Life Cycle Assessment integrating GIS as Decision Support Tool for Designing Zero Emission Neighbourhoods.

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Abstract. Climate change casts a long shadow over densely populated cities, which is a consequence of the greenhouse gas emissions. Consequently, a critical concern regarding the environmental condition was caused. Zero-emission neighborhoods offer a promising solution but designing them effectively requires balancing complex factors. The neighbourhood is divided into components such as: buildings, mobility, infrastructure, and on-site energy, which were analysed separately to facilitate deeper comprehension of the neighbourhood emission pattern, according to its ambition levels. The aim of this study was to utilize a GIS model that integrates LCA at initial stages of neighbourhood's design, in order to identify the key factors that contribute to carbon emissions. The results of the case study of New Obour City highlighted buildings, particularly during their operational phase, as major emitters, followed by the production phase. On the other hand, neighbourhood infrastructure emitted the least emissions during its life cycle. Consequently, building design should be prioritized in order to reduce energy consumption, and pave the way for a future where cities and communities thrive in harmony with the environment.

Keywords: Zero Emission Neighbourhood; LCA; GIS; Greenhouse gas emissions.

1. Introduction

Lately, the acknowledgment of environmental change as an enfolding danger and the significance of supportability as a general objective have become progressively noticeable (Yang & et al., 2021). According to the Intergovernmental Panel on Climate Change (IPCC), CO2 is one of the primary greenhouse gases (GHGs) that contribute to global warming and climate change (Yang, S., Yu, M., 2016). Rising CO2 emissions will produce dramatic temperature shifts, putting human society's long-term growth at risk. As a result, the link between CO2 emissions and climate change has garnered global attention that encloses many methodologies, strategies, and estimation procedures (Samani, 2023).

The building sector has become a major contributor to global warming, with its emissions reaching a high record in 2019, of more than 80% of emissions (Röck et al., 2023).

To reduce the impact of buildings on the climate, a zero-emission neighborhood concept should be adopted by planners to produce no greenhouse gas emissions (Martiskainen & Kivimaa, 2018). Though this concept is still blossoming, with pilot projects popping up around the globe, the goal is clear. By building more of zero emission neighborhoods, this is not only cutting emissions; but also paving the way for communities to be more both sustainable and enjoyable to live in (Nematchoua et al., 2021).

1.1. Building environmental evaluation

Life Cycle Assessment (LCA) employs an approach of analysis of a product across its complete life cycle, spreading from raw material withdrawal to final discarding (Mostafaei et al., 2023). It tracks the impact from the moment materials are taken from the earth to the final disposal of the product. LCA promises a greener and sustainable future through analyzing the economic and social sides (Peña et al., 2021).

Moreover, Geographic Information Systems (GIS) enhances LCA for designing sustainable projects, through acting as a powerful tool of design, (Hiloidhari, & et al. , 2017). GIS performs a vital role in the task of planning and distributing resources. This integration offers a solid background for how different design choices impact the environment. Planners and designers are better equipped to develop different planning alternatives not only through creative vision but also through deep integrated scientific analysis (García-Pérez et al., 2018).

1.2. Buildings vs. neighbourhoods

Analyzing buildings as a standalone construction does not comprehend all its emissions as opposing to studying the neighborhood as a whole. Nevertheless, regarding the LCA technique, it assesses planners and designers to calculate the building’s environmental impact over a period of time (Anderson et al., 2015). Neighborhoods are complicated and have a wide variety of characteristics, making it challenging to expenditure LCA method, due to this variety, different methods are taken to model LCA, which increases the complexity of conducting neighborhood level studies (Lausselet et al., 2019).

Analysis of the neighborhood components heavily rely on the life span of each element separately to calculate their emissions accurately, making the estimate of neighborhoods future emissions is a real challenge (Roux et al., 2016). While, prioritizing thermally efficient design in zero emission neighborhoods, barely requires any power for heating or cooling, aiding to minimize the effect on climate change (Lotteau et al., 2015).

