

Research Article

A Framework for the Application of Optimization Techniques in the Achievement of Global Emission Targets in the Housing Sector

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Abstract: The building construction industry holds a crucial role in the reduction of greenhouse gas emissions globally. The targets for greenhouse gas emissions may not be achieved without a defined strategic plan to meet up with the set targets from various sectors of the economy. Recognizing the enormous potential that the building industry holds in contributing to global greenhouse gas GHG emission reduction, this study describes a framework on how optimization techniques can be used as a guide for emission reduction targets for the housing sector using illustrations of the onsite and offsite building construction industry. Given that some of the GHG gases are also sources of air pollution, this study includes a discussion on how the effort to address air pollution can be used to find a consensus towards addressing the concern about GHG emissions. This study presents procedures for simplified methods of estimation of GHG emissions that various municipalities around the globe can use to estimate and report the emissions from the building construction industry. The study presents a unifying strategy for emission management. The study also demonstrates how programming methods can be applied to GHG emissions management. The approach used in this study is transferable to other industries. The study recommends a unifying strategy for the management and control of emissions in the building construction industry. The study also recommends a coordinated effort in sharing best practices for emission control and management from all jurisdictions globally. In the effort to reduce global emission targets, further studies like this and its expansion is recommended for all sectors of the global economy. It is recommended that these studies should be followed by a concrete effort to achieve good implementation of sustainable emission reduction targets globally.

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1. Literature review

The building sector consumes up to 40% of all energy and contributes up to 30% of global annual greenhouse gas emissions [1, 2]. The built environment has a significant impact on the natural environment; given that the construction industry plays a major role in sustainability assessment [3]. Citing the International Energy Agency, IEA 2021, the United Nations' (UNs') global status report for buildings and construction reported that in 2020, the sector accounted for 37% of energy-related CO₂ emissions, and 36% of global final energy (as compared to other use sectors). The report also indicated that transportation has a 23% share of global CO₂ emissions [4]. There is an important role for the construction industry in the reduction of global carbon emissions, as the embodied carbon of construction materials shares an increasing part of the lifecycle of carbon dioxide emissions in buildings [5]. On a regulatory level (within building sector

initiatives), there is an increasing interest in the importance of embodied energy and embodied greenhouse gas emissions from buildings [6]. If we want to achieve the ambitious targets of the Paris Climate Agreement, in addition to striving to achieve zero-carbon building operations through energy efficiency and decarbonisation of the grid, the building industry needs to strive towards achieving zero embodied Carbon [1]. Among other things, some of the key messages for the fifteenth meeting of the Conference of the Parties to the Convention on Biological Diversity, COP 15 include:

1. "The building sector has the most significant and cost-effective GHG emission reductions.
2. Countries will not meet emission reduction targets without supporting energy efficiency gains in the building sector." [2].

Benchmarks are considered useful instruments to encourage the reduction of emissions [5]. Building energy performance benchmarking increases awareness and help stakeholders to make better-informed decisions for the design, operation, and renovation of sustainable buildings [7].

1.1. Global targets for greenhouse gas emissions

The global target for GHG emissions is to limit the warming to 2°C above the pre-industrial level. Scientific evidence suggests that the cumulative emissions of CO₂ from 2010 – 2050 should be capped at 657.1 GT in order to have a 75% chance of limiting warming in 2100 to 2°C above the preindustrial level [8].

1.1.1. The Intergovernmental Panel on Climate Change (IPCC)

IPCC reported that human activities are estimated to have caused approximately 1.0 degrees centigrade of global warming above pre-industrial levels, with a likely range of 0.8 to 1.2 degrees centigrade [9]. From 1850 - 1900, the emissions of greenhouse gases from human activities are responsible for about 1.1°C of warming [10]. If the temperature continues to increase at the current rate, global warming is likely to reach 1.5 degrees centigrade between 2030 and 2052 [9]. The report of the IPCC that summarized climate science from around the world was not the first body to note the importance of limiting global warming to 2 degrees centigrade [11].

1.1.2. The 2000-Watt Society

"The 2000-Watt Society is a vision for a livable future. People in such society care and advocate for a high quality of life that meets the goals of sustainability" [12]. The 2000-Watt society believes that for every individual on earth, 2000 watts of continuous power is enough to ensure a high quality of life and prosperity. The CO₂ emissions that are caused by this level of consumption must not exceed 1 tonne per person, per year. According to the 2000-Watt Society, "if we limit the CO₂ emissions to 1 tonne per person per year (i.e., 1000 KgCO_{2e} per person per year), the temperature can be held below 2°C above pre-industrial levels (as agreed by the international community) [12]. Some previous works noted that, for the housing sector, the threshold value that was set for GHG emissions is 370KgCO_{2e} per capita per annum [13, 14]. Some important questions in this ambitious goal are: How can these be achieved? Can this goal be achieved without negative impacts on people's lives? How will capturing and reprocessing of GHG help in alleviating fears around global warming and the expected impacts of GHG targets on people's way of life? SIA 2040 was introduced in Switzerland to define a roadmap for a target for a 2000-Watt society and 1 t CO₂-e society [14].

1.2. Challenges to the claims on the causes of global warming and establishment of a middle ground for better environmental air quality management

Many scholars [15, 16, 17, 18, 19, 20] have claimed that global warming and climate change are associated with the amount of greenhouse gas emissions as measured by

carbon dioxide equivalence. However, the literature also showed that there is no global consensus on this claim [21, 22]. A report [23] mentioned that most of the leading scientific organizations around the world have issued public statements that endorse a position that 'climate warming trends over the past century are extremely likely due to human activities', and that the majority of actively publishing climate scientists (97%) agree that humans are causing climate change and global warming [24]. The phrase, "most of" confirms that although many people support the claim that human activities contribute to changes in climate, some do not. Another report [25] mentioned that "most members of the intergovernmental panel on climate change believe that current climate models do not accurately portray the atmosphere-ocean system". "The 97% figure has been disputed and vigorously defended with emotional arguments and counterarguments published in a number of papers" [26]. A different report [27] mentioned that according to a new survey of 88,125 climate-related studies, more than 99.9% of peer-reviewed scientific papers agree that climate change is majorly caused by humans. Meanwhile, nearly half of U.S. adults say climate change is due to human activity and a similar number says either there is no evidence of warming or the earth's warming results from natural causes [28]. Although climate change could occur as a result of persistent anthropogenic forcing through changes in land use or the addition of greenhouse gases, black carbon, and sulfate aerosols to the atmosphere, climate change could also occur naturally as a result of a change in the energy of the sun on the earth's orbital cycle i.e., natural climate forcing [29]. Among other things, a previous study mentioned that global warming is often misunderstood to imply that there will be uniform warming in the world. The authors mentioned that an increase in the average global temperature will also result in a change in the circulation of the atmosphere resulting in higher temperatures in some areas while some will not have as much warming. Hence, the term 'global warming' is seen as a 'wrong term' that is frequently used by the media and others to describe climate change [29]. While there is a lot of planning and efforts to develop mitigation strategies against the potential impacts of the increase in greenhouse gas emissions, it will be good to see good efforts in the development of mitigation and adaptation strategies for the potential impacts of 'natural-climate-forcing'. Some scholars [21] applied the laws of physics (gas laws) to the gases in the atmosphere that act as ideal gases. The study reported that regardless of its concentration in the atmosphere, CO₂ is a cooling gas as the air temperature increases from winter to summer while CO₂ is a warming gas as air temperature changes from summer to winter. The study further reported that the effect of CO₂, methane and trace gases on climate change and atmospheric temperature is very small as to be negligible. Another study reported that there is a need for a major reconstruction of climate models as it appears most of the models work on the basis that global warming occurs as a result of increasing levels of CO₂. The scholars noted that the concentration of water vapor in the atmosphere is controlled by the sun, and it in turn controls radiation, the temperature of the atmosphere, and climate. The study further mentioned that the effect of back radiation on earth's atmosphere is up to 200 times more than that of CO₂ contributions, works opposite, and overrides the effect of CO₂ to the extent that the contribution of CO₂ to atmospheric temperature is negligible [22]. Regardless of the contradictions, it is still a commendable thing to make effort to improve the air quality in the environment where we work, live, and grow. In that light, efforts towards the reduction of emission of undesirable gases into the atmosphere are good. This could be done in terms of the implementation of technologies to capture and reprocess these gases into desirable forms, or exploring more efficient ways for energy conservation while completing various tasks. With a division on this topic, it will be difficult to achieve progress in better environmental management. Hence, there is a need to establish a middle ground that cannot be disputed and that is agreeable to all parties. This leaves us with a challenge on how to move forward on this matter. A middle ground can be reached in terms of the need to take good care of the environment where we live, play, grow, work, worship, etc. It is well understood that

a highly polluted environment is not good for the health of anyone. Hence, a compromise can be reached on this ground.

1.3. Where do we have a consensus? Care for the environment to ensure the chance of better health for all

1.3.1. Impacts of pollution on the environment air

Scientific evidence indicates that ambient air quality is one of the main environmental issues that are related to human health [30]. Air pollution has a significant impact on natural systems and human health worldwide [31]. "Every year, exposure to air pollution is estimated to cause 7 million premature deaths and results in the loss of millions more healthy years of life" [32]. In many Asian cities (including Korea) air pollution levels remain well above WHO guidelines [30]. Several reports have shown the direct association between exposure to poor air quality and increasing rate of morbidity and mortality mostly due to respiratory and cardiovascular diseases [33]. Air quality affects human health, interpersonal behaviors, attitude, mood, outdoor activities, task performance, and possibly residential choice. Pollution affects the amount of time spent outdoors and the extent of physical activities. Migration and residential locations may also be affected by pollution levels. Recreation patterns, interpersonal relationships, and task performance are also affected by air pollution [34]. Air pollution (affecting the entire urban population) is presently one of the most important risk factors in our cities [35]. A scholar [30] related air pollution to mortality rates in Suwon city. The study used the WHO approach to assess the impact of atmospheric pollution on the human health of the inhabitants of Suwon city. Human behavior such as the choice of transportation mode and energy use affects the production of air pollution. Human attitudes such as economic and political decisions also indirectly affect pollution levels. Research on the health effects of air pollution in humans has been conducted both on-site (where aggregate correlations between pollutant levels and disease rates are obtained) and also in the laboratory. Major constituents of ambient air pollution are carbon monoxide, nitrogen oxides, sulfur oxides, photochemical oxidants (smog), and particulates [34].

