tonnes of recycled crushed waste concrete were reused saving £1 million and around 20,000 lorry movements.

This was supported by removing the upper tier of the stadium and reduce the total capacity. The upper tier will be retained for the use in the new stadium efficiently (CE100, 2016).

This case study showed us the revolutionized method of construction, aiming at cost saving, minimal resource utilization, and possible reuse of structural components to align in the vision of achieving sustainability. The scope of Life Cycle Thinking approach has been expanded through designing for deconstruction, in order to have a minimum impact on the environment. The direct indicators have been determined keeping in mind of all the strategies mentioned.

5.4 CASE STUDY 4: Demountable steel structure, Chobham Manor Marketing Suite, London

Chobham Manor was created in London's Queen Elizabeth's Olympic Park (CE100, 2016). The case study revolutionized the way sustainable construction has been implemented in the industry. It was built in 8 weeks. The aim was not only to reduce the carbon emissions but also to promote sustainable development. Under the proposal at the bidding stage, a total of £104.5 million was to be paid for the site.

Chobham Manor is a steel structure construction based on selective deconstruction. In order to do that, the buildings in the neighbourhood were examined and evaluated if there were any materials that could be reused once they were demolished (CE100, 2016). This has been an alternative to the conventionally designed buildings and environmentally viable as well. The building was constructed on a contaminated ground. It was a foundation less structure with complete deconstruct able steel frame which can be removed after the service life. It was seen that around 80% of the joints were pin jointed systems. Most of the steel in the grid are reusable after 5 years of its life span. Complex foundation system was eliminated by the revolutionary steel pad feet. Due to the foundation less system, the construction time is less, and it has a lower embodied carbon which would result in low carbon emissions.

The waste produced by the construction activity of Chobham Manor, less than 1% of the excavation waste was sent to landfills. Around 82% of the waste was recycled and 18% of energy was produced from the recycled waste. 20 % of the construction materials to be used from a recycled or used source. 25% of recycled content of aggregates is to be utilized. Carbon emissions is expected to be reduced by 15%. Rainwater harvesting and greywater treatment has been incorporated in the design. It was seen that GDP after the Olympics rose from 1% to 1.5 % through 2015 (Bank of England, 2015).

This case study is like that of Queen Elizabeth's Olympic Park showed us the revolutionized method of temporary construction, aiming at cost saving, minimal resource utilization, and possible reuse of structural components to align in the vision of achieving sustainability. The scope of Life Cycle Thinking approach has been expanded through designing for deconstruction, in order to have a minimum impact on the environment. The direct indicators have been determined keeping in mind of all the strategies mentioned.

The table below shows the categorization of different case studies according to the indicators, the strategies involved, the scope of Life Cycle Thinking and the measurement type depending on the indicators and strategies.

Table 3 Categorization of different case studies

Case Studies → **Indicators**	**Kai Tak Airport (Hong Kong) (After optimization)**	**SD Modelling (Bangkok)**	**Olympic Park (London)** (Environmental Sustainability Report 2014/15, 2015)	**Chobham Manor (London)** (Environmental Sustainability Report 2014/15, 2015)
Waste Generation	✔	✔	✔	✔

	(23,653 tonnes of broken concrete produced; 10% non inert waste generated)	(an average of 1.5 million tonnes of combined waste between 2009-2012)	(13% reduce in the waste generation)	(Less than 1% waste generated and 15% reduction in Carbon Emissions)
Recycling Rates	✓ (10% inert waste recycled by crushing)	✓	✓ -98.50%	✓ -82%
Recycling/ Recovery from waste streams	✓ (80% of the inert waste reused)	✓	✓ -22%	✓ -20%
Contribution of recycled materials to raw materials demand	✓ ($163 USD savings per day)	✓	✓ (20,000 tonnes of virgin materials saved)	✓ (25% of recycled aggregates used)
Trade from the European Union	X	X	✓ (used in Rio Olympics)	X
Value addition and investments	✓ 87% (Average Utilization rate of resources)	✓	✓	✓ (Saving £5 Billion between 2015-2030)
Patents	X	X	X	X
Strategy Scope	3,4,5 1	3,4,5 1	1,2,3,4,5 2	1,2,3,4,5 2
Measurement type	Direct	Direct	Direct	Direct

6. THE STUDY OF OLD CHAMPLAIN BRIDGE

The Champlain bridge, now, also known as the Old Champlain Bridge, is a 3.5 km long steel truss cantilever bridge constructed in 1962, located over the St. Lawrence River in Montreal. Connecting Brossard and Iles des Soeurs with the island Of Montreal, the six-lane bridge was constructed at a cost of approximately $35 million. (excluding the approaches).

The main components of the bridge are steel, concrete and asphalt. The bridge served as a major public transit and freight transport for the economy to flourish between Canada and the Eastern United States. Most of the road transportation of goods and other services worth $20 billion each year used to take place through this bridge. The bridge used to serve the pathway to around 59 million commuters per year which was good from an economic point of view but not from the bridge's structural point of view. The bridge was originally designed considering no allowances for a future increase in dead or live loads. With the passage of time, the maintenance of the bridge could not meet the ever-increasing traffic. The Champlain Bridge was one of the busiest bridges in the entire Canada. The number of vehicles crossing it has been ever increasing. It started from an annual average daily traffic of 7,300 vehicles in the year 1963, further increasing to 33,400 in 1968, 109,700 in 1989 to an average annual daily traffic of 134,000 in 1999. Out of that 8% were trucks. Now, approximately 59 million vehicles cross the Champlain Bridge every year (JCCBI Community Heritage Website, n.d.). This ever-increasing traffic led to a major rehabilitation of the bridge in the year 1990. The reinforced concrete deck on the bridge was replaced with the cantilever steel superstructure. The piers were also rehabilitated due to the vertical and horizontal cracks that were found in the portion underwater. Though the maintenance cost of the structure were increasing, the problems were still unresolved and sporadic. The government of Canada announced that the bridge had reached the end of its service life and that it will be replaced with a new Bridge ((JCCBI Community Heritage Website, n.d.). In 2013, there was a crack on the edge girder detected, for which the corporation installed a 75 tonne super beam to stabilize the cracked girder (JCCBI Q&A Website, n.d.).

The Jacques Cartier and Champlain Bridges Incorporated (JCCBI) is responsible for the Jacques Cartier Bridge, the Champlain Bridge, the Champlain Bridge Ice Control Structure. The deconstruction of the bridge would prove to be socially, economically, and environmentally viable. This study is focussing on the economic viability of process of deconstruction of the Old Champlain Bridge, which is set to take place in the beginning of 2020, determining the circularity in economy keeping in mind the concept of environmental sustainability by incorporating reuse, recycle and reduce (3 R's) in construction and demolition waste (deconstruction waste, in this case).