1.3. Problem Statement

Egypt's greenhouse gas emissions have increased by 44% in the past 15 years, much faster than the global average of 24% (Simões & et al., 2022). This accounts for 0.73% of global emissions, (Henrique Morgado Simões and Branislav Stanicek, 2022) and is one of the reasons for Egypt's temperature increase of 1.61 degrees Celsius (Kamer, 2023).

Buildings and transportation account for most cities' global CO2 emissions, which are estimated to be 75% (Programme., 2023). To drastically reduce greenhouse gas emissions, significant changes to the way of planning and building structures and neighborhoods, need to be taken,

How can a GIS based LCA decision making tool help in sustainable urban planning?

- What are the factors contributing to carbon emissions on the neighborhood scale?
- How can LCA be used in assessing greenhouse gas emissions in neighborhoods?
- How is LCA used in the initial stages of design to achieve zero emission neighborhoods?

1.4. Site description

New Obour City is rising to become a shining example of a sustainable city that is still not fully designed and still under construction which complies with the aim of this research (New Urban Authority, 2024). This city presents an opportunity for planners to explore how Life Cycle Assessment (LCA) and Geographic Information Systems (GIS) can be utilized to create neighborhoods that produce zero emissions. New Obour City master plan is all about green living, highlighting features like neighborhoods perfect for walking and abundant green spaces (New Urban Communities Authority, 2024).

2. Method

The empirical data of four sectors have been collected and examined, each sector represents components of the neighborhood: Buildings, Mobility, Infrastructure, and On-site Energy. Beyond its application to this specific case, the model's underlying framework and calculations offer a universal roadmap for conducting LCA studies at the neighborhood level.

The following table was developed after Carine Lausselet and then experts in urban planning were shown the modular framework shown in Table 1, and their insightful comments resulted in several significant improvements. The model's adaptability has been increased by these modifications, making it a potent tool for urban planners operating in a range of environments, particularly in Egypt. Carbon emissions will be calculated using GIS model that integrates LCA stages as follows: Production Stage, Construction Stage, Use Stage, and End of life Stage.

Table 1:LCA Modular Structure (developed after Carine Lausselet by Author, 2024)

LCA PHASES		**PRODUCTION PHASE**			**CONSRUCTION PHASE**		**OPERATION PHASE**			**END OF LIFE PHASE**		
Neighborhood component/ elements	**Ambition Levels**	Source of Raw Materials.	Ship to Manufacturer	Production	Transportation to site	Instalment	Replacement	Maintenance	Energy in operation	Demolition	Waste Processing	Disposal
BUILDINGS	ZEN COME	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
MOBILITY	ZEN O								▨			
INFRASTRUCTURE	ZEN OM	▨	▨	▨			▨	▨	▨			
ON-SITE ENERGY	ZEN OM								▨			

2.1. Modular structure

The LCA model, as illustrated in Table 1, features a modular framework organized around two axes: the different physical components of the neighborhood (such as buildings, transportation, infrastructure, and local energy systems) and the various stages included in the LCA analysis, with relation to the ambition levels which are set according to each physical elements and their emission patterns.

Zero emission neighborhoods indicate the degree of ambition the project needs to reach (Lausselet al. 2019). Table 1 shows the levels that correspond to the different phases in the components of the life cycle for the neighborhood's, to enable a strategy to reach zero emissions. The following is an endorsement of these ambition levels, modified from the ZEB Definition: ZEN O: This represents the lowest ambition level, emphasizing operational emissions, as indicated by the table 1 operation phase elements.

ZEN OM: Expanding upon ZEN O, this level incorporates not only operational emissions, but also the embodied emissions associated with the materials utilized in the neighborhood's construction. This encompasses production phase elements, representing the environmental impact of material acquisition, production, and shipping to site.

ZEN COM: This intermediate level further broadens the scope by integrating the construction phase into the zero-emission ambition. This level accounts for the emissions arising from the construction of infrastructure and structures within the neighborhood.

ZEN COME: Representing the most comprehensive approach, this level encompasses all previously stated modules along with the end-of-life phase. This final level incorporates the environmental impact of demolition and managing materials at the end of the neighborhood's lifecycle (Lausselet et al., 2019).