Other studies have also shown that poor health can be associated with regions with high concentrations of air pollutants. With drivers decelerating and stopping at lights, then revving up more quickly when lights turn green, the peak-particle concentration at intersections has been found to be 29 times higher than the situation during free-flow traffic conditions [36]. Some scholars reported that stationary measurement data that was collected in an apartment near the roadside showed a substantial effect of emitted pollutants such as black carbon, ultrafine particles, and nitrogen oxides. The researchers concluded that "the air pollution around the road intersection has adverse effects on the health of residents living within the 3-D spatial extent within at least 120 m horizontally and a half of building height vertically during the morning rush hours"[37]. Short- and long-term exposure to air-suspended toxicants has different toxicological impacts on humans including respiratory and cardiovascular diseases, skin diseases, long-term chronic diseases such as cancer, irritation of the eyes, and neuropsychiatric complications [33]. Many studies have assessed the impact of air pollutants on the general population, and have found an increased risk of miscarriage and reduced fertility rates [35]. In a study about the risks of air pollution on mental health, some scholars [38] reported that psychological disorder is significantly increased by air pollution.

Air pollution is caused by both natural phenomena and human actions [33]. Some scholars [39] noted that Nitrogen oxides (NO_x) are emitted from a range of combustion sources including electric power generators, on-road mobile sources, and non-road mobile sources. NO_x is also formed by wildland fires, lightning strikes, and emissions from the soil. Motor vehicles are a major source of urban air pollution. Adverse effects on health due to proximity to roads have been observed after adjustments for social economic

status and noise. Exhaust emissions are a major source of traffic-related pollution. Many toxicological and epidemiological studies have linked exhaust emissions with adverse effects on health. Toxicological research has also indicated that non-exhaust pollutants such as those from brake wear, tire wear, and road abrasion could be responsible for some of the observed adverse health effects [40]. Another report [41] noted that air pollution from trucks, cars, and other motor vehicles is in higher concentrations near major roads. People who work, attend a school, or live near major roads appear to have an increased incidence and severity of health problems associated with air pollution exposures related to roadway traffic. These include higher rates of asthma onset and aggravation, impaired lung development in children, childhood leukemia, cardiovascular disease, and premature death. One of the ways the effect of aggravated air pollution near major intersections can be reduced is by allowing for an increased distance for residences, and offices from major intersections. Another is through innovative emission capture technology for road vehicles. A previous study [34] noted that photochemical oxidants are produced by photosynthetic processes that involve hydrocarbon and emissions of nitrogen oxide from internal combustion. The major toxic component of oxidants is ozone. Results from toxicological studies show that low-level ambient range exposures of humans to ozone cause substernal soreness, mouth dryness, and eye irritation. The combustion of fossil fuels is the major source of ambient sulfur oxides. Within an ambient range, human toxicological exposures to sulfur oxides generally produce irritation of upper respiratory passages, reduced pulmonary functioning, and reduced mucociliary clearance. Nitrogen oxides which are abundant in the air are also produced by the combustion of fossil fuel in motor vehicles and in the production of electricity. Carbon monoxide results primarily from incomplete combustion in motor vehicles and also from cigarette smoking. Human toxicological studies indicate that dizziness, headache, and nausea are related to oxygen deprivation. Particulates can absorb various chemicals (including carcinogens), increasing their level of penetration and longevity in the lungs. Major particulates of concern are lead, mercury, asbestos, halogen, and several other heavy metals. Toxicological effects from lead include gastrointestinal cramping, impaired neural functioning, and anemia. Toxicological effects from mercury include neural dysfunction, upper respiratory inflammation, and thyroid disturbance; toxicological effects from asbestos include mesothelial tissue damage, pulmonary lesions, and carcinoma [34]. Environmental tobacco smoke (ETS) is also a major source of particulate matter (PM) pollution. For indoor PM concentrations, ETS contributes up to 10-fold of those that are emitted from an idling EcoDiesel engine [42]. Some other scholars [43] reported that with an increase in traffic-related air pollution levels (particularly for the coarse fraction of particulate matter), there is a statistically significant reduction in fertility rates. An increased concentration of PM_{2.5} in the air leads to an increase in negative emotions such as depression, nervousness, powerlessness, restlessness, or fidgety [38]. The world health organization also reported that levels of pollutants such as carbon monoxide, NO₂ polycyclic aromatic hydrocarbons (PAHs), black carbon, ultrafine particles, and some metals are more elevated near roads. PM_{2.5} is slightly elevated near roads [40]. "Personal exposures to respirable fine particles and organic carcinogens (such as PAH) were correlated with excretion of PAH metabolites in urine, several trace metals in blood and DNA adducts in blood cells" [44].

1.4. Achieving a unifying strategy in global emission management

The causes and solutions of two major global challenges (climate change and air pollution) are closely linked. The complex interactions between air quality and climate change imply that future policies that are geared toward mitigating these twin challenges will benefit from greater coordination [45]. There appears to be some phobia towards combating climate change through regulations. In addressing the issue of climate change, recognizing that there are different viewpoints on climate change, among other opinions

on climate change that were reported by a researcher [46], one says "the response to climate change goes even further; it not only expands the scope of regulation but demands that these regulations affect a major transformation of our basic economic system and our personal lifestyles".

The obstacles to taking good actions toward better environmental management are partly political, partly economical, and partly social. The economic factors that relate to emissions are also associated with some social factors around people's lifestyle. While the economic power of various nations or jurisdictions that profit from the sale of materials that are known to result in environmental pollution is at stake (depending on the management approach), the social status of many people (as relates to job security, a good source of income, level of social interaction when people are unemployed or underemployed, etc.,) are also at stake. Hence, rather than making this a political issue, or a win-lose battle, a good way forward is to find a middle ground that unites everyone without harming the economic power, or the social well-being of any of the stakeholders involved. A government that wants to present a good strategy towards the reduction of emissions will have to show empathy towards all stakeholders including those that benefit economically from the proceeds of the sale of fossil fuel, and those that are affected by the emissions (especially the immuno-compromised). In the fight to reach global GHG emission reduction targets that will be welcomed by all, there is a need for a change of perspective on the handling of GHG emissions. A good strategy for emissions management will be helpful in achieving the goal of emission reduction through various optimization techniques. It appears the world lives with a belief that 'it is not possible to have zero emissions with fossil fuel-powered vehicles.' With improved research on this, it may be surprising to see that the assumption that tailpipe emissions will always be associated with fossil-powered vehicles (including fossil-powered construction equipment) may be proved wrong in no distant time. One of the questions for the research community is, 'can the internal combustion of fossil fuel-powered vehicles be operated in a closed loop system with adequate air purification and recirculation while achieving a great level of fuel economy?'

To address this issue, there is a need for a political will. This political will has to be followed by good (unifying) actions. The following strategies may be followed:

1. Announce an award for a scientist/engineer/researcher (student or professor) or a group of researchers, or an organization that develops a working technology that achieves zero-emission for fossil-powered vehicles (regardless of the nationality of the researcher). In addition to international recognition, this can also include a sizeable monetary reward.
2. Announce an award for the educational institution or organization that these researchers are affiliated with (if they provide adequate support and good funding for the researcher throughout the time of the research).
3. Announce an award for a company that is able to commercialize the product in an affordable fashion.
4. Announce awards for notable additional improvements to the first innovative design up to a predefined level. This award may be open to anyone that is able to achieve a specified objective for the technology.
5. Announce an award for technological innovations that can convert present fossil-powered vehicles on the road to a zero-tail pipe emission status.
6. Announce funding for institutions or private organizations that are seriously working on the project towards zero emissions for fossil-powered vehicles (These include industrial vehicles, machinery, and motor vehicles that are powered by fossil fuel).
7. Announce similar awards for organizations that are working towards zero emission status for electricity power plants, regardless of whether they are powered by fossil energy or other forms of energy.

8. Announce awards for researchers who are able to convert GHG emissions of concern into beneficial materials for the global ecosystem.

A strategy like this (that includes efficient and affordable emission capture technologies) can be seen as a unifying strategy that can encourage further interest and research in achieving the zero-emission target not only for the construction industry but for all industries in the global economy. With this, the concern about air pollution can be greatly reduced when there are innovative technologies to capture emissions of concern (and reprocess them to beneficial forms). This can also indirectly help reduce the concern about GHG emissions (if emission capture technologies are encouraged, adequately funded, and good results are achieved). Progress in the above can be helpful in the setting of targets to further reduce global emissions. This can lead to a win-win situation for those who are concerned about the impact of emissions on human health and those who are concerned about the impact of emissions on climate. Various municipalities have developed plans to gradually move away from fossil fuels, especially in transportation. While the idea of conservation of natural resources is good to ensure that future generations have good access to the resources that they will need, in the meantime, while natural resources (including fossil fuels) are being explored to serve the present generation, it is a commendable effort to explore ways to achieve zero-tail pipe emissions for fossil-powered means of transportation and fossil-powered equipment.

