Life Cycle Analysis of Construction Materials Using LCA Tool

Introduction

This is a Life Cycle Analysis (LCA) Tool that helps analyze and visualize the environmental impacts of products throughout their entire life cycle. The tool is designed to help users understand and quantify the environmental impact of different products and materials, making it useful for environmental assessment, product design decisions, and sustainability planning. The project uses Python and integrates data science libraries to process data from various formats (CSV, JSON) and create comprehensive environmental impact assessments. It's structured as a complete analysis pipeline, from data input through calculations to visualization of results.

Target Dataset and Impact Factors

The project uses a CSV dataset containing product information across different lifecycle stages (manufacturing, transportation, end-of-life) with metrics like energy consumption, transport distance, and waste management rates. A JSON file stores impact factors for different materials (like steel and aluminum) and their environmental impacts at each lifecycle stage, which are used to calculate the total environmental footprint of products. This data structure allows for flexible analysis of different materials and products while maintaining consistent impact calculations.

```
Sample of Product Data (Key Columns):
  product_id          product_name life_cycle_stage material_type  ...  waste_generated_kg  recycling_rate  landfill_rate  incineration_rate
0       P001    Reinforced Concrete    Manufacturing      Concrete  ...               125.0             0.1           0.80               0.10
1       P001    Reinforced Concrete   Transportation      Concrete  ...                 0.0             0.0           0.00               0.00
2       P001    Reinforced Concrete      End-of-Life      Concrete  ...              2500.0             0.1           0.80               0.10
3       P002  Structural Steel Beam    Manufacturing         Steel  ...                25.0             0.9           0.05               0.05
4       P002  Structural Steel Beam   Transportation         Steel  ...                 0.0             0.0           0.00               0.00

[5 rows x 11 columns]

Available Materials: ['steel', 'aluminum', 'plastic', 'paper', 'concrete', 'wood', 'clay', 'glass', 'copper', 'mineral_wool', 'cement']
```

Main Functions Inside the Tool for Impact Calculations

- **calculate_impacts:** This is the main calculation function. It goes through product data row by row (for each life cycle stage) and calculates the environmental impact by combining the raw data (quantity_kg) with the impact factors loaded during initialization. Quantity data in the csv file correctly matches with every impact factor in the JSON file and the result of the multiplications are added to the pre-given impacts which gives a final impact value for every category.

Example Result:

Calculated Impacts (Essential Columns):

	product_id	product_name	life_cycle_stage	carbon_impact (kg CO2e)	energy_impact (MJ)	water_impact (L)
0	P001	Reinforced Concrete	manufacturing	700.0	3870.0	150150.0
1	P001	Reinforced Concrete	transportation	150.0	770.0	0.0
2	P001	Reinforced Concrete	end-of-life	200.0	50.0	50.0
3	P002	Structural Steel Beam	manufacturing	1350.0	10300.0	75200.0
4	P002	Structural Steel Beam	transportation	350.0	2540.0	15000.0

- **calculate_total_impacts:** After the impacts for all the individual stages are calculated, this function sums them up to give a single, total impact score for each product across its entire life cycle.

Example Result:

Total Impacts by Product:

	product_id	product_name	carbon_impact (kg CO2e)	energy_impact (MJ)	water_impact (L)	waste_generated (kg)
0	P001	Reinforced Concrete	1050.0	4690.0	150200.0	2625.00
1	P002	Structural Steel Beam	1850.0	12870.0	90230.0	525.00
2	P003	Engineered Wood Beam	300.0	1205.0	8100.0	105.00
3	P004	Clay Brick	11.0	72.0	112.0	2.75
4	P005	Glass Panel	800.0	3850.0	10115.0	52.50

- **normalize_impacts:** This function scales environmental data (carbon, energy, and water impacts) to values between 0 and 1 by dividing each value by its category's maximum. For instance, carbon impacts of [100, 200, 300] become [0.33, 0.67, 1.0], where 1.0 represents the highest impact and 0.0 the lowest. This makes different environmental impacts directly comparable regardless of their original units.