6.1 ASSUMPTIONS

Before getting into details of the project, we made some assumption in the project. These assumptions came into account as a result of inaccessibility to even publicly available data on the Champlain bridge, and some assumptions based on requirement and trend.

1. The case study of the Champlain bridge has been assessed as a business case since the research is focussed on assessing the benefits by adopting a circular approach. All the

economic analysis related to the bridge are based on the available data, and the rest have been developed based on the variation in the data values.

2. All the results obtained are based on theoretical evaluation of the bridge during its useful life. The same assumptions are applied to both circular and non circular approach.

3. The maintenance cost of the Champlain bridge has been calculated by the data available for the last two decades. Therefore, a non- linear increase in the maintenance cost is assumed to calculate the annual maintenance of the bridge.

4. All the rehabilitation costs have been considered as overhaul cost. Any rehabilitation that has been performed over a period, has been uniformly distributed over the same period (say, in years).

5. Due to the variation in inflation over the lifecycle of the bridge, we took average of the inflations for the years that had similar values and arrived on 5 different inflation values to work on.

6. The grade of concrete used in the construction is assumed as M35, HYSD bars are used for reinforcements and the grade of asphalt used for the bridge pavement is assumed to be Hot mix Asphalt (H2).

7. For approximate estimation of materials, it is assumed that the bridge has the same grade of concrete and steel reinforcements throughout the bridge deck, pier shaft and footings.

8. All the pier heights are of the same dimensions.

9. Any benefits incurred from the bridge are not taken into consideration because we are concentrating on comparing the capitalized cost for both circular and non- circular approach.

10. Based on our inputs we assumed that the bridge stands for at least its actual lifecycle period while making the cashflow

11. Following the design conditions, the quantity of steel reinforcements is not to exceed 4% of the total quantity.

6.2 IDENTIFY

6.2.1 APPROXIMATE ESTIMATE

In this chapter, we are analysing the lifecycle of the Old Champlain Bridge. From the circularity point of view, our approach is to recycle, recondition and reuse the deconstructed materials in a way as efficient as possible. It has been found that the main components of the bridge are concrete, steel and asphalt. Therefore a thorough review of (Robitaille, Gariepy, & Montminy, 2016-2017) (CAC, 2016)provided us with the approximate estimation of materials that can be recovered during the deconstruction of the structure. The Champlain bridge is divided into 3 sections. Section 5, 6 and 7. Section 5 and 7 are the concrete spans whereas, section 6 is the steel span.

Table 4 Approximate Quantities for Deck of Section 5 and 7 (Robitaille, Gariepy, & Montminy, 2016-2017)

Approximate Quantities for the Deck			
	Section 5 & 7A	Section 7B	Total
Number of Spans	44	6	50
Number of Girders	308	42	350
Width of Girders and Diaphragm per span	1210 t	1030 t	59420 t
Slab Weight per span	345 t	335 t	17190 t
Barrier Weight per span	130 t	125 t	6470 t
(Concrete)			1925 t
TOTAL CONCRETE			85,005 t (34,037 cu.m)
TOTAL REINFORCEMENT STEEL			4795 t
TOTAL ASPHALT per span	190 t	185 t	9470 t

Table 5 Approximate Quantities for Foundation of Section 5 and 7 (Robitaille, Gariepy, & Montminy, 2016-2017)

Approximate Quantities for the Foundation			
	Section 5	Section 7	Total (in t)
Number of Piers	39	9	48
Weight of pier cap	365 t	365 t	17,520 t
Mean Height Of pier Shaft	16.90 m	15.10 m	
Mean Weight Of pier Shaft	935 t	840 t	44025 t
TOTAL			61545
Shaft			59083.2
Minimum height of the Pier Shaft		3.30 m	9.30 m
Maximum height of the Pier Shaft		26.15 m	22.85 m
Mean Weight of footing	920 t	920 t	44745
Total Volume of Concrete Fotings			42955.2
Weight of reinforcements (Steel lining in Pier Shaft and Pier Caps)			2461.8
Weight of reinforcements (Footings)			1789.8

Table 6 Approximate Quantities for Deck of Section 6 7 (Robitaille, Gariepy, & Montminy, 2016-2017)

Approximate Quantities For the Deck				
	Section 6 (4W-3W and 3E- 4E)	Section 6 (3W-2W and 2E- 3E)	Section 6 (2W- 2E)	Total
Number of edge trusses	4	4	2	
Number of Internal Trusses	4	4	1	
Weight of Edge Trusses	434 t	441 t	1896 t	2771 t
Weight of Internal trusses	508 t	513 t	1639 t	2660 t
Weight of Bracing	156 t	151 t	943 t	1250 t
Weight of steel deck	990 t	996 t	3276 t	5262t
Weight Of steel railings			559 t	559 t
TOTAL STEEL (STRUCTURAL)				12502
Concrete barriers	341 t	343 t		
TOTAL CONCRETE				684
TOTAL Steel				1.026
TOTAL ASPHALT	445 t	458 t	1391 t	2294

Table 7 Approximate Quantities for Deck of Section 6 7 (Robitaille, Gariepy, & Montminy, 2016-2017)

Approximate Quantities For the Deck	
SECTION 6	in t
Number of Piers	8
Minimum height of the Pier	25.71
Maximum height of the Pier	37.37
Mean Height Of pier Shaft	30.61
Weight Of pier Shaft	34,765
Weight of footing	26,287
Total Weight	61,052
Weight of reinforcements (Steel lining in Pier Shaft)	1390.6
Weight of reinforcements (Footings)	1051.48
Volume of Concrete in pier shaft	33375
Volume of concretein footing	25236

Table 8 Quantities Obtained 7 (Robitaille, Gariepy, & Montminy, 2016-2017)

Materials	Quantity obtained after deconstruction (in Tones)
Concrete	203,383
Asphalt	11764
Reinforcement Steel	11490
Structural Steel	12502

The above table shows the quantity of materials that can be recovered from the deconstruction of the Old Champlain Bridge and sent for recycling. (Robitaille, Gariepy, & Montminy, 2016-2017)

The minimum area of steel should not me less than 0.01(Gross area) and should not exceed 0.08 (Gross area). Also, Maximum 4% of steel reinforcement is permitted in columns. (CAC, 2016). Taking the 4% of quantity of, the quantity of steel was calculated for both the shaft and the footings. The minimum reinforcement in the deck should be around 0.12% Of gross area.