Prospective research area on the achievement of zero tail-pipe emission from automobiles may include an addition of a separate tank that collects GHG emissions from automobiles as it is produced, temporarily store, purify and recirculate the purified air for the continuation of the combustion process. Alternatively, research on how to achieve adequate capturing, compression, and temporary storage of the GHG emissions from the tailpipe of fossil fuel-powered vehicles may be explored. An appropriate system to replace the storage system every time the gas storage system is filled up may be developed. This may help in the creation of additional job opportunities for those who will be involved in the collection and reprocessing of these emissions at external facilities. The end goal will be to reach a point in which non-renewable fossil fuels will be reserved for situations in which technological innovations of the time have not reached a level to avoid some dependency on fossil fuels. In the meantime, there is a need to ensure a good strategy that achieves a win-win for all in the move toward transitioning to renewable energy. When there is a good consensus in emission management, it will be easier to set targets to achieve emission reduction for every sector of the global economy.

The above strategy should not stop the development and promotion of electric vehicles as this allows for a diversification of sources of energy for transportation. Although a sizeable portion of electric vehicles may use electricity from electric grids that are powered by fossil fuels (with associated emissions), electricity from renewable energy sources can also be sustainable if the technology for this is well developed.

1.5. Contribution of the building construction industry to global GHG emissions

Historically, embodied carbon has been largely ignored, but they account for about 11% of global carbon emissions [47]. According to the feasibility study for SIA 2040, 27% of GHG emissions are attributed to embodied part and 9% are attributed to the operational part. A low operational impact can be used to compensate for a high embodied impact, and vice versa [14]. Some scholars [48] reported the life cycle energy and life cycle carbon for wooden residential buildings: Prefabricated versus conventional construction. The embodied energy for prefabricated wood buildings that were reported in the study ranges from 2.1 - 10.5GJ/m². The embodied carbon for prefabricated wood residential buildings was reported as 65 - 535 KgCO₂e/m² while the embodied carbon for conventional wood construction varies from 65 -156 KgCO₂e/m². The operational energy for prefabricated residential wood buildings ranges from 0.88 - 0.91GJ/m²y. The operational carbon for prefabricated wood residential buildings ranges from 11.6 - 45.8KgCO₂e/m²y. The

operational energy for conventional wood residential buildings ranges from 0.1 - 0.58 GJ/m²y. The energy reported for the end-of-life phase for prefabricated wood residential buildings ranges from -7.2 - (0.45) GJ/m². The embodied carbon for prefabricated wood residential buildings ranges from -1.3 - 105.4 KgCO₂e/m². The embodied energy and embodied carbon that were reported are from various works in different countries. Particulate matter in the atmosphere can be transported over long distances. In the effort to achieve a reduction in global emission targets for the construction industry, it is important to allow for easy information sharing on best practices to achieve targeted emission reduction. Countries that are able to achieve very low emissions should be willing to share emission reduction procedures with other countries. Countries with high emissions should also be open to learning about emission reduction strategies from countries that are able to achieve low emissions.

1.5.1. Benchmarking in the efforts to apply optimization techniques in the minimization of emissions in the whole building life cycle.

Application of optimization techniques in the effort to minimize environmental impacts involves the setting of targets or benchmarks. These benchmarks can be set using a top-down, bottom-up, or a combination of the two approaches. Benchmarks are reference points for which comparisons can be made. Types of benchmarks include (1) limit values (2) reference values (3) target values. Limit values indicate the minimum requirement for the lower and upper values for different aspects of performance. In most cases, limit values are defined by national standards, or set by regulations. Reference values are often from national or international collaboration by various stakeholders. This may be based on local surveys using a representative sample of building types or other types of construction, demonstration projects, etc. Target values are set by policymakers, investors, industry owners, or others who define targets for different aspects. Target values can be values set by consensus through voluntary industrial policy or other programs, Target values can also be developed through a bottom-up or top-down approach. In a bottom-up approach, target values are developed through statistics, feasibility studies, etc. In a top-down approach, target values can be formed through science-based targets, international agreements, or policy targets. Benchmarks can also be developed based on best practices [49]. Some scholars [14] combined top-down and bottom-up approaches for benchmarking (called the dual benchmark approach).

1.5.2. Top-Down Methods.

In a previous work [14] a top-down approach is derived from a global budget of GHG emissions per capita. The bottom-up approach is based on the embodied GHG emissions of typical building elements for residential buildings in Switzerland. To define benchmarks for residential buildings in Switzerland, in the top-down approach, the global 2-degree target serves as a basis. The global carbon budget can be translated to budget per capita [8, 50]. A target value of 1t CO₂e per capita per year by the year 2050 was used in a previous study [14]. According to the Swiss 2000-Watt Society and German Environmental Agency, this is said to be sufficient to reach climate neutrality. To achieve that value, the Swiss emission yearly means of 7.8 tCO₂-e per capita has to be reduced by a factor of 7.8. In 2018, Canada's per capita household GHG emissions is 4.1 tonnes per person [51]. To achieve the Swiss 1tCO₂e per capita per year, Canadian emission of 4.1 tonnes per person in 2018 has to reduce by a factor of 4.1. While the 2000-Watt Society aimed to achieve this target (1 t CO₂-e/(c·a) by 2100, SIA 2040 aimed to achieve an intermediate target for the year 2050. For residential buildings, the goal of the top-down benchmark is to define a GWP value that can serve as a target value in the design process for the whole building [14].

1.5.3. Bottom-Up Methods.

A previous study [14] reported that the bottom-up approach is based on the embodied GHG emissions of typical building elements that is used in residential buildings in Switzerland - expressed per surface area of building elements. The authors reported that the benchmarks that are derived from both approaches can be related at the building level, but they cannot be compared directly.

1.6. Why do we need environmental benchmarks for building design and construction?

Clients and designers find it difficult to interpret the results that are obtained through LCA and set environmental performance targets to improve building design. Hence, the need for benchmarks or reference values. The target value for GHG emissions varies by building type. A previous work reported that the target value for GHG emissions from residential buildings to restaurants varies between 11 KgCO_{2e}/m²a and 20.3 KgCO_{2e}/m²a. The target value for the whole building can help to show if the building meets the required environmental performance, but it cannot indicate optimization potentials. Benchmarks that consider different material options on the element level are needed [14]. Although some target value has been specified in previous works as mentioned, it is important to note that, with the goal for the achievement of continuous improvements of environmental impacts of construction, there should be a yearly effort towards improvement in the industry [53]. As the world experience positive growth through an increase in global population, without effort to continue to reduce the target value and actual emissions in different sectors, global emission will be on a trajectory for a continuous increase. Hence, the target value for emissions should reduce continuously. i.e., there should be a continuous effort toward emission reduction.

2. Problem statements and objectives

2.1. Problem statements.

Towards the goal of achieving global emission targets, it is widely recognized that the building construction sector holds a huge potential in helping to reduce global GHG emissions. However, there is a need for the development of reliable optimization techniques to ensure adequate planning to achieve global targets in every sector. In this light, this study proposed the following research question:

- How can we apply optimization modeling techniques as a guide in the development of emission targets?
- How can we develop a simplified and unified methodology that every nation can use to have a reasonable estimate of the quantity of emissions that is generated every year from their building construction industry?

2.2. Aims and objectives.

There has been a big concern about the environmental impacts of construction operations. Various studies have also echoed the fact that significant opportunities exist within the building industry to reduce the global GHG emission targets. In the effort to ensure that the construction industry plays her part in contributing to the entire global emission targets, the objectives of this study are to:

- Develop a framework to apply optimization modeling techniques for the minimization of environmental impacts (in terms of emissions) in construction operations.
- Develop a simplified framework to estimate the embodied and operational energy, as well as embodied and operational carbon for a community.

This will allow various communities to have access to a simplified method that they can use to monitor the embodied and operational impacts of buildings in their

communities. When adequately coordinated at a central level, it will also allow for an evaluation of how the housing industry contributes to global emissions.

3. Methodology

During this research, a desktop study/literature review was conducted for more understanding of the whole building LCA, and the identification of variables that contributes to GHG emissions in building construction. Site visits allow for a first-hand view of some of the construction processes. Reviews were done on barriers to the achievement of a global consensus in emission management. Mathematical models that different countries can use for a unified process for the estimation of emissions from the building construction industry were developed. Optimization models were also developed for the minimization of environmental impacts for different stages of the whole building life cycle (in the lens of emission reduction).

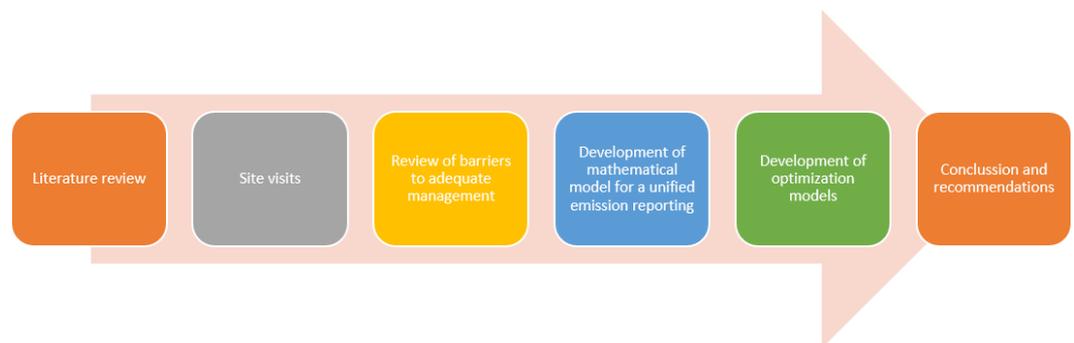


Figure 1. Project Methodology

While it is good to have a holistic review for a general evaluation of the contributions of the building industry to global GHG emissions, sometimes, there is a need for a sectional study of various parts of the entire building system. System boundaries define the limit (extent) to which a project is studied. This study provides a framework for the application of optimization modeling in the minimization of environmental impacts for building construction works from cradle to grave and cradle to cradle. A major focus was given to the construction phase A4 – A5 for both onsite and offsite construction. [Figure 2](#) describes the processes in LCA for buildings. The major difference between the LCA for traditional onsite and offsite construction is that for traditional onsite construction, construction materials are transported from the production facility directly to the site (could be through retailers) whereas, in offsite construction, the materials that are to be constructed offsite are transported from the material manufacturer/supplier to the offsite construction facility where they are prefabricated before transportation to the site for assembly. In addition, worker transport, is mostly to the final site in traditional onsite construction, while worker transport is mostly to the offsite construction facility in offsite construction. In a study on “a framework for the evaluation of the decision between onsite and offsite construction using LCA and system dynamics modeling”, a scholar [53] presented descriptions of the LCA for the construction phase of both onsite and offsite building construction.