Example Result:

Normalized Impacts (showing relative scale 0-1):

	product_id	product_name	life_cycle_stage	carbon_impact	energy_impact	water_impact
0	P001	Reinforced Concrete	manufacturing	0.518519	0.375728	1.000000
1	P001	Reinforced Concrete	transportation	0.111111	0.074757	0.000000
2	P001	Reinforced Concrete	end-of-life	0.148148	0.004854	0.000333
3	P002	Structural Steel Beam	manufacturing	1.000000	1.000000	0.500833
4	P002	Structural Steel Beam	transportation	0.259259	0.246602	0.099900

- **compare_alternatives**: The compare_alternatives function takes two specific products from the dataset and compares their environmental impacts. It calculates the percentage difference between them for each impact type (carbon, energy, water), showing how much better or worse one product performs compared to the other. This direct comparison helps identify which of the two selected products has better environmental performance across different impact categories.

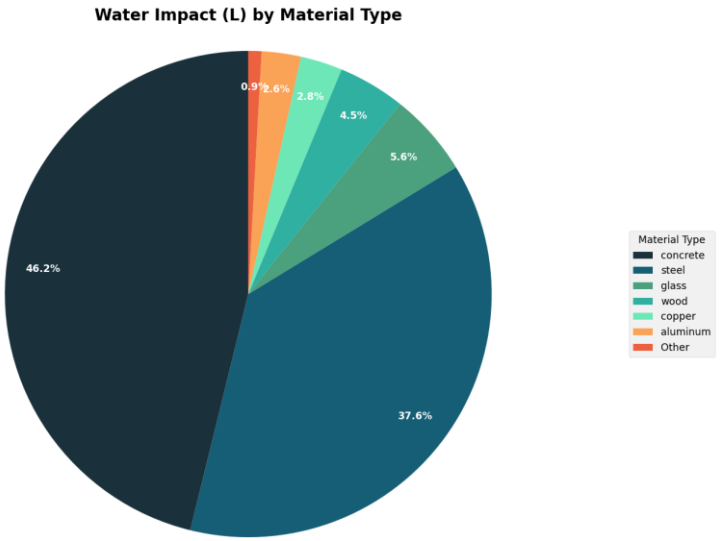
Example Result:

```
--- Product Comparison: Relative Performance (%) ---
     Product  carbon_impact (kg CO2e)_relative_%  energy_impact (MJ)_relative_%  water_impact (L)_relative_%
Plastic Pipe                                0.0                            0.0                          0.0
 Copper Pipe                              146.9                         2075.8                      11465.7
```

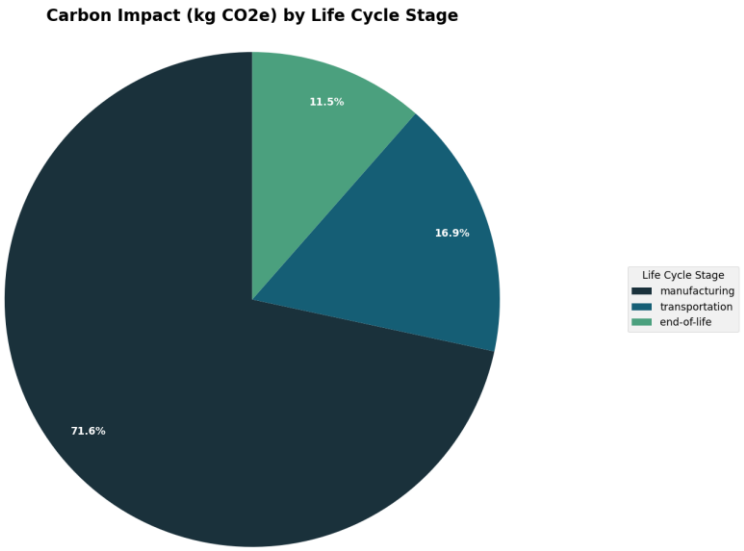
Visualisation Functions and Key Insights

- **plot_impact_breakdown:** Creates a pie chart to show what percentage each category contributes to a specific environmental impact. It groups the data by the chosen category (like material type), sums the type of impact (e.g.., carbon impact) for each group, and then uses matplotlib's ax.pie() function to draw the pie chart with auto-calculated percentages.