6.2.2 INFLATION AND INTEREST RATES

In order to determine the costs incurred, we need to start working with the inflation and the interest rates that plays an important role throughout the lifecycle of the bridge. The values of inflation and real interest rates throughout the years have been taken from the World Bank Data for Canada (World Bank Website, n.d.)and (Statista Inflation Rate Website, n.d.). The structure was operational from 1962-2019, for a period of 57 years. These 57 years have seen a high and low in the inflation and the real interest rates.

Since we had different inflation throughout the lifecycle of the bridge, we took the average of the inflation for the periods where the inflation rates were not showing much difference.

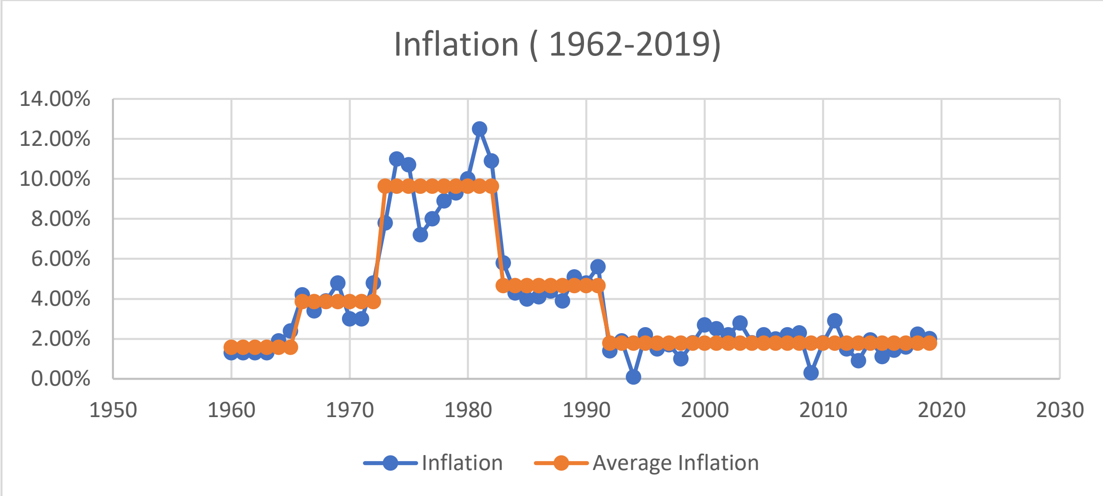

Figure 6 Inflation

Since we had different values of inflation that can be applied through the lifecycle of the bridge, we took an average of the inflation for the years successive years that had around the same values and came up with 5 inflation values that we would apply to the cashflows.

Table 9 Inflation Values

Inflation	Years
1.58%	1960-65
3.87%	1966-72
9.63%	1973-82
4.67%	1983-91
1.79%	1992-2020

6.3 OPTIMIZE

6.3.1 ECONOMIC ANALYSIS

The designing of a methodology or system in order to get the right path to the solution keeping in mind of the sustainable approach has been the main concern throughout. In order to achieve that, cash flow analysis was performed.

The initial cost of the bridge was found to be $35 million in 1962 (Ali, Aslam, & Mirza, 2016). But the annual cost for the following years were not mentioned. The only cost that was mentioned in the (Therrien, 2011) is that the annual maintenance expenditure in the next ten years rose from 18 million to 25 million from 2011. Therefore, using **the declining balance method** in the excel

sheet, the depreciation in the maintenance cost from 2019 through 1962 in the backwards was calculated for each decade, followed by the same declining balance method to determine the depreciating maintenance for every year through the decades.
The depreciation rate (d) for each decade = -28%. The negative value here indicates that the calculation is going in the backward direction, therefore the maintenance cost will decrease through all the previous decades.

The depreciation rate (d') for each year = -30%. The negative value here indicates that the calculation is going in the backward direction, therefore the maintenance cost will decrease through all the previous decades.

Which proves that,

d (For the decade) = (1/10) d' (for every year)

The overhaul costs were also included in the cashflow. Considering the installation of orthotropic deck at a cost of $40 million through four years (1990-1993) has been divided into 10 million each year.
Another installation of super beam in the year 2013 -2014 that cost around 158 million was again dived into 2, making $79 million per year. The benefits were also calculated. The bridge's traffic data was collected from (JCCBI Website, n.d.) which stated that in 1962, the number of vehicles travelling have been increasing over time. The annual average daily traffic in 1963 was 7,300 increasing to 33,400 vehicles in 1968 and 109,700 in 1989. The daily average was seen to be 134,000 in the year 1999. Website gave the information that around 66% of those vehicles were commuters (Champlain Bridge (1962-2019) Wikipedia, n.d.). A toll was charged at $0.08 for commuters and $0.25 for trucks and other passers by.
With the information above, we deduced the graph and corresponding values of AADT for all the years.

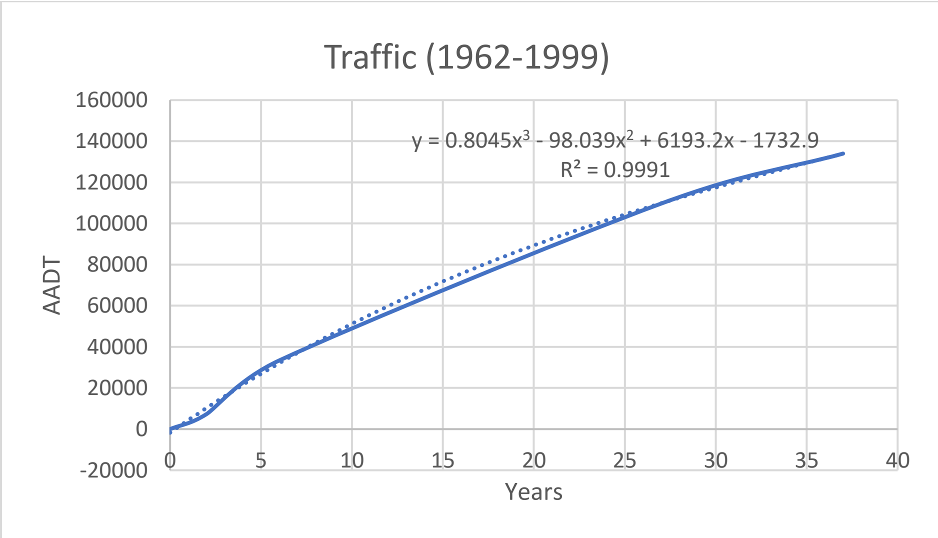

Figure 7 Traffic (1962-1999)