2.2. *LCA model for New Obour City*

The model will be applied to an under construction residential neighborhood in New Obour City, Cairo, Egypt, a shown in fig 1. This will ensure that the model is applicable to any neighborhood under construction anywhere, if the data needed for the equations are available to be replaced in the model builder designed in ArcGIS Pro.

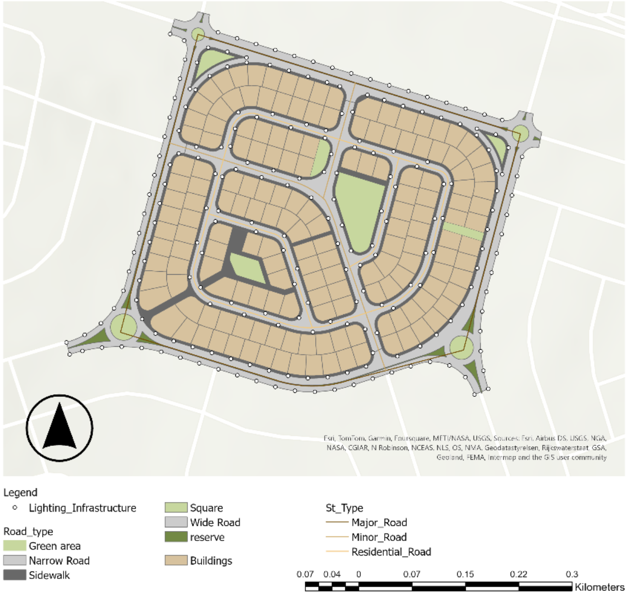

Figure 1: New Obour Neighbourhood Map, (Author.2024)

2.3. *First sector "Buildings"*

For the building sector equations available calculate emissions in all LCA stages such as, emissions from materials in the production and replacements phase, operation phase emissions found in the energy use of the building and the end-of-life phase which is estimated to be after 60 years of the construction of the buildings.

2.3.1. *Production and replacement stages*

Equation 1: Buildings production stage emissions equation (Lausselet,& et al., 2019)

$$Building\ materials\ emissions_{(kgCO2-eq/m2)} = \sum_{bt}\{[\,(E_{mat,prod})_{bt}\cdot A_{bt}] + [\sum_{i=0}^{60}(E_{mat,repl})_{bt,i}\cdot A_{bt}]\}$$

The equation was developed after Carine Lausselet, $E_{mat,prod}$ denotes emissions embodied in the building materials production phase, $E_{mat,repl}$ denotes emissions from materials replacement over 60-

year period of the building life cycle according to each materials lifespan, A is the floor area (m^2) and (bt) represents the building type, in the case study only residential buildings were analyzed.

Table 2: Building materials emissions (Author, 2024)

Building Parts	**Building Components**	**Materials**	**Emissions/m^2**	**Requires replacement ?**
Foundations	Piled foundations	Concrete/steel	270.39	No
Superstructure	Columns	Concrete/ reinforcing steel	250.39	No
Outer walls	Loadbearing/non-loadbearing	Concrete/ reinforcing steel/plaster/paint	359.72	Yes
	Windows/doors	Wood/aluminum/glass		
Inner walls	Non-loadbearing	Concrete/ reinforcing steel/plaster/paint	282.21	Yes
Floor Structure	Loadbearing	Concrete/ reinforcing steel/plaster/sand/tiles	536.52	Yes
Outer roof	Primary construction/roof covering	Concrete/ reinforcing steel/plaster/insulation/gypsum	3.11	No
Stairs	Internal stairs	Steel/gravel/cement	0.93	No

2.3.2. Construction stage

Equation 2 Buildings construction stage emissions equation, (Lausselet,& et al., 2019)

$$Building\ Construction\ emissions = CEF \times A_{bt}$$

CEF denotes construction emission factor embodied in the construction process and transportation of materials to construction site, which is assumed to be 45.1 kgCO2e/m^2 (Zhang et al., 2024), and then multiplied by the area of the building.