Example Result:



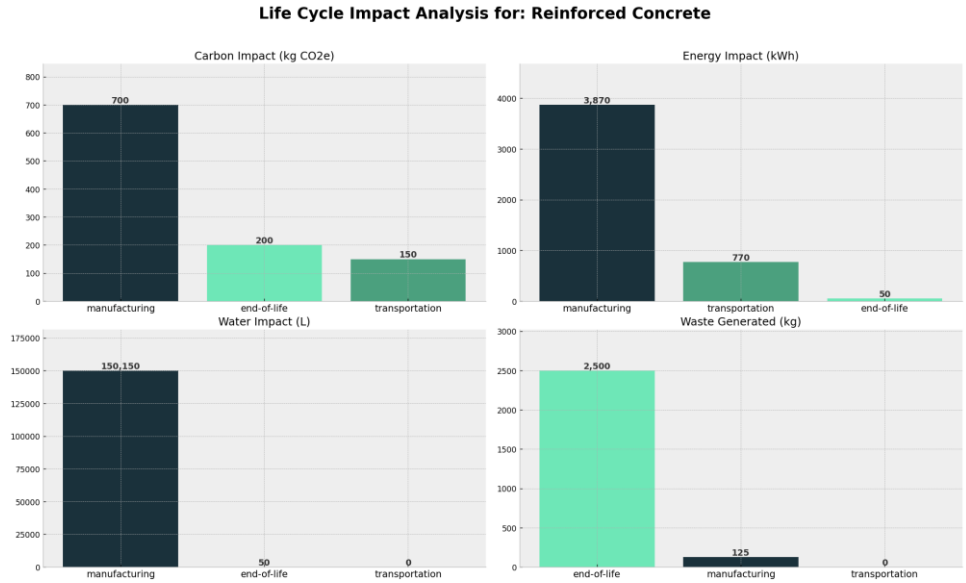
The result shows that concrete and steel are the products that consume the most water throughout their life cycle in this project dataset.



This is another chart shows that the most carbon impact comes from the manufacturing stage in this project dataset.