3. Results and discussion

3.1. Mathematical models for standardized and unified calculation and reporting of GHG emissions and embodied energy for different jurisdictions globally.

In the effort to reduce global emissions, it is important to have a unified approach to the estimation, reporting, and management of emissions. Although some communities may be more advanced in the technologies for emission management, it is important that

this knowledge be shared with other communities around the globe. A centralized knowledge-sharing system (if well managed) is expected to help ensure good coordination and dissemination of information on best practices for emissions management. For simplicity, the emissions from the housing sector can be estimated based on (1) the number of buildings (existing and new buildings) in the community. (2) The population of the community.

3.2. Scenario 1: Using the population of a community to project the embodied energy, embodied carbon, operational energy, and operational carbon for a community.

To achieve emission reduction for the housing sector, the planning has to include a deep look at the embodied energy for buildings, the operational energy, and the energy that is associated with the end of life of the buildings (including recycling, reuse, and disposal processes-where ever those are applicable). In this planning, the factors to be considered include (1) The average living area per person. (2) The population of the community (3) The embodied energy that is required to provide adequate accommodation for each person in the community (4) The associated embodied carbon (GHG emissions) that comes with the provision and maintenance of the accommodation for each person in the community. This includes the operating energy and the associated GHG emissions during the use period for the building.

To use the population estimation method for the evaluation of emissions, a community will have to ensure adequate accommodation is provided for all. The embodied energy, operational energy, embodied carbon and operational carbon per living area per person will have to be calculated. The number of people in the community can be multiplied by the embodied energy per living area per person per year for each country. Improvement targets including GHG capturing mechanisms can be set accordingly. On a global scale, emission targets for the building construction industry can be based on the projected global population.

3.2.1. Calculating the annual embodied energy and embodied carbon for buildings.

Various definitions exist for embodied carbon. Some researchers [1] defined embodied carbon as the greenhouse gas emissions that are generated before the buildings are occupied (including the GHG from extraction, and manufacturing of building materials). A more recent study presented a broader definition of embodied carbon. Citing a previous work, the report [54] identified embodied carbon as the GHG emissions that are produced during the extraction and transportation of raw materials, the manufacturing of building components and construction, renovation and maintenance for a building over its useful life span, demolition, disposal, or recycling of the materials for the building at the end of its life. Another work [55] noted that embodied energy and embodied carbon are the sum of the energy used and greenhouse gas emissions that are associated with material production, construction, and the end-of-life stages of a building. These embodied carbons are more critical in meeting climate targets than they are commonly assumed [1]. Citing previous works, some researchers [55] noted that 28% of global GHG emissions and 38% of energy-related emissions are from buildings. 26% of this is allocated to embodied carbon emissions while 74% is allocated to operational carbon emissions by the United Nations Environmental Program. Some scholars [56] presented a case study of 97-apartment-type building in Portugal as regards the embodied and operational energy (heating, electricity, and hot water). The scholars reported that while the embodied energy has an average of 187.2 MJ/m²/yr., the embodied energy account for 2372 MJ/m² representing 25.3% of the operational energy for a 50-year service life. The operational energy and operational carbons are the energy used and the associated GHG emissions during the operational (use) phase of a building (Stage B6 of LCA).

3.2.1.1. Embodied energy and embodied carbon per annum.

For simplicity, the average embodied energy per annum, EE_y (joules/year) can be calculated by dividing the total embodied energy that is expected for a building over its useful lifetime, EE_{UL} by the number of years the building will be in use, n . Similarly, the average embodied carbon per annum, EC_y (KgCO₂/year) for a building is the total embodied carbon that is expected over the useful lifespan of the building, EC_{UL} divided by the number of years the building is in use.

$$EE_y = \frac{EE_{UL}}{n} \quad (1)$$

$$EC_y = \frac{EC_{UL}}{n} \quad (2)$$

3.2.2.2. Embodied energy and embodied carbon per annum per unit of building area.

The embodied energy per annum per unit of building area, EE_{yA} (joules/year. square meters) can be represented as the embodied energy per annum for the building divided by the area of the building, A . Likewise, the embodied carbon per unit of building area per year, EC_{yA} can be estimated by dividing the average embodied carbon per annum by the associated building area, A .

$$EE_{yA} = \frac{EE_{UL}}{nA} \quad (3)$$

$$EC_{yA} = \frac{EC_{UL}}{nA} \quad (4)$$

Living area per person

The average living area per person varies in different parts of the world. A previous study [14] gave energy reference area and living space per resident for five different living space scenarios. The living spaces(m²) illustrated are 60, 52.5, 45, 37.5, and 30 m². The corresponding energy reference areas are 80, 70, 60, 50, and 40 m² respectively. The energy reference area is also referred to as the gross floor area within the thermal building envelope (a reference area for the calculation of the operational energy demand in Switzerland). A fixed value of 60m² for the energy reference area is used in defining the GWP targets in SIA 2040. Citing another report, a previous work [57] provided information on the average living area per person in nine countries (US, Canada, Australia, Germany, France, UK, Spain, Mexico, and Brazil). The average living area per person presented ranges from about 32 m² to 61m². There is a need to ensure that adequate living space is provided for people in every community. Some scholars [58] noted that 'a constricted living space may be an environmental threat for myopia development in children'. In the study ocular axial length and refractive status of 1075 people (mean age 9.95 years) were measured. Further study is recommended on adequate living space and satisfaction and happiness of people. Regardless of geographical location, it is important that each person have an access to adequate living area in accordance with international law on rights to housing. Hence, the effort to minimize energy use and also reduce emissions should not go to the extent in which the living space of people will be reduced to unhealthy sizes. With an assumption that everyone in a community has access to a good living area (that follows an average living area), and there are no excess uninhabited dwelling units, the embodied energy and the embodied carbon from a community can be calculated based on the population of the community. On this wise, the embodied energy for housing per annum per person, EE_{yhpA} can be estimated by a multiplication of the

average embodied energy per annum per unit of living area, EE_{yA} by the average living area per person, L_A in the community.

$$EE_{yhpA} = EE_{yA} * L_A \quad (5)$$

Giving that the energy reference area, L_{AE} (area of the building that requires some energy for its good upkeep) can be more than the living area, the use of the energy reference area for the calculation of the embodied energy for the community will be more inclusive.

$$EE_{yhp} = EE_{yA} * L_{AE} \quad (6)$$

Embodied energy for housing for the whole community, EE_{yhc} for the year can be represented as the number of people in the community n_p multiplied by the embodied energy per person per EE_{yhp}

$$EE_{yhc} = EE_{yhp} * n_p \quad (7)$$

For the five energy reference areas defined in a previous study [14], equation 8 shows the relationship between the energy reference area per resident and the living area per resident.

$$L_{AE} = \frac{L_A}{0.75} \quad (8)$$

The energy reference area for each building could vary. If a wide variation is noticed, building-specific conditions may be incorporated into the calculations for the energy reference area for the buildings. The embodied carbon per annum per person for the housing sector can be estimated by the product of the embodied carbon per unit of building area per year and the living area, L_A per person. To be more inclusive, the energy reference area per person can be used in place of the living area per person for the calculation of the embodied energy L_{AE} .

$$EC_{yhp} = EC_{yA} * L_{AE} \quad (9)$$

The embodied carbon per annum for the housing sector for the whole community, EC_{yhc} can be estimated by the product of the embodied carbon per annum per person, EC_{yhp} and the number of people in the community, n_p

$$EC_{yhc} = EC_{yhp} * n_p \quad (10)$$

3.2.2.3. Operating energy and the associated GHG emissions for the community per year.

The operating energy for the community, OE_{ycp} is the operating energy that is used for the upkeep of the living area per person, OE_{Ap} multiplied by the number of people in the community, n_p

$$OE_{ycp} = OE_{Ap} * n_p \quad (11)$$

The average operating energy that is used for the upkeep of the living area per person, OE_{Ap} is the total operating energy for all buildings in the community divided by the number of people in the community.

$$OE_{Ap} = \frac{OE_{yc}}{n_p}$$

The associated operating GHG emissions for the upkeep of residences for people in the community for the year, OC_{ycp} is the operating carbon (GHG emissions) that is

associated with the maintenance of the living area per person, OC_{Ap} multiplied by the number of people in the community, n_p

$$OC_{ycp} = OC_{Ap} * n_p \quad (12)$$

3.2.2.4. Total embodied carbon (GHG emissions for the community) using the population approach.

The total embodied and operating carbon (GHG emissions) for the community for the year, using the population estimation approach, TC_{cop} is the sum of the embodied, EC_{ytp} and operating carbon, OC_{ytp} for the upkeep of all the residents of the community for the year.

$$TC_{cop} = EC_{yhc} + OC_{ycp} \quad (13)$$

$$TC_{cop} = (EC_{yhp} * n_p) + (OC_{Ap} * n_p) \quad (14)$$

3.2.2.5. The total embodied and operating energy for the community for the year (using the population approach).

The total embodied and operating energy for the community, TE_{cop} for the year is the sum of the embodied, EE_{yhc} and operating energy, OE_{ycp} for the upkeep of all the residents of the community for the year.

$$TE_{cop} = EE_{yhc} + OE_{ycp} \quad (15)$$

$$TE_{cop} = (EE_{yhp} * n_p) + (OE_{Ap} * n_p) \quad (16)$$

For this to have a reasonably high degree of accuracy, the government of the country must be committed to the international law that declares access to good housing as a fundamental human right for all. "Adequate housing is a human right enshrined in international human rights law. Failing to recognize, protect, and fulfill the right to adequate housing results in the violation of a plethora of fundamental rights including the right to work, education, health, and security." UN Habitat [59]. The number of housings provided should not be too much in excess of what is needed in the country, otherwise, there will be wastage of energy resources in the manufacturing of materials for accommodation that is not needed. There will also be waste of resources to ensure a good maintenance of those accommodation that are not used. If there are lots of empty houses in a community with housing crisis, these should be put into good use to accommodate the people.