2.3.3. Energy use in operation

Equation 3:Buildings use stage emissions, (Lausselet,& et al., 2019)

$$Energy\ use\ emissions\ in\ buildings_{(kgCO2-eq/m2)} = \sum_{bt}\sum_{et} 60[(E_{ei})_{et}\ .\ A_{bt}]$$

The equation was developed after Carine Lausselet, E_{ei} denotes emission intensity of each energy type (*et), A* is the floor area (m^2) and (*bt*) represents the building type, in our case study only residential buildings analyzed, E_{ei} is assumed to be 30 gCo2/m^2 as it is a high residence area.

2.3.4. End of life stage

Equation 4: Buildings end of life stage emissions, (Lausselet,& et al., 2019)

$$Demolition\ Emissions_{(kgCO2-eq/m2)} = \sum_{bm} m(bm)\ .\ EF(bm)$$

A summation of all building materials emissions in this equation according to (*bm*) building materials, (*m*) amount of materials mass(kg), and (*EF*) emission factor for the material.

2.4. Second Sector "Mobility"

For mobility sector equations available calculate emissions only in the use phase as the production and the end-of-life stages are outside the neighborhood variables and the emissions that affect the neighborhood scale is the daily travel of the citizens within the neighborhood and the emissions produced form different vehicle types and how to minimize them.

2.4.1. Energy use in operation.

Mobility emissions are calculated in the use stage only for different fuel types, according to this equation.

Equation 5:Mobility Use stage personal vehicles emissions (Lausselet,& et al., 2019)

$$\begin{aligned} &Personal\ cars\ emissions_{(kgCO2-eq/m2)} \\ &\qquad = 60 \times cars\ avg\ number \times St.length \times avg.\ petrol\ car\ emissions \end{aligned}$$

60 stands for the analysis period of our study, average number of cars per citizens in the neighborhood, which is estimated to be 2 per high residence household in addition to 10% of the total number dedicated to visitors, St. length is the total streets length of the neighborhood, and avg. petrol car emissions is estimated to be 207 gCo2/km for average size petrol engine cars.

Equation 6: Mobility use stage taxis emissions, (Lausselet,& et al., 2019)

$$\begin{aligned} &Regular\ taxis\ emissions_{(kgCO2-eq/m2)} \\ &\qquad = 60 \times avg.passenger\ num \times St.length \times avg.\ emissions/\ passenger\ km \\ &\qquad \times taxis\ avg.num \end{aligned}$$

60 stands for the analysis period of our study, St. length is the total streets length of the neighborhood, avg. emissions/ passengers are estimated to be 161.3 gCo2/km, average passenger number is 2, and taxis average number is assumed to be 45% of residence cars, which is equal to 73.92.

Equation 7: Mobility use stage local mini buses emissions (Lausselet,& et al., 2019)

$$\begin{aligned} &Local\ mini\ bus\ emissions_{(kgCO2-eq/m2)} \\ &\qquad = 60 \times avg.passenger\ num \times St.length \times avg.\ emissions/\ passenger\ km \\ &\qquad \times buses\ avg.num \end{aligned}$$

60 stands for the analysis period of our study, average passenger number is calculated for the worst case scenario of a full bus to be 20 passengers at all times, street length assuming the route for only major roads, average emissions per passenger km is assumed to be 115.8 gCo2/km, and average bus number is assumed that the bus route goes every 30 minutes for 12 hours, then 24 buses pass through the neighborhood.

Equation 8: Mobility use stage motorcycles emissions (Lausselet,& et al., 2019)

$$\begin{aligned} &motorcycles\ emissions_{(kgCO2-eq/m2)} \\ &\qquad = 60 \times emissions/\ km \times St.length \times motorcycles\ avg.num \end{aligned}$$

60 stands for the analysis period of our study, emissions per km is assumed to be 93.9 gCo2/km for medium sized petrol fueled motorcycle, St. length is the total streets length of the neighborhood, and average motorcycle number is assuming that 50% of households have one motorcycle.

2.5. Third sector "Infrastructure"

Understanding the environmental footprint of open spaces requires a two-pronged approach. One equation estimates the greenhouse gases emitted during the construction and upkeep of the physical infrastructure, like pathways and roads. The other equation calculates the emissions associated with electricity usage for tasks like illuminating features.

2.5.1. Product and replacement stage.

Open spaces emissions in the production and replacement stage are calculated regarding emissions from materials used in the infrastructure of the neighborhood roads, using this equation.