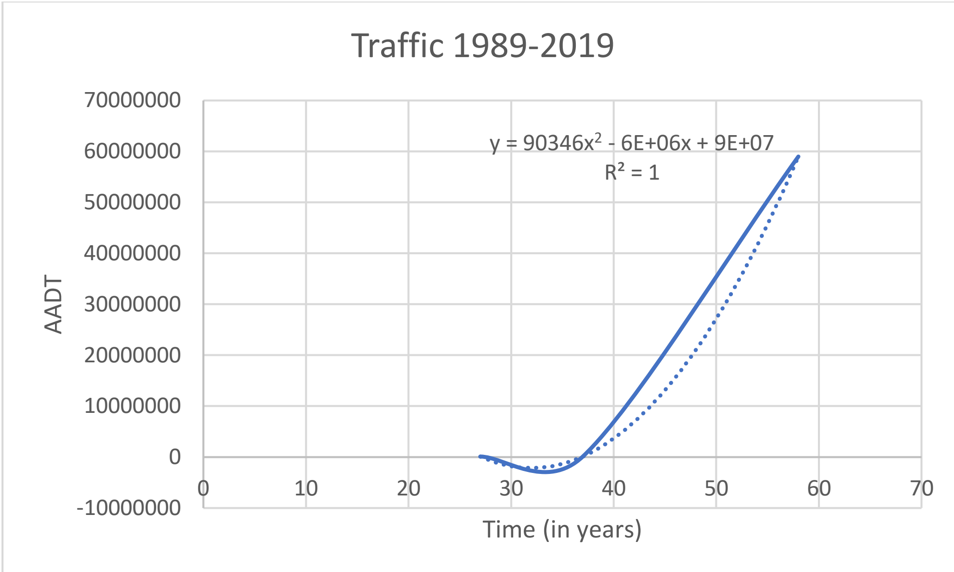

Figure 8 Traffic (1989-2019)

For example,
For year 1968
AADT: 37092 vehicles
Number of days in a year= 366 (leap year)
Commuters= 66%
Benefit from toll for the year 1968 = 37092*366* (0.66*0.08+0.34*0.25) * (10^-6)
= $1.87 million

The present worth of cost and benefit were calculated accordingly and a cashflow was drawn.

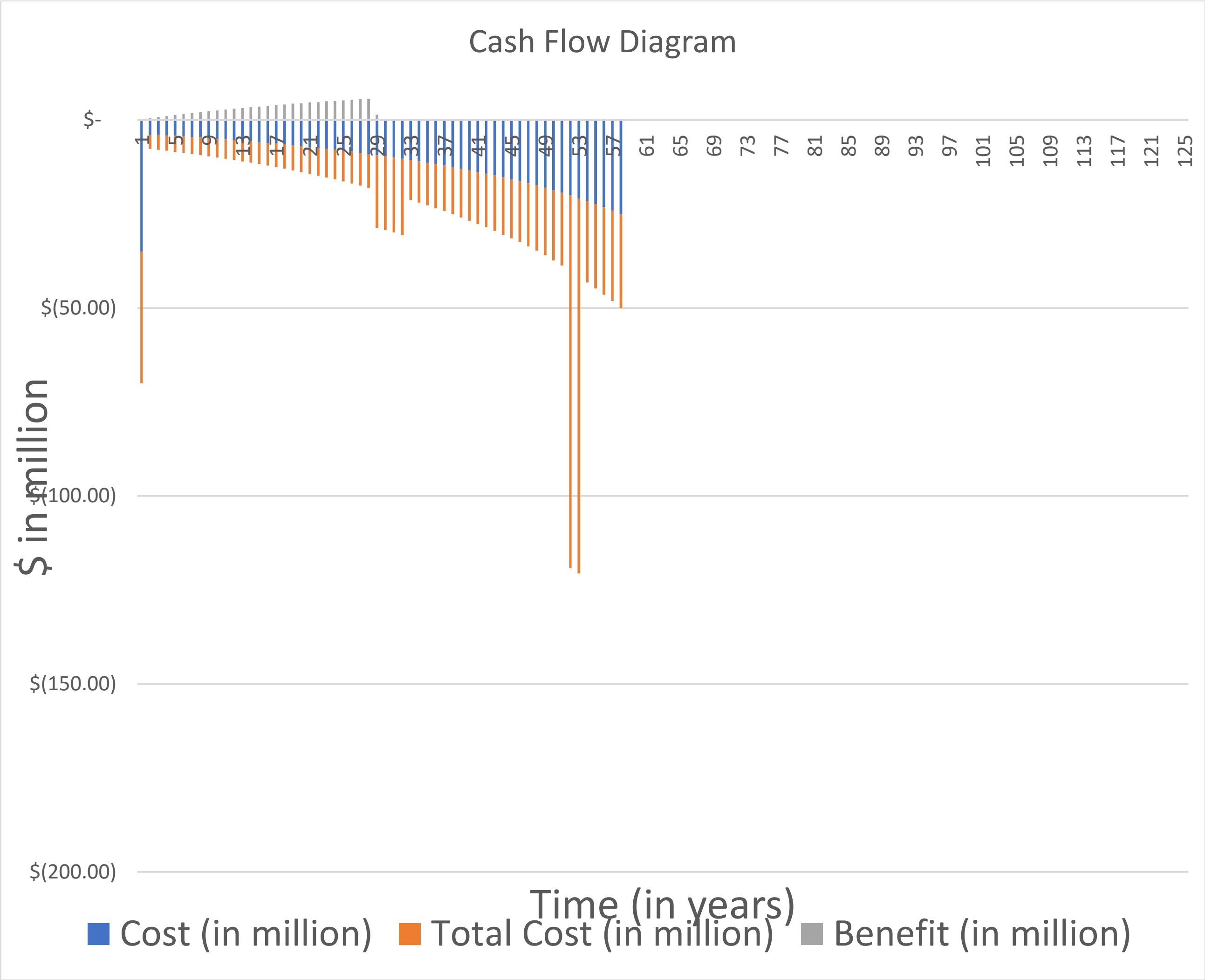

Figure 9 Cash Flow Diagram

All the costs are in millions (CAD$) unless specified

6.4 LOOP

This is the check stage. Where the resources/ wastes that have been efficiently retrieved are put in a circular utilization loop to check their behaviour in the construction project in terms of time, cost, recycling rates, environmental friendliness.