3.3. Scenario 2: Using the number of buildings to project the embodied energy, embodied carbon, operational energy, and operational carbon for a community.

A good plan for the expected number of new buildings that are expected in a community every year can be helpful in energy use and emission management planning. In a situation where no plan exists for the expected number of new buildings, an estimate for the expected embodied energy and GHG emissions from the housing sector can be made using the trends from the history of building construction in previous years. This can be used to forecast the expected trends in embodied energy and the associated GHG emissions for future years.

For the existing buildings in a community

For simplicity, the embodied energy per annum, EE_{yex} (joules/year) for all the existing buildings in the community can be estimated by multiplying the number of existing buildings in the community N_{ex} by the average embodied energy that was described for equation 1.

$$EE_{yex} = \frac{EE_{UL}}{n} * N_{ex} \quad (17)$$

For the new buildings in a community

For simplicity, the embodied energy per annum, EE_{ynw} (joules/year) for all the new buildings in the community can be estimated by multiplying the number of new buildings in the community N_{nw} by the average embodied energy that was described for equation 1.

$$EE_{ynw} = \frac{EE_{UL}}{n} * N_{nw} \quad (18)$$

The operating energy for all the existing buildings in a community for the year OE_{yex} can be estimated by multiplying the average operating energy for the existing buildings in the community for the year OE_{ayex} by the number of existing buildings in the community N_{ex} .

$$OE_{yex} = OE_{ayex} * N_{ex} \quad (19)$$

The operating energy for all the new buildings in a community for the year OE_{ynw} can be estimated by multiplying the average operating energy for buildings in the community for the year OE_{aynw} by the number of new buildings in the community N_{nw} .

$$OE_{ynw} = OE_{aynw} * N_{nw} \quad (20)$$

The embodied energy for all the existing buildings in a community for the year EE_{yex} can be estimated by multiplying the average embodied energy for the existing buildings in the community for the year EE_{ayex} by the number of existing buildings in the community N_{ex} .

$$EE_{yex} = EE_{ayex} * N_{ex} \quad (21)$$

The embodied energy for all the new buildings in a community for the year EE_{ynw} can be estimated by multiplying the average embodied energy for buildings in the community for the year EE_{aynw} by the number of new buildings in the community N_{nw} .

$$EE_{ynw} = EE_{aynw} * N_{nw} \quad (22)$$

The total energy for the housing sector (all the buildings in the community), TE_{com} is the sum of the embodied energy for the old and new buildings, and the operating energy for the old and new buildings in the community.

$$TE_{com} = OE_{ynw} + OE_{yex} + EE_{yex} + EE_{ynw} \quad (23)$$

$$TE_{com} = (OE_{aynw} * N_{nw}) + (OE_{ayex} * N_{ex}) + (EE_{ayex} * N_{ex}) + (EE_{aynw} * N_{nw}) \quad (24)$$

Similarly, the average embodied carbon per annum, EC_{yex} (joules/year) for all the existing buildings in the community can be estimated by multiplying the number of existing buildings in the community N_{ex} by the average embodied carbon that was described for equation 2.

$$EC_{yex} = \frac{EC_{UL}}{n} * N_{ex} \quad (25)$$

The operating carbon for all the existing buildings in a community for the year OC_{yex} can be estimated by multiplying the average operating carbon for existing buildings in

the community for the year OC_{ayex} by the number of existing buildings in the community N_{ex} .

$$OC_{yex} = OC_{ayex} * N_{ex} \quad (26)$$

For new buildings in the community for each year, the embodied energy, embodied carbon, operating energy, and operating carbon can be estimated by a similar approach stated above.

$$EC_{ynw} = \frac{EC_{UL}}{n} * N_{nw} \quad (27)$$

Where EC_{ynw} is the embodied carbon for all the new buildings per year, N_{nw} is the number of new buildings in the community for the year.

The total embodied carbon for the buildings in the community for the year will be a summation of the embodied carbon for new buildings and the embodied carbon for existing buildings in the community for the year.

$$EC_{ytb} = \left(\frac{EC_{UL}}{n} * N_{nw} \right) + \left(\frac{EC_{UL}}{n} * N_{ex} \right) \quad (28)$$

The operating carbon for all the new buildings in a community for the year OC_{ynw} can be estimated by multiplying the average operating carbon for new buildings in the community for the year OC_{aynw} by the number of new buildings in the community N_{nw} .

$$OC_{ynw} = OC_{aynw} * N_{nw} \quad (29)$$

The total operating carbon for the buildings in the community for the year will be a summation of the operating carbon for new buildings and the operating carbon for existing buildings in the community for the year.

$$OC_{ytb} = (OC_{aynw} * N_{nw}) + (OC_{ayex} * N_{ex}) \quad (30)$$

Note that this is a simplified approach to estimating the embodied energy, embodied carbon, operational energy, and operational carbon for new and existing buildings in a community. If desired, more complex formulas may be developed that examines how variation in building-specific parameters may affect the overall environmental impact for the whole community.

Alternatively, this can be expanded as presented in the equation below. This is simply a summation of the yearly operating carbon for individual buildings in the community. OC_{nw} represents each new building, and OC_{ex} represents each existing building.

$$OC_{ytb} = \sum_{i=1}^j OC_{nw} + \sum_{k=1}^l OC_{ex} \quad (31)$$

The total GHG emissions (total 'carbon') for the whole community for the year, TC_{com} is the sum of all the GHG emissions for the new and existing buildings in the community. This includes the embodied and operational GHG emissions that are described earlier.

$$TC_{com} = OC_{ytb} + EC_{ytb} \quad (32)$$

$$TC_{com} = (OC_{aynw} * N_{nw}) + (OC_{ayex} * N_{ex}) + \left(\frac{EC_{UL}}{n} * N_{nw} \right) + \left(\frac{EC_{UL}}{n} * N_{ex} \right) \quad (33)$$

3.3.1. Estimating the contribution of the housing sector to global GHG emissions.

The mathematical models presented above will allow individual nations to give a reasonable estimate of the contribution of their housing sector to global GHG emissions. The total global GHG emissions from the housing sector, GL_{GHG} can be estimated by the summation GHG emissions reported for each country (i to j). Each country can estimate its total operating and embodied carbon from new and existing buildings as described.

$$GL_{GHG} = \sum_{i=1}^j (\sum_{k=1}^l OC_{nw} + \sum_{m=1}^n OC_{ex} + \sum_{o=1}^p EC_{nw} + \sum_{q=1}^r EC_{ex}) \quad (34)$$

This information can allow for coordinated planning in global emission reduction from the building construction industry (housing sector). Other industries can use a similar approach in the evaluation and management of the environmental impacts of their operations.

3.4. Environmental impacts on construction operations

The environmental impacts in construction are often classified into impacts that are associated with the emissions during the use of equipment for construction operations, and transportation of materials, equipment, and manpower to and from the construction site. Energy use, water use, and general resource use are also part of the impacts of construction operations. Athena's impact estimator for buildings IE4B creates a cradle-to-grave life cycle inventory (LCI) profile for a whole building. The user has to select the expected life cycle for the building. The following mid-point life cycle impact assessment measures were supported by IE4B: Global warming potential - (CO₂ equivalent mass), acidification (air) potential - (SO₂ equivalent mass), Smog (air) potential - (O₃ equivalent mass), Human health particulate - (PM_{2.5} equivalent mass) Ozone Depletion (air) potential - (CFC 11 equivalent), Eutrophication (air & water) potential - (N equivalent mass), Total primary energy consumption - (MJ), Non-renewable energy Consumption - (MJ), Fossil fuel consumption - MJ [60].

3.5. Whole building life cycle analysis (WbLCA)

LCA is a standardized method that is used to quantify the environmental impacts in the lifecycle of a product from resource extraction to the production of material (manufacturing stage), use and end of life, disposal, and recycling [61]. Life cycle analysis (LCA) is one of the management tools that is used to evaluate environmental concerns [62]. LCA can support sustainable decisions while predicting the environmental impact of buildings during their life cycle. Some researchers [63] noted that most LCA studies for buildings present a rough estimate of the materials and fuels that are used in construction. These exclude choices on a variety of construction methods, materials, machines, and specialties. The report further mentioned that the roughness of LCA practice undermines its credibility and hinders its application as a decision-supporting tool for low-carbon design. While efforts are ongoing to find ways to reduce the environmental impacts of construction, LCA still plays a good role in giving reasonable estimates that can help in the development of reasonable mitigation strategies. The whole building LCA follows the progression in Figure 2. Consideration is given to the whole building LCA while developing the framework for the application of optimization techniques to achieve global emission targets in the building construction industry.