Equation 9: Infrastructure Production stage emissions (Lausselet,& et al., 2019)

$$E_{inf,mat\,(kgCO2-eq/m2)} = \sum_{rt} \{[(E_{mat,init})_{rt} \cdot A_{rt}] + \sum_{i=0}^{60} [(E_{mat,repl})_{i,rt} \cdot A_{rt}]\}$$

Table 3: Infrastructure materials emissions, (Author, 2024)

Open Space Category	Open Space components	Materials	Initial Materials Emissions/m^2	Replacement Materials Emissions/ m^2
Wide Road	Lane	Asphalt/gravel/concrete/aggregate	78.57	99.53
	Reserve	Stones/gravel/concrete/aggregate	6.56	0
Narrow Road	Lane	Asphalt/gravel/concrete/aggregate	78.57	99.53
Sidewalk	Lane	Tiles/stones/gravel/concrete/aggregate	27.25	31.35

The equation was developed after Carine Lausselet, $E_{inf,mat}$ denotes emissions embodied in the infrastructure materials in the production stage, $E_{mat,repl}$ denotes emissions from materials replacement over 60-year period of the neighborhood's life cycle according to each materials lifespan, A is the floor area (m2) and (rt) represents the road type, for this specific case study roads analyzed are wide roads, narrow roads and sidewalks.

2.5.2. Energy use in operation.

For the use stage emissions calculated are the emissions of the lighting system of the streets.

Equation 10: Infrastructure use stage emissions (Lausselet,& et al., 2019)

$$E_{lighting,oper\,(kgCO2-eq/Wh)} = \sum_{St} N.I.h.P_{st}$$

The equation was developed after Carine Lausselet, $E_{lighting,oper}$ denotes emissions embodied from lighting system in the neighborhood in the use stage, N denotes number of lighting units, P is the power according to each street type, h is the hours of operation, I is the emissions intensity of electricity per year, for fossil fuel-based neighborhood, emissions per kWh equals 0.00082 kgCO2-eq/Wh.

Table 4: Street lighting calculations, (Author, 2024)

Street Type	Number of lighting /km	Average distance (m)	Power (W)	Emissions (kgCO2eq/Wh)
Residential	15-25	40-60	40-60	0.00082
Minor Road	20-30	30-45	50-80	0.00082
Major Road	30-40	25-30	70-100	0.00082

2.6. Fourth sector "On-site energy"

The analyzed case study reveals a critical dependency on fossil fuels for on-site energy generation within the neighborhood. This reliance translates to substantial emissions accumulating during the use stage of its life cycle. In simpler terms, the way the neighborhood currently obtains and uses its energy significantly contributes to its overall environmental footprint.

2.6.1. Energy use in operation

Energy emissions are calculated by adding emissions from every sector that used energy in its use stage, which for this case are buildings and open spaces.

Equation 11: On-site energy use stage emissions (Lausselet,& et al., 2019)

$$On-site\ energy\ emissions =\ E_{lighting,oper} + Energy\ use\ emissions\ in\ buildings$$

3. Results

Previous research developed complex equations to assess the environmental impact of various neighborhood elements (Lausselet al. 2019). This research showed that for real-world applications, the complex equations are transformed into user-friendly model builders within ArcGIS Pro. These model builders effortlessly connect with digitally drawn neighborhood outlines and precise area measurements, ensuring accurate results tailored to the specific design. Combining all of them ensures accurate calculations for the emissions of each component's LCA phase.

Furthermore, the GIS map drawn automatically creates an attribute table for each drawn item with a unique ID and area of the shape for assembling data in a unique table format. It initiates with an emission value for various building types and materials. Designers are permitted to adjust entries to reflect the materials they intend to use, offering flexibility making it easier for the users to assess their different alternatives and promptly calculate the expected emissions.

The ArcGIS Pro model builder makes complex calculations easy to handle and encourages users to tailor it to their needs, enabling designers and stakeholders to play a hands-on role in developing sustainable neighborhoods.