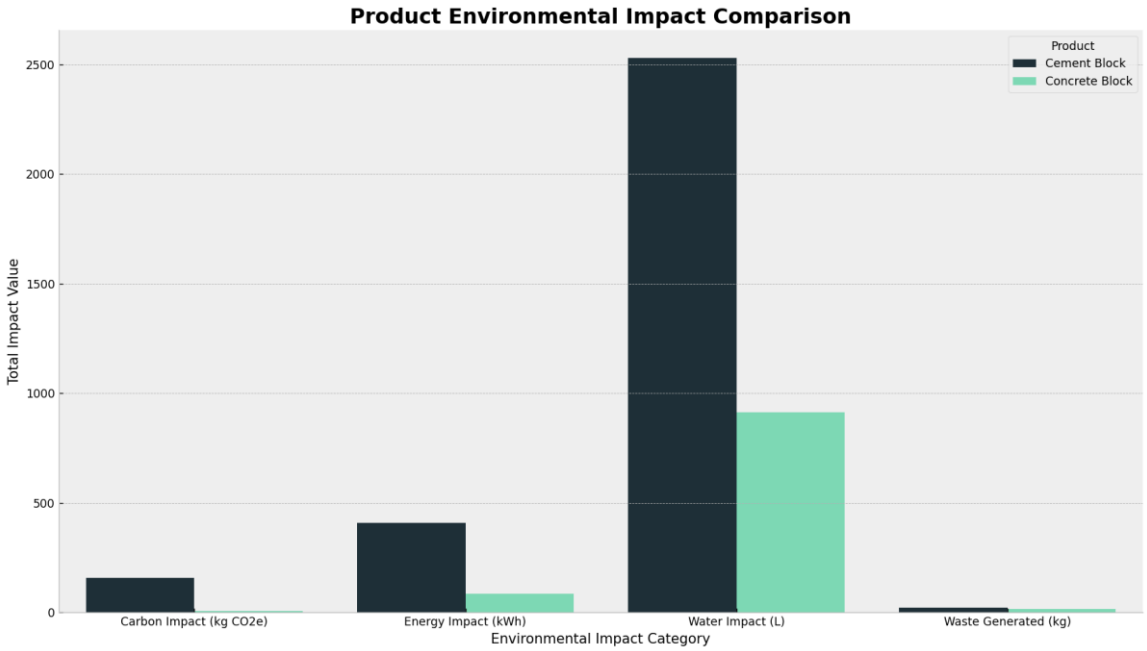
- **plot_impact_breakdown:** This function focuses on a single product and generates a set of bar charts to visualize its environmental footprint. For each impact type it creates a separate chart that breaks down the total impact into its three core life stages. This makes it easy to see which stage of the product's life cycle contributes the most to its overall environmental harm.

Example Result:

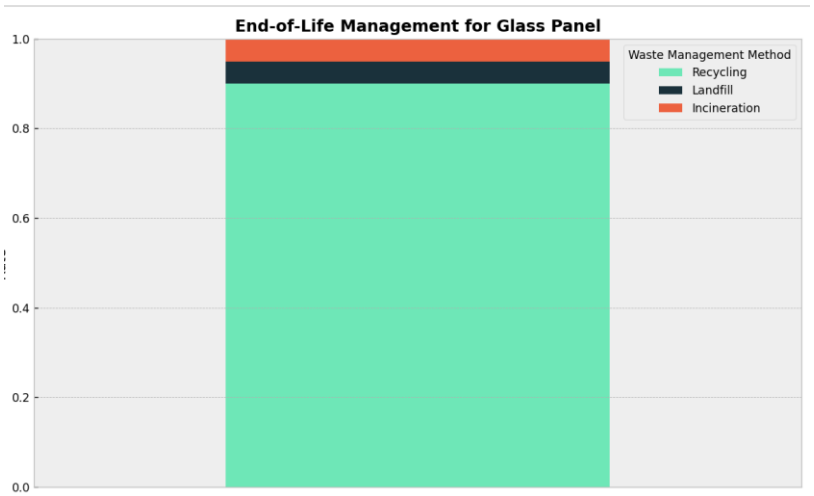


The charts show that main carbon, energy and water impacts come from the manufacturing stage and main waste generation comes from the end-of-life stage for reinforced concrete in this project dataset.