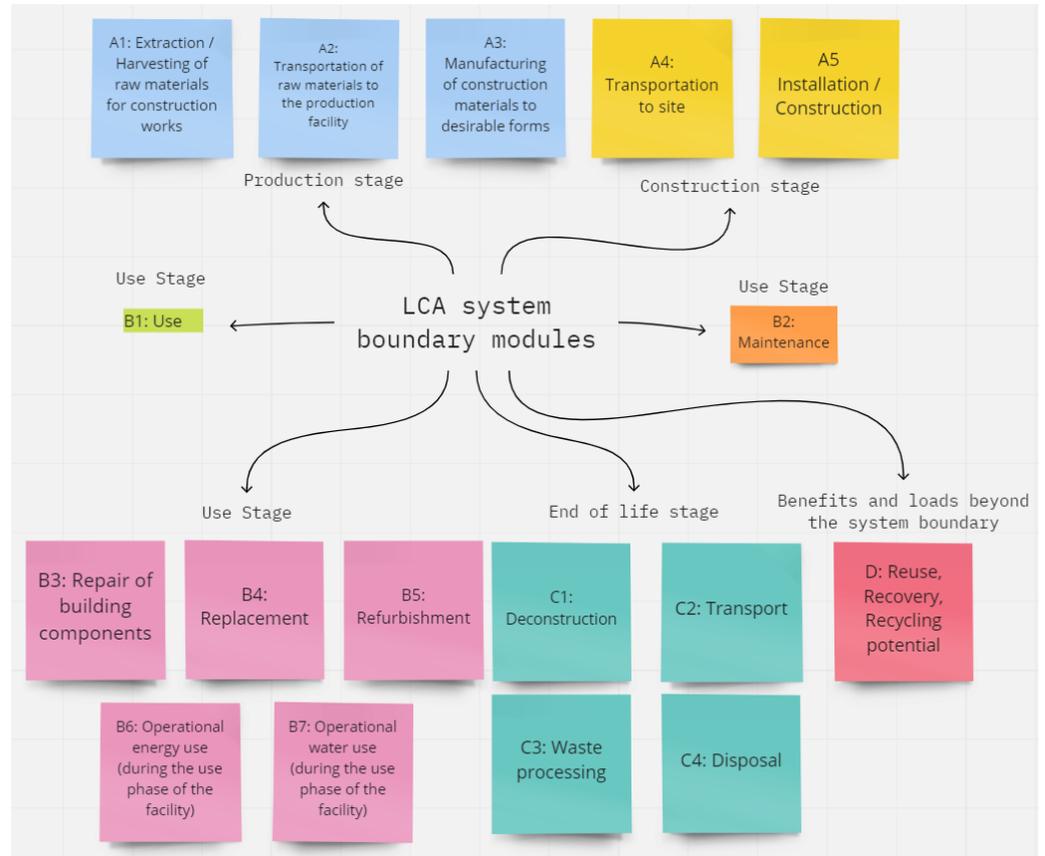


Figure 2. LCA system boundary modules (Adapted from AWC, & CWC, 2020, Mofolasayo, 2022)

To achieve the global emission targets in the construction industry, the total emission for the whole building (for all the modules described in Figure 2) has to be less or equal to the emission targets for the life cycle of the whole building. This means that the emissions at the production stage (material extraction and processing), construction stage (transportation of construction materials and subsequent construction), use stage (normal facility operations, maintenance, repair of building components, replacement, refurbishment, operational energy use, operational water use), end of life (deconstruction, transport, waste processing, disposal) of each building has to be less than the specified emission targets.

$$E_{Prod} + E_{Const} + E_{use_stage} + E_{EOL} \leq E_{target} \quad (35)$$

Where

E_{Prod} is the emission target for the production stage of the construction materials used for the building construction.

E_{Const} is the emission target for the construction stage of the building.

E_{use} is the emission target for the use stage of the building.

E_{EOL} is the emission target for the stages at the end-of-life of the building.

E_{target} is the emission target for the whole building LCA.

Given that emissions increase as the number of building construction increases, it is important that due efforts be made to increase efficiency in building construction while reducing emissions. After the end-of-life of a building, (when the building components

get to their reuse phase), emissions after this stage can be included in a new set of emission targets for the new building in which it is being used.



Figure 3. Strategy toward the achievement of global emission reduction targets in the construction industry

The strategy for whole building life cycle emission reduction is one that involves multiple stakeholders. To achieve the above target, each subsection of the whole building life cycle has to meet individual targets. A previous work [47] gave a list of stakeholders that can address some specified goals. These stakeholders include non-government organizations, networks and researchers, policymakers (governments and cities), investors, developers, designers, and material manufacturers. A yearly target that reflects the goal for emission reduction will be ideal. If the world will meet her global emission reduction targets, it is important that every aspect of the global economy contribute its part to meeting the targets for emission reduction. Figure 3 shows a protocol that can be followed in the effort towards ensuring that the construction industry contributes her part to the global emission reduction. While investigating how the environmental impacts on offsite and onsite building construction can be improved, a scholar [52] described a framework for establishing present and future state maps for the environmental impacts of construction works. The protocol that is discussed in Figure 3 can be used in conjunction with the framework that was described in the study.

3.6. Breaking the emissions down to sub-units of the whole building life cycle

3.6.1. The production stage

As indicated in Figure 2, the production stage involves extraction and production at the upstream (A1), transportation of raw materials to the production facility (A2), and manufacturing of construction materials to desirable forms (A3). The emission targets for the production stage will involve the stakeholders that are involved in the sub-sections of the production of raw materials for construction. Achieving emission reduction targets in the production stage will involve the identification of the maximum allowable emission for material production every year, meeting with stakeholders that are involved in the production of raw materials, identification of variables that contribute to emissions during the material production, development of strategies for continuous improvement to

achieve the emission reduction target, implementation of the emission reduction strategies, monitoring and reporting of quarterly and yearly progress, reviewing of achievements and development and implementation of new goals for the next reporting period.

$$E_{Prod} = E_{extr} + E_{trar} + E_{manc} \quad (36)$$

E_{extr} is the emission target for the extraction/harvesting of raw materials for construction.

E_{trar} is the emission target for the transportation of raw materials from the point of extraction to the manufacturing factory.

E_{manc} is the emission target for the manufacture of raw materials (transformation of raw materials into desirable forms for construction).

3.6.2. The construction stage

The construction stage includes transportation to the site (A4) and Installation/Construction (A5). The emissions can be represented as follows:

$$E_{Const} = E_{transp} + E_{install_Const} \quad (37)$$

E_{Const} is the emission target for the entire construction operations

E_{transp} is the emission target for the transportation of raw materials from the manufacturing factory to the final building construction site or to the offsite construction facility and then to the final construction site.

$E_{install_Const}$ is the emission target for the final installation or onsite construction.

In the case of prefabricated modules, emissions that are generated from the energy that is used in the production of panels / modules will count towards the variables to be considered in the emission reduction activities. Emission reduction for onsite and offsite construction is further explained in this article.

3.6.3. The use stage

The use stage depicted in [Figure 2](#) includes use (B1), maintenance (B2), Repair (B3), Replacement (B4), Refurbishment (B5), operational energy use, (B6), and operational water use (B7). In order to meet the total emission target for the building construction industry, the sum of the individual emission category in the use stage has to be less or equal to the emission target for the use stage.

$$E_{use} + E_{maint} + E_{repr} + E_{repl} + E_{refub} + E_{opeg} + E_{opwt} \leq E_{use\ stage} \quad (38)$$

Where

E_{use} , E_{maint} , E_{repr} , E_{repl} , E_{refub} , E_{opeg} , and E_{opwt} are the emissions that are associated with the use, maintenance, repair, replacement, refurbishment, operational energy use, and operational water use for the building, respectively. To meet the global targets for emissions, these have to be less than the specified emission targets for the use stage $E_{use\ stage}$ for the building.

3.6.4. The end-of-life stage

The end-of-life stage includes deconstruction (C1), transport (C2), waste processing (C3), and disposal (C4). In order to meet the total emission target for the building construction industry, the sum of the individual emission category for the end-of-life has to be less or equal to the emission target for the end-of-life stage.

$$E_{tranEOL} + E_{wastp} + E_{deconst} + E_{disp} \leq E_{EOL} \quad (39)$$

Where

E_{wastp} , $E_{tranEOL}$, $E_{deconst}$, E_{disp} are the emissions that are associated with waste processing, transportation, deconstruction, and disposal at the end-of-life of the building. It includes the transport of material to the point of reuse, recycling, or other purposes. E_{EOL} is the targeted emissions for the end of life of the building.

3.6.5. Benefits and loads beyond the system boundary

The emissions at the benefits and loads beyond the system boundary include emissions in the reuse, recovery, and recycling potential phases. If recycling and recovery are already classified under waste processing, there is no need to include another target for these. The emissions in the reuse phase can be classified under the new building for which it is used.

3.7. End-of-life of building structure

Modern timber construction is not currently aligned with circular economy principles and is seldomly taking the end of life of buildings into account. Even though it is evidently possible, to date, the structural reuse of timber is not a widespread approach. A lack of demand for salvaged materials, lack of design standards, and prohibitive building regulations form the barriers to the use of reclaimed structural components [54]. The ease with which a building can be deconstructed for potential reuse depends on the method of construction. Designing buildings for ease of disassembly and reuse will help reduce the embodied energy of the building construction industry (if well managed). Some scholars [64] summarized novel design concepts for deconstruction and reuse that could be used in modern timber buildings.

3.8. Establishment of localized emission targets for offsite and onsite construction

3.8.1. Onsite and offsite construction

Both offsite and traditional onsite construction has been around for a long time. According to the extent of the prefabrication rate, offsite construction can be classified into sub-assembly, non-volumetric preassembly, volumetric pre-assembly, and modular construction [65]. Prefabrication (also known as offsite construction, modular construction, offsite manufacturing, modern methods of construction, and industrialized building) is a construction method in which parts of the building are produced in the factory and moved to the site for assembly. The prebuilt parts can be manufactured in a variety of sizes from any material, from pre-cut pieces to entire buildings [66]. In the past decade, offsite construction has gained rapid growth worldwide. However, there is a lack of critical review of building performance such as energy performance and carbon emissions for offsite built facilities [65]. A scholar [53] presented models for the environmental impacts of onsite and offsite construction in a previous study. These are described below

3.8.2. Model equations for offsite construction

The total emissions for offsite construction are the sum of the emissions from material transport, employee transport (including inspector transport to the fabrication yard for general oversight on code compliance), equipment transport, equipment use, building operation, module transport, and onsite work for foundation construction and final installation of modules.

$$TE_{OSC} = E_{OSC} + E_{ONS_OSC} \quad (40)$$

Where:

TE_{OSC} is the total emissions for offsite construction.