6.4.1 RECYCLING RATES

Recycling rates of all the construction materials identified within the scope of the work have been tabulated.

Table 10 Recycling rates of the materials

Materials	Quantity obtained after deconstruction (in Tones)	Recycling Rate
Concrete	203,383	80%
Asphalt	11764	80%
Reinforcement Steel	11488.68	71%
Structural Steel	12502	98%

(Giroux & Consulting, 2014) provided with the recycling rate concrete and asphalt in Quebec as 80%, whereas Fothergill, 2004 and Gorgolewski, Straka, Edmonds, & Sergio (2006) provided the rates of reinforcing steel and structural steel in Canada as 66-75% and 98% respectively. Here, the recycling rate of steel reinforcements has been taken as an average of 66% and 75 %. On an average around 82% of the materials could be recycled overall.

6.4.2 RECYCLED QUANTITIES

Based on the recycling rates determined, the recycled quantities were determined by multiplying the rate of recycling of each quantity with the quantity obtained after deconstruction.

Table 11 Recycled quantities of the materials

Materials	Quantity obtained after deconstruction (in Tones)	Recycling Rate	Recyclable Quantity (in tones)
Concrete	203,383	80%	162706.56
Asphalt	11764	80%	9411.2
Reinforcement Steel	11488.68	71%	8156.9628
Structural Steel	12502	98%	12251.96

A sample calculation shows that,
Recyclable Quantity of concrete = Quantity obtained after deconstruction * Recycling rate
= 204841* 80%
= 163872.8 tonnes
Recyclable Quantity of Asphalt = 11764*0.80= 9411.2 tonnes
Recyclable Quantity of Rebars = 11489* 0.71= 8157 tonnes
Recyclable Quantity of structural steel = 12502 *0.98 = 12252 tonnes

Now, as we proceed, the data collection plays a vital role in calculating the costs pertaining to the respective materials and their quantity.

6.4.3 RECYCLING COST

An associate from the Bonus Metal Canada Inc. gave the price for recycling reinforcement steel and structural steel as $95/ tonne and $115/ ton respectively. While the recycling cost of concrete was mentioned in an US EPA Archive Document, n.d as $15 per ton and the cost for asphalt as

$78 per tonne in the website for Asphalt recycling cost website, n.d. The costs were adjusted according to US- Canada currency value.

Table 12 Recycling cost of the materials

All the costs are in millions (CAD$) unless specified

Materials	Recycling cost in 2020) Millions	
Concrete	$	3.22
Asphalt	$	0.97
Reinforcement Steel	$	0.77
Structural Steel	$	1.41
	$	6.37

Recyclable cost of concrete = Quantity obtained after recycling * Cost / tonne
= 204841* 15
= 3.22 million
Recyclable cost of Asphalt = 11764*78= 0.97 million
Recyclable cost of Rebars = 11489* 95= 0.77 million
Recyclable cost of structural steel = 12502 *115 = 1.41 million

6.4.4 PURCHASING COST

The purchasing cost of concrete have been taken from a 2019 value provided by Purchasing Cost of Concrete Website, n.d. as $186/cu.m (for an M35 grade). The minimum grade of concrete that can be used in the bridge construction is M35. The cost for asphalt was taken as $260.67/tonne (item F980), reinforcing steel as $1.55/kg and structural steel as $4542/tonne in the (Average Unit Price Report, 2015-2017). All the prices were adjusted for inflation to the year 2020 costs.

Table 13 Purchasing cost of the materials

All the costs are in millions (CAD$) unless specified

Materials	Purchasing cost		Year	in 2020 million	
Concrete	$	12,609,758.40	2019	$	12.93
Asphalt	$	2,453,217.50	2016	$	2.45
Reinforcement Steel	$	17,809,044.30	2015	$	17.81
Structural Steel	$	56,784,084.00	2015	$	56.78
Total				$	89.98

All the costs have been considered under LOOP because we are going to use this cost in a circular loop to achieve sustainability. The purchasing cost and the recycling cost are derived in order to determine the circularity by saving the amount by recycling materials instead of purchasing the same.

Also, in order to determine how this approach is environmentally viable, we need to evaluate the carbon footprints of the material that were used to construct the bridge. The carbon emissions for each quantity has been identified from varies journals and internet resources.

Table 14 Quantity of CO_2 emissions for the materials

Co2 emissions	in tonnes of Co2/ tonne	
Virgin Steel	1.85	(Bellona Steel and Emissions Website, n.d.)
Virgin Concrete	0.18	(Carbon Emissions for Virgin Concrete Website, n.d.)
Virgin asphalt	0.05	(Al Adday, 2019)
Recycled steel	0.464	(Carbon Footprint of Steel Website, n.d.))
Recycled Concrete	0.145	(Carbon Emissions for Recycled Concrete Website, n.d.)
Recycled Asphalt	0.045	(Al Adday, 2019)

6.5 EVALUATE

The is the final stage to evaluate the costs that needs to be accumulated to keep the structure and its services running. For showing the results obtained by adopting a circular approach and determining if there is a necessity to go with a better technology or a better resource, we need to make a comparison in the cashflow for linear economic model and circular economic model. The cost spent on recycling and cost saved from purchasing the new materials have been incorporated in the table to find the

1. Cost saved in the year 2020
2. Cost in terms of 1962 money.

3. The amount saved is expressed as the net % initial cost to be invested in the next lifecycle to maintain circularity.

The table below shows the costs that are to be used to measure circularity in this scenario.

Table 15 Costs and net initial cost

All the costs are in millions (CAD$) unless specified

net % of initial cost to be invested	Cost (in $ Million)	
Purchasing cost	$	89.98
Recycling cost	$	6.37
Cost saved (in 2020)	$	83.60
Cost saved (in 1962)		$6.38
net %of initial cost to be invested in the next lifecycle		81.78%

Total Purchasing cost of new materials = $89.98 million
Total Recycling cost = $ 6.37 million
Total cost saved (in 2020 million) = 89.98-6.37 = $83.60 million

The cost was converted to 1962 money value to calculate the cost saved in 1962
For this we used all the 5 inflations

1. For converting 2020 (final value) cost to 1992 (present value) we used =
-PV (real interest rate 0.75% + inflation 1.79%, 28 (years),0, $83.60 million) = $41.42 m

2. For converting 1992 (final value) cost to 1983 (present value) we used =
-PV (real interest rate 0.75% + inflation 4.67%, 9 (years),0, $41.42 million) = $25.76 m