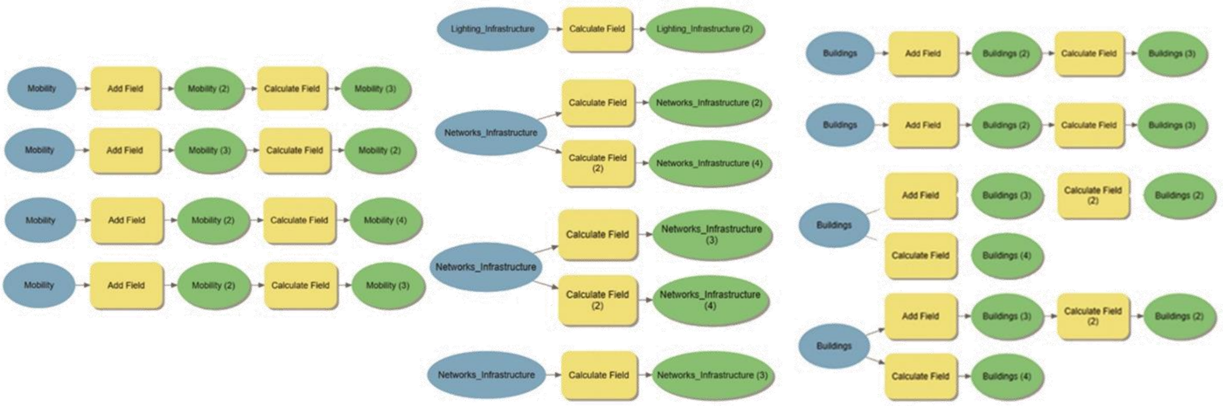

Figure 2: GIS model builder, (Author, 2024)

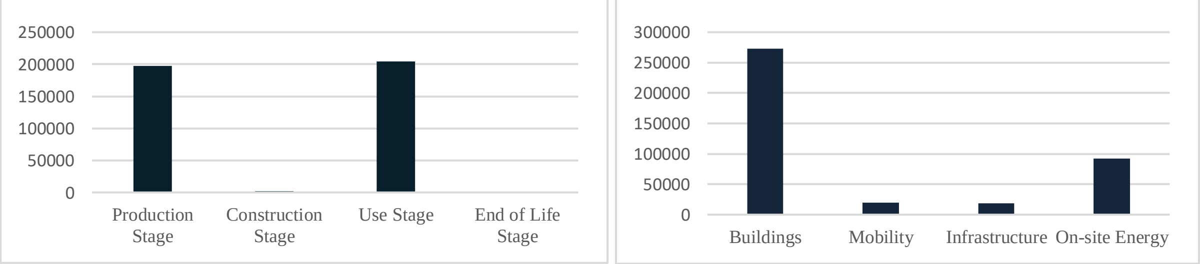

Figure 3: New Obour City neighbourhood emissions, (Author, 2024)

As shown in the bar charts after conducting the model builder equations and calculating emissions for every sector and LCA stage, however, building's end of life stage emissions was not calculated due to shortage of time, fig. 3 shows that buildings contribute to most emissions, tracked by on-site energy. While, for LCA stages the use stage shows most emissions followed by the production phase.

4. Conclusion

Designing eco-friendly neighborhoods requires analyzing various factors contributing to their carbon footprint. Using New Obour City, Egypt as a case study, researchers developed a user-friendly LCA model builder within ArcGIS Pro. This research delved into blending Life Cycle Assessment (LCA) with Geographic Information Systems (GIS) to foster sustainable urban development. Focusing on New Obour City in Egypt as a practical example, the researchers presented an easy-to-use LCA model builder right within ArcGIS Pro, making it accessible for users to explore and apply these concepts by allowing them to gather numerical and statistical data for their design choices and how to achieve the least emission intensive options, aiming for achieving zero emission neighborhoods at the early stages of design, as a way to combat the ongoing increase of environmental impacts over the climate change.

The study identified buildings and on-site energy as the main contributors to emissions, while the "use stage" (ongoing energy consumption) dominated across all sectors. This highlights the importance of focusing on these areas during design to minimize environmental impact. Integrating LCA models early in the design process empowers informed decision-making about materials, layouts, and infrastructure systems, ultimately leading to the creation of more sustainable communities.

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