E_{ONS_OSC} is the emissions from the onsite portion of the offsite construction project. This includes the emissions from the construction of the foundation onsite (E_{FDN}), emissions from the assembly of the modules or panels onsite (E_{MASB}) i.e., panel/module installation on site, and the emissions from other associated onsite works like fencing, landscaping, connection to utilities, etc. (E_{MISC}).

$$E_{ONS_OSC} = E_{FDN} + E_{MASB} + E_{MISC} \quad (41)$$

Environmental impact models for onsite and offsite construction

$$E_{OSC} = E_{BM} + E_{MT_OSC} + E_{EPT_OSC} + E_{LD} + E_{TCM} + E_{EQT_EPT} + E_{EQU_OSC} \quad (42)$$

Where:

E_{OSC} is the emissions from the offsite portion of the construction. This includes emissions from the offsite facility's building maintenance (E_{BM}), round-trip material transportation to the offsite construction factory (E_{MT_OSC}), all employee transportation (round-trips) to the offsite facility (E_{EPT_OSC}), equipment use in the offsite facility (E_{EQU_OSC}), loading of completed modules at the offsite factory (E_{LD}), transportation of completed modules to the site (E_{TCM}), E_{EQT_EPT} is the emissions related to the transportation of equipment and employee to the final site, for installation of modules, E_{EQU_OSC} are the emissions from the use of equipment at the offsite construction facility, E_{EQU_ONS} are the emissions from the use of equipment on site during the final assembly of the building onsite. Hence,

$$\begin{aligned} TE_{OSC} = & E_{BM} + E_{MT_OSC} + E_{EPT_OSC} + E_{LD} + E_{TCM} + E_{EQT_EPT} \\ & + E_{EQU_OSC} + E_{EQU_ONS} + E_{FDN} + E_{MASB} + E_{MISC} \end{aligned} \quad (43)$$

To achieve a targeted value for the environmental impacts for both onsite and offsite construction, Monte Carlo simulation (What if analysis) can also be used with the above equation, to evaluate how changes in the variables on the right-hand side (RHS) of the equation can help to achieve a targeted impact on the left-hand side (LHS). A scholar [67] noted that Monte Carlo simulations can be used to perform hundreds or thousands of 'what if' analysis that points to trends that relate to the decisions that are being considered (when looked at together).

3.8.3. Model equations for onsite construction

Similar to the calculation of total emissions for the offsite construction, the total emissions for the onsite construction, TE_{ONS} is the sum of the impacts from material transport to the final site (E_{MT_ONS}), employee transport (E_{EPT_ONS}) to the site (including inspector transport to the site for code compliance), equipment transport to the site (E_{EQT_ONS}), the use of equipment for the building construction on site (E_{EQU_ONS}) for the construction of both the foundation, E_{FDN} and the superstructure, E_{SPT} for the building.

$$TE_{ONS} = E_{FDN} + E_{SPT} \quad (44)$$

$$TE_{ONS} = E_{MT_ONS} + E_{EPT_ONS} + E_{EQT_ONS} + E_{EQU_ONS} \quad (45)$$

To minimize the impact for onsite and offsite construction, feasible targets can be set for the environmental impacts of each variable that sum up to the total impacts, (using present and future state maps of value stream mapping technique [52]) given consideration to potential constraints. With these targets, an optimization model for offsite and onsite construction can be developed as follows:

Minimize:

$$\begin{aligned}
TE_{OSC} = & E_{BM} + E_{MT_OSC} + E_{EPT_OSC} + E_{LD} + E_{TCM} + E_{EQT_EPT} \\
& + E_{EQU_OSC} + E_{EQU_ONS} + E_{FDN} + E_{MASB} + E_{MISC}
\end{aligned} \tag{46}$$

Subject to:

$$\begin{aligned}
E_{BM} &= T_{BM} \\
E_{MT_OSC} &= T_{MT_OSC} \\
E_{EPT_OSC} &= T_{EPT_OSC} \\
&\vdots \\
E_{MISC} &= T_{MISC}
\end{aligned}$$

T_{BM} , T_{MT_OSC} , T_{EPT_OSC} , and T_{MISC} are the emission targets for building maintenance, material transport for offsite construction, employee transport for offsite construction, and miscellaneous activities.

To be within the global or localized target impact value for emission for individual buildings, (considering growth in the number of buildings), $TE_{OSC} < T_L, T_G$ where T_L , and T_G are localized and global targets for emissions respectively. i.e.,

$$\sum_i^j E_{BM}, E_{MT_OSC}, E_{EPT_OSC}, E_{LD}, E_{TCM}, E_{EQT}, E_{EQU_OSC}, E_{FDN}, E_{MASB}, \dots E_{MISC} < T_L, T_G \tag{47}$$

For all categories of emissions, E_c , the summation of individual impacts for each building process has to be less than the localized or global targets for environmental impacts. i.e., for localized targets,

$$\forall E_c, \sum_{i=1}^j E_c \leq T_L \tag{48}$$

For global targets,

$$\forall E_c, \sum_{i=1}^j E_c \leq T_G \tag{49}$$

An alternate method is to set emission targets for each section of building construction, such as emission targets for foundation construction, flooring, framing, roofing, landscaping, etc. Given that the environmental impact from each component above is mostly dependent on the energy use during the construction process, each emission category can be further broken down into the type of energy that goes into the process. The targets can be based on the energy/impact reduction strategies for each of the individual components.

For example, a scholar [53] described the emission relationship during the transportation of equipment to the building construction site as follows:

$$E_{EQT_ONS} = \sum_{i=1}^n D_{EQT_ONS} \times EN_{urvEQT} \times N_t \times I_{uEQT} \tag{50}$$

Where

E_{EQT_ONS} is the expected emission for equipment transport to the building construction site (onsite construction)

D_{EQT_OSC} is the round-trip distance from the equipment storage yard to the building construction site.

EN_{urvEQT} is the energy use rate for the vehicle that is used to transport the equipment

I_{uEQT} is the impact per unit of the energy used during the transportation of equipment to the site.

N_t is the number of trips for the transportation of the equipment to the building construction site.

n is the number of equipment types that are to be transported to the building construction site.

A reduction of all the factors that are on the right-hand side of the above equation will result in a reduction of the total impact that is expected from the transportation of equipment to the site. Given that factors such as distance, energy use rate, and the number of trips can be pre-planned (assuming the product of this is 7.5), assuming, a target of 2 KgCO_{2e} is given to GHG emissions for equipment transport, to achieve this target, during planning and construction monitoring process, the constraint for equipment transport in the optimization equations can be presented as:

$$7.5 I_{uEQT} = 2$$

The impact per unit rates for each of the variables can be changed to a unified form of classification for clarity. For example, impact per unit for variables using electric energy, diesel, or gasoline can be represented as E, D, G , respectively. Hence, if the energy that is used during equipment transport for the above is electric energy, the equation for equipment transport can be written as:

$$7.5 E = 2$$

Each of the other variables can have similar equation. If a process (e.g., the equipment transport described above) uses both electricity and fossil fuel, the equation can be

$$aE + bD + cG = 2$$

Where a, b , and c are numbers that can be derived from other variables in equation 50. E, D, G represents the impact per unit rate for electricity, diesel, and gasoline respectively.

A solution for the model described above (given consideration to any hard constraints which may be difficult to adjust at the time of construction) is expected to show how much emission allowance is available for any other variable that can be adjusted during the construction processes. With this knowledge, efforts can be intensified in research on how to achieve the targeted impact per unit for each of the energy type that is used during the construction operation. This process can be done for both offsite and onsite construction.

3.9. Monte Carlo simulation approach for allocating targets per sub-units of the emission variables

Monte Carlo simulation is a useful mathematical method for the analysis of uncertain scenarios and the provision of probabilistic analysis of different situations. It relies on repeated random sampling and statistical analysis to compute results. The method of simulation is closely related to random experiments in which the specific result is not known in advance. Hence, Monte Carlo simulation can be seen as a way of performing a 'what-if' analysis [68]. Monte Carlo Simulation is a useful technique for modeling and analysis of real-world systems and situations. It can quantify the effects of risk and uncertainty in project schedules and budgets. This gives the project manager a statistical indicator of the performance of the project as regards budget and project completion date [69]. Monte Carlo simulation is a modeling tool that is widely used in many scientific domains [70]. It is used by financial analysts to model various scenarios. It is also used in reliability engineering. Monte Carlo simulations can be used as a tool in six sigma efforts to enable six sigma leaders to identify the optimal strategy in selecting projects, providing probabilistic estimates for project cost benefits, predicting the quality of business processes, identifying defect-producing process steps that drive unwanted variations, creating virtual testing grounds in later phases for proposed product and process changes.

Monte Carlo simulation is used to provide the numerical solution for complex multi-dimensional partial differentiation and integration problems. It is also used to solve optimization problems in operations research. In mechanical engineering one of the most common uses of Monte Carlo simulation is to estimate the reliability of mechanical components [68].