3. For converting 1983 (final value) cost to 1973 (present value) we used =
-PV (real interest rate 0.75% + inflation 9.63%, 10 (years),0, $25.76 million) = $9.59 m

4. For converting 1973 (final value) cost to 1966 (present value) we used =
-PV (real interest rate 0.75% + inflation 3.87%, 7 (years),0, $9.59 million) = $6.99 m

5. For converting 1966 (final value) cost to 1962 (present value) we used =
-PV (real interest rate 0.75% + inflation 1.58%, 4 (years),0, $6.99 million) = $6.38 m

Net% of initial cost to be invested on the next cycle = ($35 million -$6.38 million)/ ($35 million) = 81.78%

The annual maintenance cost for the bridge each year till 2019 was assumed as a final cost and therefore, Present value (P) in 1962 was calculated by applying the formula

$$P=F\ (P/F,\ I',\ N)$$

(Or)

$$P= F^*\ (1/(1+ i')^n$$

The aim is to convert all the costs to Equivalent uniform annual cost through the lifecycle period of n.

Therefore, all the Present value were converted to an annual cost by applying the formula

$$A=P\ (A/P,\ I',\ N)$$

(Or)

$$A= P^*\ (i')^*(1+i')^n/((1+ i')^n-1)$$

Here we divided the annual cost into 5 different numbers because we had 5 different inflation values to be applied to each set of values. Let us say A_1, A_2, A_3, A_4, A_5

Where,

A= Annual cost

P= Initial cost converted by assuming all the previously found annual costs as Final sum.

I= Real interest rate

N = Lifecycle of the bridge.

For a non-circular approach,

The initial cost was taken as the same initial cost of $35 million for the next lifecycle of the bridge as the virgin materials well be used to construct the bridge.

$$A'=P\ (A/P,\ I',\ N)$$

(Or)

$$A= P^*\ (i')\ ^*(1+i')^n\ /((1+ i')^n-1)$$

Similarly, we divided the annual cost into 5 different numbers so that we can apply corresponding inflation to every set of annual cost separately. Let us say A'_1, A'_2, A'_3, A'_4, A'_5

For a circular approach,

The initial cost was taken as the net % initial cost of $35 million to be invested for the next lifecycle of the bridge as the recycled material will be used along with the virgin materials.

$$P'= (\text{Net \% of initial cost})\ X\ P$$

$$A'= P'\ (A/P,\ I',\ N)$$

Similarly, we divided the annual cost into 5 different numbers so that we can apply corresponding inflation to every set of annual cost separately. Let us say A''_1, A''_2, A''_3, A''_4, A''_5

For example, by using the recycled materials, we were able to reduce the initial cost by 10%. The initial cost of the next cycle would be

$P' = (100\% - 10\%)\ P$ (this is the net % initial cost to be invested in the next lifecycle)

In order to find the circularity involved, we find the Capitalized cost (P_0 and P'_0)

$$P_0 = P + (A+A')/I \qquad \text{(For non- circular)}$$

$$P_0 = P + ((A + (\text{net \% of initial cost}) * A'')/(I) \quad \text{(for Circular)}$$

Where I is the actual interest rate (Real interest + inflation)

6.6 RESULT

Following the framework,

The evaluation of environmental friendliness was performed. This deals with the amount of carbon emissions reduced by adopting a circular approach.

Table 16 Total carbon emissions and reduction in emissions

	Virgin Materials				Recycled Materials		
	Material Quantity (From a non circular approach)	Carbon emmisions/ tonne	Total carbon Emmisions (in tonnes)		Material Quantity (From a circular approach)	Carbon emmisions/ tonne	Total carbon Emmisions
Concrete	203,383	0.18	36608.976		162706.56	0.145	23592.45
Asphalt	11764	0.05	588.2		9411.2	0.045	423.504
Reinforcement Steel	11488.68	1.85	21254.058		8156.9628	0.464	3784.831
Structural Steel	12502	1.85	23128.7		12251.96	0.464	5684.909
Total			81579.934				33485.7
	Percentage of carbon emissions reduced			59%			

It was seen that by adopting this circular approach. We can reduce carbon emissions by 59% of what we used to do with the virgin materials. In order to evaluate the economic viability, comparison of Capitalized cost for both the Non- circular Approach and the circular Approach was compared. Considering the average lifecycle of the bridge to be 70 years from Lifecycle of a Bridge Website, n.d., which is 13 years more than the lifecycle of the Champlain Bridge, the results were evaluated.

Table 17 Variable

i'	0.75%
net % initial cost to be invested in the next lifecycle	81.78%
Lifecycle of the bridge (years)	70

Using the above variables, the comparison has been done in the table below.

Table 18 Capitalized Cost Comparison

All the costs are in millions (CAD$) unless specified

For Non-Circular Approach (In $ million)		For Circular Approach (In $ million)	
A' (Recurring Cost)	Capitalized Cost (p) - 1962	A' (Recurring Cost)	Capitalized Cost (p)
$ 0.38	$ 484.33	$ 0.312	$ 472.32
For Non-Circular Approach (In $ million)		For Circular Approach (in $ million)	
P1	$35.00	P'1	$35.00
P2	$25.62	P'2	$13.60
P3	$12.37	P'3	$12.37
P4	$9.77	P'4	$9.77
P5	$26.93	P'5	$26.93
P6	$374.64	P'6	$374.64
	Capitalized Cost (Non-circular, 2020) in million		Capitalized Cost (Circular, 2020) in million
	$531.14		$517.97
	$728.71		$710.64
	$1,956.40		$1,907.88
	$3,146.05		$3,068.02
	$6,350.07		$6,192.57
Difference		(in million)	$157.49

The difference in the capitalized cost between circular and non- circular approach in 2020 is around $157.49 million (CAD). Which means we can save $157.49 million during every lifecycle of the bridge.

Saving $157.49 million over the lifecycle of the bridge is around 2.5% as compared to this day's construction costs. But this saving has been confined to only considering the Construction material costs, If, we look at the assumptions, all the assumptions are based on the limitations of this case study subjected to unavailability of publicly available date. The reduction in carbon emissions can have a tremendous amount of impact on the environment, therefore saving us billions of dollars of money, but here it is also on a small scale. Therefore, this would have a very small impact on social, economic, and environmental perspectives.

7. CONCLUSION

Using a circular approach, generates more employment as there is a huge scope of transporting materials from one point to the other point is involved. Further adding on reducing the GHG emissions during transportation, electrical vehicles (EV) can be a better alternative over the gasoline. Recycling sector, which is on the boom, is generating more employments that will automatically boost the per capita income of the country.