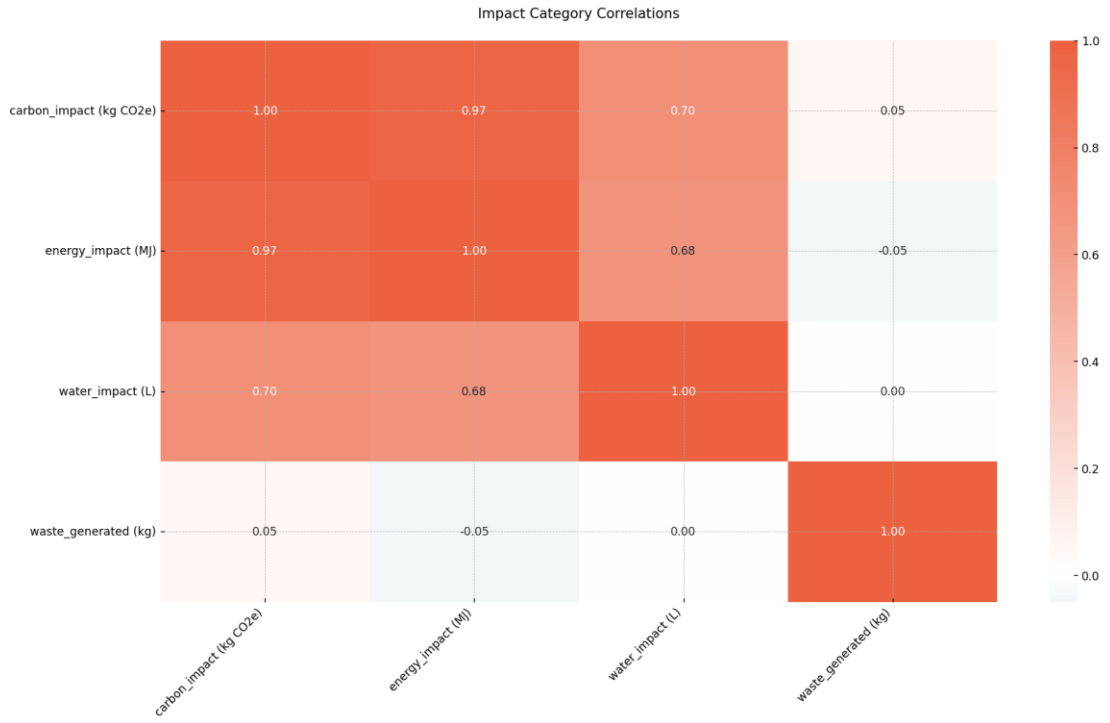
- **plot_product_comparison:** This function directly compares the total environmental impacts of multiple products by generating a grouped bar chart. For each impact category it displays bars for each product side-by-side. This format makes it easy to see at a glance which product performs better or worse in a specific area, providing a clear and straightforward visualization of their relative environmental footprints.



- **plot_end_of_life_breakdown:** The plot_end_of_life_breakdown function creates a stacked bar chart showing how a product's end-of-life waste is managed across different stages. It displays the proportions of waste that are recycled, landfilled, and incinerated, using distinct colors for each management method (green for recycling, dark for landfill, and red/orange for incineration). This visualization helps users quickly understand the environmental sustainability of a product's end-of-life treatment and identify opportunities for improving waste management practices.



- **plot_end_of_life_breakdown:** The plot_impact_correlation function creates a heatmap showing the relationships between different environmental impacts (carbon, energy, water, waste) across all products. It uses a color gradient from white (no correlation) to red (positive correlation), where darker colors indicate stronger relationships. This visualization helps identify which impact types tend to increase or decrease together, making it easier to understand the interdependencies between different environmental factors in the product lifecycle.



Test Functions

The test functions verify that each visualization component works correctly by checking if they return valid matplotlib Figure objects and handle data appropriately. They test various scenarios including impact breakdowns by material and lifecycle stage, product comparisons across different environmental factors, end-of-life waste management visualization, and impact correlations. The tests use sample data with predefined values to ensure the visualizations can process the data correctly and include error handling checks to verify proper response to invalid inputs. Each test confirms that the visualization functions can generate the expected plots without crashing and maintain the correct data relationships in their visual representations.

Test Results:

```
-- Docs: https://docs.pytest.org/en/stable/how-to/capture-warnings.html
========================================================= 14 passed, 6 warnings in 11.19s =========================================================
```

Conclusion

To conclude, Life Cycle Analysis tool evaluates environmental impacts of products by calculating and visualizing carbon emissions, energy consumption, water usage, and waste management across different lifecycle stages. It helps identify sustainable alternatives through impact comparisons and correlations, supporting better environmental decision-making in product development and selection.