In Monte Carlo simulation, a model of a real-life system or situation is developed. This model contains certain variables. These variables have different possible values that are represented by a probability distribution function of the values for each variable. In the Monte Carlo method, the entire system is simulated many times, randomly choosing a variable from its probability distribution each time. The outcome is a probability distribution of the overall values of the system from calculations in the iterations of the model [69]. Every Monte Carlo Simulation starts with a deterministic model that closely resembles the real scenario. This is followed by input distribution identification, generation of random variables analysis, and decision-making. The input distribution can be based on historical records or random variables that are generated from discrete or continuous distributions. The input and output can also be represented in the form of base-case, worst-case, and best-case scenarios [68]. Whilst discussing the advantages of Monte Carlo simulation in project management, some researchers [69] noted that Monte Carlo simulation is a powerful tool when trying to understand and quantify the potential effects of uncertainty of the project. The scholars also noted that Monte Carlo simulation is as good as the information that is fed into it and the model it is simulating. Real-world activities will not be reflected in a project model that is incomplete. Hence, there is a need for diligence in ensuring adequate updates to the model anytime there are changes in the factors that will affect the functionality of the model. With this in mind, although the model given in this article may show the present factors that contribute to emissions from construction operations, it is important to ensure adequate update to the model when new factors are known to contribute to global GHG emissions. Some other scholars [54] used Monte-Carlo analysis to compare the embodied carbon of mass timber buildings and post-tensioned concrete buildings. The result indicated that the embodied carbon of mid-rise mass timber buildings ranged from 196KgCO₂-e/m² to 590 KgCO₂-e/m² with an average of 417KgCO₂-e/m². The embodied carbon for a post-tensioned concrete building range from 307 to 618KgCO₂-e/m², with an average of 465KgCO₂-e/m². The authors reported that mass timber buildings typically have a lower embodied carbon than concrete buildings but the results are dependent on the input data and the assumptions that are made. Further study is recommended on how Monte Carlo simulation can be applied in prediction and target setting for emission control and management in various sectors of the global economy.

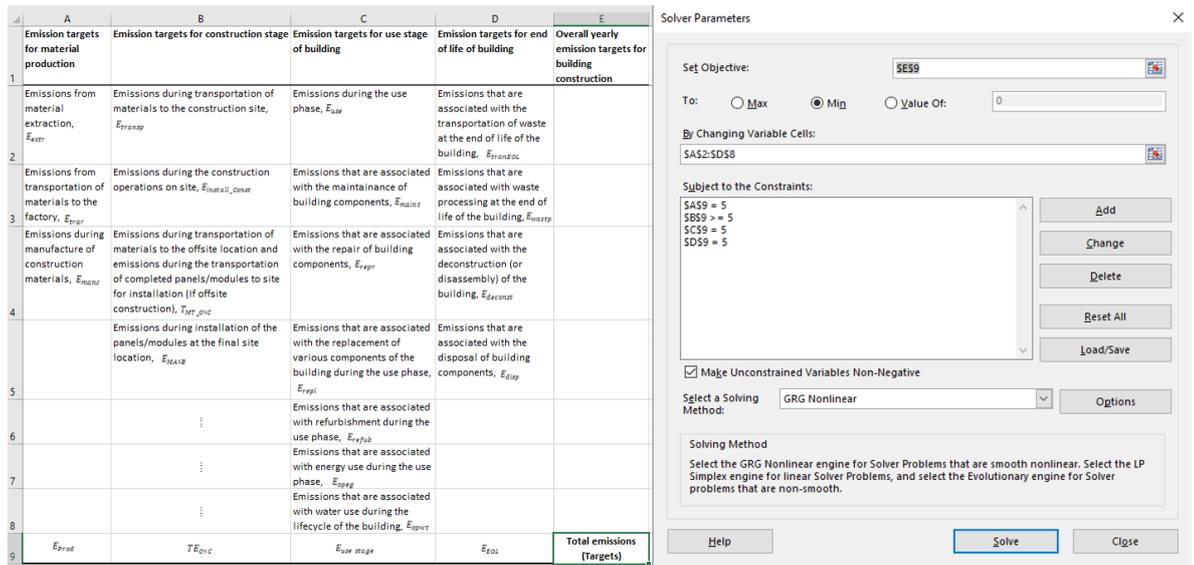


Figure 4. Illustration of input variables into a template for an optimization problem solving for minimization of GHG emissions

For Figure 4 above, a goal may be to seek to minimize column E9, by changing A2, to D8, and subject to specified constraints that may be applicable to the emission targets for columns A9: D9. The solver function in excel is designed to be able to provide mathematical solutions to certain programming problems. Note that column B9 indicates the total emission targets for offsite construction, meanwhile columns B2:B3 address aspects of onsite construction. Some of the aspects of offsite construction are mentioned in B3:B4. This list can be expanded with other variables that are mentioned in this report. If the evaluation is for onsite construction projects, information for offsite construction may not be included. If the evaluation is for offsite construction, information for onsite construction may not be included. If the evaluation is system-wide, information for both offsite and onsite construction will be included in the analysis. Note that the constraints that are specified in Figure 4 are hypothetical. These will have to be determined based on global emission goals.

During target-setting procedures, sometimes technological limitations may put a limit on the amount of change that can be achieved. In that situation, that constraint may be specified in the overall model. For example, in Figure 4, while the total emissions for each stage of the building life cycle were set to be equal to a targeted value, a ‘greater, or equal to’ sign was used in the constraint for the construction stage. This is for illustrative purposes. During the emission management planning stage, efforts should be made to reduce the emissions on construction projects to as little as possible. The constraints for the optimization problem will be set to reflect various limiting conditions that are identified. The transportation should include round-trip transportation. A scholar [53] gave More details about other factors to consider during the onsite and offsite construction operations. A “what if analysis” using the goal seek function can also be used to see how a specific target can be achieved while changing a specific variable.

The optimization formula for the achievement of the target can be written as

Minimize:

$$E_{Prod} + E_{Const} + E_{use_stage} + E_{EOL} \leq E_{target} \tag{51}$$

Subject to:

$$E_{prod} = T_{prod} \tag{52}$$

$$E_{Const} = T_{Const} \quad (53)$$

$$E_{use_stage} = T_{use_stage} \quad (54)$$

$$E_{EOL} = T_{EOL} \quad (55)$$

Note that some of the variables such as the impact during the use stage are often reported on a yearly basis. However, for consistency of units, this can also be evaluated based on the expected life span of the building.

To achieve the global emission target, there has to be an emission target for each construction. This could eventually form part of the building approval process. If the construction industry will contribute her quota to the goal to achieve global emission targets, there has to be a definite plan in place. If there is no coordinated effort on this, it may be difficult to achieve the global emission targets in the construction industry. The chain of command that may be followed is described below:

1. The environmental branch of the United Nations (based on open and verified science reports) specifies emission-targets that are agreeable to all nations.
2. The leaders of each nation communicate the targets to the various ministers in charge of each sector of the economy (including the minister in charge of infrastructure and construction works).
3. Necessary meetings are held in each nation to develop a plan to achieve the target in every sector of the economy (including the construction industry).
4. Realisable targets are set for allowable emission levels for construction for each year (this will be dependent on the expected number of new constructions that is necessary to provide conducive accommodation for everyone in the country).
5. The federal ministers hold a meeting with the applicable regional ministers for each sector of the economy (including the construction industry) to communicate the target and develop a strategy to achieve the targets at the local level.
6. Regional ministers hold a meeting and develop adequate strategies with various stakeholders within the industries under their jurisdiction (These strategies will be geared towards meeting the emission targets for their sector).
7. In conjunction with local engineering bodies (including construction companies), the Local agencies for various project approvals specify the limit for allowable emissions and strategies towards the achievement of the limit for every construction in their jurisdiction for that year (These targets should be made available to the public).
8. A plan to meet the specified emission targets is included as a requirement for new project approval.
9. The local project approval bodies specify enforcement plans to monitor and ensure compliance with emission targets for each project.
10. The local project approval bodies (through various local environmental protection units) monitor projects to ensure compliance with good environmental standards.
11. The local project approval bodies collate the reports for compliance with emission targets for various projects, record lessons learned, and new strategies to reduce emissions at the local levels, and share this report with the regional ministers, the federal ministers, the leaders of each nation and subsequently to the United Nations environmental protection agency.

12. The United Nation's environmental protection agency shares lessons learned and strategies to further reduce global emissions (as reported by individual countries) with all countries around the world.

The above procedure can be followed to ensure good compliance with yearly global emission targets. It can also be used as a basis for continuous development in emission management for the housing (building construction) industry. These strategies can be easily adapted for other sectors of the global economy for GHG emissions management.

4. Conclusion and recommendations

In recent years, there has been concern about global warming (most often attributed to GHG emissions). Some scholars have also reported that the effect of methane, CO₂ and some other trace gases on climate change is very small 'as to be negligible'. Regardless of the dispute in climate science, it is important that we make good efforts to care for our environment, especially as regards the air quality in relation to associated health impacts from air pollution. To alleviate the concern of air pollution and also curb the potential concerns from GHG emissions, it is important that every sector of the economy establish procedures to achieve localized and global targets for the reduction of 'unwanted' emissions. In this effort, it is important to note that sustainability principles are multifaceted (including economic, social and environmental impacts). Hence, due consideration needs to be given to all these aspects of sustainability to arrive at a holistic approach that will be agreeable to all.

Recognizing the disputes and contentions with issues around GHG emissions and global warming, among other things, this study presents a unifying strategy that can be helpful in addressing both the concerns about air pollution as well as concerns about GHG emissions. The study presents a strategy to have simplified emission calculation and reporting systems for various countries. An emission target setting and information sharing on best practices for emission management among nations are also presented. The study also demonstrated how to use an optimization technique to evaluate minimization potentials for GHG emissions. To see good progress in global emissions management, this study recommends a unifying approach in global emission management. The study also recommends that information sharing on best practices for emission control and management should be freely shared among all nations.

Considering the growth in population and the need for the construction of more buildings to provide good accommodation for the growth of humanity, the optimization framework developed in this study can be used to guide research works on the emission targets for different aspects of the whole building life cycle. Further study is recommended on the development of strategies to achieve a reduction in impact per unit for various forms of energy that are used during construction operations. Further studies are recommended on illustration of how emissions from the building and construction industry contribute to global emissions and any associated impacts through a system dynamics perspective. Further studies are also recommended on robust mathematical modeling for the achievement of targeted emission reduction goals for every sector of the global economy.

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