Through the case Study of the Champlain Bridge, all the strategy mentioned by Moraga, et al. (2019) have been thoroughly analysed, by measuring the indicators mentioned.

Table 19 Indicators for the case study

INDICATORS→ Case Study	Waste Generation	Recycling Rates	Recycling/ Recovery from waste streams	Contribution of recycled materials to raw materials	Trade from the European Union	Value addition and investments	Patents	Strategy	Scope	Measurement type
Old Champlain Bridge (Case Study)	**around 240,000 tonnes of deconstructed materials were obtained,**	✓	**(82% of the deconstructed waste reused)**	**Increase in the lifecycle of the bridge, 59% reduction in the carbon footprint.**	X	**Capitalized cost of $157.49 million can be saved.**	X	**1,2,3,5**	**2**	**Direct**

The circular approach which uses the indicators measure the effects from the cause of technological cycles regarding environmental, economic, and/or social aspects with the RRR considerations. All the strategy to increase the lifetime of the structure such as durability, reuse or restore, to preserve the essential components of the structure through reuse and recovery and rehabilitation, recycling the materials and measure the progress of CE keeping linear economy as a reference model have been achieved through the study.

The data in this theoretically analysed business case have been calculated from by extending the numbers based on the patterns observed in the existing data. When we try to reduce the costs by adopting a new approach, we tend to compromise with the environment. Any one of the two is sacrificed. Though this is a theoretical case study of the Champlain bridge, analysed by the limited data available, the cost savings determined in this study can be much higher than what we will be determining in a practical case (with all data publicly available). The cost spent in practice totally depends on the field construction budget and is not necessarily equal to the value determined theoretically.

8. FUTURE SCOPE

Studies explore a better understanding of circular economy in construction waste recovery. The technological advancements waste management will reduce the amount of waste materials generated, therefore increasing the recycling and recovery rates. The possibilities have been identified in the studies in technical aspect as well as in the business perspective. Further studies are also being carried out in shaping the definition and approach, identifying all the publicly available data to design an integrated model the precisely compares the benefits and risk of investments on a structure throughout its lifetime to monitor the economic feasibility of the project.

1. Circular economy if adopted throughout Canada, can save billions or trillions of $CAD. The exact amount will be determined only by the size of the projects undertaken.
2. There are a lot of environmental benefits as it accounts for the reduction in carbon emissions, the pollution level can be controlled to a very large extent.
3. The circular economy has a scope of offering enormous job opportunities in the field of construction as it requires deconstruction and proper recycling.
4. A planned deconstruction can save marine lives and other peripheral living species from migrating. Therefore, ecological balance would be maintained.

9. LIMITATIONS AND SHORTCOMINGS

In the evaluation of circularity of the Old Champlain Bridge, various assumptions were made to address the limitations of the project. Considering this case study as a theoretical business case, as the focus was on saving the capitalized cost, keeping in mind of controlling the environmental degradation, the importance of flow of materials through approximate estimation that plays a vital role in identifying the type of waste helps determining the amount of resources that can be segregated to be reused and recycled, therefore, reducing the amount of waste to be landfilled. All the benefits were neglected as the focus was on how the costs are affected by incorporating circularity in this study.

The shortcomings were sited in the availability of publicly available data on the transportation costs of the materials, the actual usage of reinforcement and structural steel in each section and the annual maintenance cost of the bridge. The approaches which costed another $18 million during the construction of the bridge were not included in the calculations as the data was inadequate. The shortcomings were a result of non-availability of data.

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APPENDIX

1. APPROXIMATE ESTIMAE FOR QUANTITY OF STEEL

Quantity of steel is to be calculated/ verifying if the quantity of steel is appropriate for the section.

Concrete Design Handbook (2016) by CAC has given the guidelines:

$A_{st(minimum)} = 0.01 * A_g$ or $A_{st(maximum)} = 0.08 * A_g$

Similarly, $V_{st(minimum)} = 0.01 * V_g$ or $V_{st(maximum)} = 0.08 * V_g$

$\rho_{min} = 1\%$ and $\rho_{max} = 8\%$

Also, the quantity of steel reinforcement in the columns is to be kept as a maximum of 4% and a minimum of 0.12% for slab/deck (HYSD bars for the deck) to get a balanced structure.

Unit weight of concrete = 2400 kg/ cu.m

Unit weight of steel = 7850 kg/ cu.m

There using this,

1. Section 5& 7 Deck

   Total Asphalt = 9470 t
   Total weight of concrete =85005 t
   Volume of concrete = 85005 t * 1000 kg/(2400 kg/ cu.m)
   Volume of concrete = 35418 cu.m
   Total weight of steel =4975 t (Already given)
   Volume of steel = 4975 t * 1000 kg/(7850 kg/ cu.m)
   Volume of steel = 663.3 cu.m
   % of steel by volume = 663.3 /(35418 + 663.3)
   = 1.8% >0.12% required for the deck.

2. Section 5& 7 Foundation

   Total weight of pier shaft =61545 t
   Quantity of steel = 4% * total weight
   Weight of steel =2461.8 t
   Weight of concrete = 61545-2461.8 = 59083.2 t
   Volume of concrete = 59083.2 t * 1000 kg/(2400 kg/ cu.m)
   Volume of concrete = 24618 cu.m
   Volume of steel = 2461.8 t * 1000 kg/(7850 kg/ cu.m)
   Volume of steel = 314 cu.m
   % of steel by volume = 314 / (24618 + 314)
   = 1.26% >1% and less the 8%, hence it is within the limits.

Similarly,
Weight of steel for footing =1789.8 t
Weight of concrete for footing = 42955.2 t
Volume of steel = 228 cu.m
Volume of Concrete = 17898 cu.m
% of steel by volume = 1.25% >1% and less the 8%%, hence it is within the limits.

3. Section 6 (Steel Span) For the deck
   Weight of Structural steel=12502t
   Weight of concrete= 684t
   Weight of steel is not mentioned. Therefore, according to the standards we shall assume that minimum reinforcement is 0.15% of the Gross volume.
   Weight of the steel comes out to be = 1.026 t
   Total Asphalt = 2294t (given)

4. Section 6 (Steel Span) for the foundation
   Total weight of pier shaft =34765 t
   Quantity of steel = 4% * total weight
   Weight of steel =1390.6 t
   Weight of concrete = 34765-1390.6 = 33375 t
   Volume of concrete = 33375 t * 1000 kg/(2400 kg/ cu.m)
   Volume of concrete = 13906.25 cu.m
   Volume of steel = 1390.6 * 1000 kg/(7850 kg/ cu.m)
   Volume of steel = 177.146 cu.m
   % of steel by volume = 177.15 / (13906 + 177.15)

   = 1.26% >1% and less the 8%, hence it is within the limits.

5. Similarly,
   Weight of steel for footing =1051.5 t
   Weight of concrete for footing = 25236 t
   Volume of steel = 134 cu.m
   Volume of Concrete = 10515 cu.m
   % of steel by volume = 1.26% >1% and less the 8%%, hence it is within the limits.

2. ECONOMIC ANALYSIS (to find the annual maintenance cost)

Depreciation by declining balance method.

BV_{2019}= 25 million

BV_{2010}= 18 million

d' = Depreciation rate

BV_{2010}= (1+d') BV_{2019}

18= (1+d') 25

d'= -0.28 % (As we go backwards, the maintenance cost will decrease.

Based on the depreciation rate,

Maintenance cost for every decade is,

BV_{2019}= 25 million

BV_{2010}= 18 million

BV_{2000}= 18- 0.28(18) = 12.96 million

BV_{1990}= 12.96- 0.28(12.96) = 9,33 million

BV_{1980}= 9.33- 0.28(9.33) = 6.71 million

BV_{1970}= 6.71- 0.28(6.71) = 4.83 million

BV_{1960}= 4.83- 0.28(4.83) = 3.48 million

Similarly,

For intermediate years, $BV_t = B(1+d)^t$

$BV_{2019} = B_{2010} = (1+d)^{10}$

d= 0.03 = (1/10)*d' (Since 1 decade has 10 years)

Similarly, we will find the maintenance cost for all the intermediate years. (Done in Excel)

3. CALCULATION OF THE CAPITALIZED COST

All the maintenance costs calculated in (1) are converted to the present cost of (1962) by applying the formula:

P= F(P/F, I, n)

Single Present Value (or Discounting Amount)	*(P/F, i, n)*	$\frac{1}{(1+i)^n}$

All the maintenance costs are considered as a future cost (F) and converted accordingly.

For the year 1963, i= real interest rate= 0.75%, n increases from 1 to 58 as we move from 1962-2020.

P_1= \$3.84 million (1/ 1+0.75%) = \$3.81 million.

Similarly, all the annual costs were converted, and a summation was done to get a consolidated P.

P = \$623.32 million

Then this P value was converted into uniform annuity through the lifecycle of the bridge.

Uniform Capital Recovery	*(A/P, i, n)*	$\frac{i\,(1+i)^n}{(1+i)^n - 1}$

Since we had 5 inflation rates, the A was divided asper the inflation rates and calculated using the above formula.

All the costs are in millions (CAD\$) unless specified

A1	\$	0.25
A2	\$	0.66
A3	\$	1.17
A4	\$	1.69
A5	\$	9.52

For a Non-circular Approach

Uniform Sinking Fund	*(A/F, i, n)*	$\frac{i}{(1+i)^n - 1}$

With the same amount being invested at the beginning of every lifecycle, the annual uniform sinking fund would be

A' = \$35 million *0.75*/ (((1+0.75 ^70)-1)

= 0.38 million

For capitalized cost,

All the A_1, A_2, A_3, A_4, A_5 were converted to P_1, P_2, P_3, P_4, P_5, P_6 by using the formula below:

P_1 = \$35 million, as the recurring cost would be the same at the beginning of the next lifecycle

$P_2 = (A' + A_1)/(i)$, here I would be the inflation for the respective years = (1.58%)

= (0.38+ 0.22)/ (1.58%+0.75%)

= \$25.62 million

$P_3 = (A_2)/(i)$, here I would be the inflation for the respective years = (3.87%)

= (0.57)/ (3.87%+0.75%)

= \$12.37 million

$P_4 = (A_3)/(i)$, here I would be the inflation for the respective years = (9.63%)

= (1.01)/ (9.63%+0.75%)

= \$9.77 million

$P_5 = (A_4)/(i)$, here I would be the inflation for the respective years = (4.67%)

= (1.46)/ (4.67%+0.75%)

= \$26.93 million

$P_6 = (A_5)/(i)$, here I would be the inflation for the respective years = (1.79%)

= (9.52)/ (1.79%+0.75%)

= \$374.64 million

All the costs are in millions (CAD$) unless specified

For Non-Circular Approach (In $ million)	
P1	$35.00
P2	$25.62
P3	$12.37
P4	$9.77
P5	$26.93
P6	$374.64

Capitalized cost(P_0) = P1+ P_2+ P_3+ P_4+ P_5+ P_6

= \$ 484.33 million (1962 cost)

For 2020 = \$6350.07 million

For a Circular Approach

Uniform Sinking Fund	*(A/F, i, n)*	$\frac{i}{(1+i)^n - 1}$

With a depreciated amount being invested at the beginning of every lifecycle, the annual uniform sinking fund would be

A' = 81.78% *$35 million *0.75/ (((1+0.75 ^58)-1)

= $ 0.312 million

For capitalized cost,

All the A_1, A_2, A_3, A_4, A_5 were converted to P_1, P_2, P_3, P_4, P_5, P_6 by using the formula below:

P'_1 = $35 million, as the recurring cost wold be the same at the beginning of the next lifecycle

P'_2 = (A' +A_1)/ (i), here I would be the inflation for the respective years = (1.58%)

= (0.312+ 0.22)/ (1.58%+0.75%)

= $13.60 million

P'_3=(A_2)/ (i), here I would be the inflation for the respective years = (3.87%)

= (0.57)/ (3.87%+0.75%)

= $12.37 million

P'_4=(A_3)/ (i), here I would be the inflation for the respective years = (9.63%)

= (1.01)/ (9.63%+0.75%)

= $9.77 million

P'_5=(A_4)/ (i), here I would be the inflation for the respective years = (4.67%)

= (1.46)/ (4.67%+0.75%)

= $26.93 million

P'_6=(A_5)/ (i), here I would be the inflation for the respective years = (1.79%)

= (9.52)/ (1.79%+0.75%)

= $374.64 million

For Circular Approach (in $ million)	
P'1	$35.00
P'2	$13.60
P'3	$12.37
P'4	$9.77
P'5	$26.93
P'6	$374.64

Capitalized cost(P_0) = P'1+ P'_2+ P'_3+ P'_4+ P'_5+ P'_6

= $ 472.32 million (1962 cost)

For 2020 = $6192.57

The difference in the Capitalized cost = $157.49 million