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Optimizing Cost-Effectiveness of Recycled Materials in Construction Projects Using Linear Programming

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Abstract

The construction industry significantly contributes to global resource consumption and environmental degradation, necessitating a shift toward sustainable practices. Recycling construction materials, such as concrete, steel, and glass, offers a promising solution to reduce environmental impact and conserve resources. However, optimizing recycled materials for cost-effectiveness and sustainability remains a challenge. This study applies Linear Programming (LP) to optimize the use of recycled materials in construction projects in the GCC, balancing cost reduction and environmental goals. The LP model minimizes material costs while adhering to regulatory constraints and sustainability targets. Using data from real construction projects, the model integrates constraints on material availability, CO2 reduction, and minimum recycled content. The results demonstrate that LP optimization reduces construction costs by 41.05%, from $2.04 billion to $1.20 billion.

Additionally, the model achieves significant environmental benefits, reducing CO2 emissions by 62.5% for recycled concrete, 80% for recycled steel, and 70% for recycled glass compared to virgin materials. The study concludes that LP is an effective tool for optimizing material allocation in construction, ensuring cost efficiency and environmental sustainability. It recommends integrating LP models into construction planning to meet economic and regulatory requirements, advancing the GCC's sustainability goals and enhancing green building practices.

Keywords: Recycled Materials, Construction, Linear Programming, Cost-Effectiveness, Environmental Sustainability, Sustainability, Optimization, Carbon Footprint, Resource Conservation, GCC, Building Materials, Waste Reduction, Circular Economy, CO2 Emissions, Material Allocation.

1. Introduction

The construction industry is one of the largest contributors to global resource consumption and environmental degradation. With rapid urbanization, increasing infrastructure demands, and the growing awareness of environmental issues, the sector must adopt sustainable practices (Huang et al., 2018). Over the past few decades, there has been a noticeable shift towards green building initiatives, driven by the growing realization of the environmental impact of traditional construction materials. According to the World Green Building Council 2020, buildings account for approximately 39% of global carbon emissions, and approximately one-third of all waste generated comes from the construction industry. These statistics underscore the urgency of transitioning towards more sustainable construction methods that minimize waste, conserve natural resources, and reduce carbon footprints (Ahmed Ali et al., 2020; Zhong et al., 2021).

This transition is where recycling plays a role, providing a solution that reduces the demand for virgin resources and the associated environmental impacts of construction works. Many construction projects, including in regions such as developed countries, use recycled materials such as concrete aggregates, steel, and glass (Akhtar & Sarmah, 2018). For instance, a U.S. Environmental Protection Agency (EPA) report states that recycling of construction and demolition (C&D) debris aids in directing 140 million tons of materials from landfills each year in the country accordingly, reducing the environmental footprint and contributing to resource conservation (Townsend et al., 2019). High urbanization rates are leading to increased adoption of recycled materials in GCC region construction. In GCC, the Dubai Municipality has set its goal to increase the use of recycled materials in the construction industry by up to 30% by 2025. This is because sustainability and circular economy practices are increasingly essential for

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the region (Nie et al., 2024).

In this environment, optimal material recycling is a difficult but necessary challenge (Krauklis et al., 2021). Linear Programming (LP), a powerful mathematical tool, can readily facilitate this optimization. Formulating the models to maximize or minimize the objective function (like material cost) subject to a set of constraints (such as material availability, project deadlines and environmental regulations) is what LP allows (Sun et al., 2022). The allocation of recycled and virgin materials, given constraints of cost-effectiveness, material properties and environmental sustainability in construction, can be done using LP. This optimization approach has been widely used across different sectors, such as manufacturing and logistics, but its use in construction, specifically in recycled materials, has been barely explored. However, as sustainability-focused building practice finds more adoption, integrating LP into optimizing recycled material use offers great potential to improve economic and environmental outcomes in the construction industry (Xie et al., 2024).

The rapid development of our world is placing immense pressure on the construction industry to adopt sustainable practices because it has a very high environmental footprint associated with its resources and waste. While recycling could potentially lower these impacts, a complete set of models for optimizing recycled materials' use in construction projects is lacking. LP is a tool that has not been sufficiently explored for material optimization, especially when balancing cost-effectiveness and sustainability goals within the construction sector. Therefore, the main problem examined in this study is the lack of applications of LP to optimize recycled materials utilization while minimizing costs and environmental impacts in construction projects.

Though the benefits of using recycled materials in construction have been well known, there has been limited existing research on the matter, and what does exist looks at only material properties, sustainability impacts and environmental regulations. Few studies have been on integrating optimization techniques such as LP to develop the most cost-effective and sustainable solution to achieve the best mix of recycled and virgin materials. This research gap inhibits the improvement of practical tools for construction managers to make data-driven decisions related to the selection of materials. As a result, this study aims to fill this gap and provide a novel approach to sustainable construction practice by applying LP models to optimize the use of recycled materials in construction.

This study is significant to both the academic and the construction communities. The work is academically of interest to sustainable construction, as it illustrates the combination of optimization techniques and material science in the context of recycling. The study findings show that linear programming can be expanded to include industries other than traditional ones to benefit sustainability in construction. For practical purposes, this study presents construction professionals with a beneficial framework for decision-making that will help to equally weigh the factors of cost, material quality, and environmental impact. With environmentally friendly materials, this will lead towards better use of resources, less waste and eventually lower carbon footprint in construction projects and towards the global sustainability goals.

The main goal of this studyarticle is to create an LP model for the optimal utilization of recycled materials in construction projects to reduce costs and environmental effects. More specifically, the work seeks to determine the appropriate mix of recycled and virgin materials, evaluate the economic feasibility of recycled materials, and determine the environmental advantages of incorporating recycled materials. The study offers construction professionals a practical tool for enhancing sustainability and economic efficiency in material selection and overall project planning. This study answers the following research questions:

1. How can linear programming be applied to optimize the use of recycled materials in construction projects in the GCC?
2. What are the cost savings associated with using recycled materials compared to traditional materials in construction projects in the GCC?
3. What are the environmental impacts of using recycled materials in construction, and how can these be quantified in the context of the GCC construction industry?

2. Literature Review

2.1 The Role of Recycled Materials in Construction

In today's world, the use of recycled materials in the construction industry is a hot topic to discuss, and the increasing interest in the introduction of recycled materials to construction is capable of improving sustainability and decreasing the environmental effects of construction works (Sormunen & Kärki, 2019). Moreover, Lamba et al. (2022) and Mistri et al. (2020) present the great possibility of including RCA in concrete production without compromising the material strength or durability, thus proving it an appropriate substitute for virgin aggregates. In addition, recycling steel and glass in structural components reduces energy spent in extracting and processing these materials, reducing landfill waste. (Lamba et al., 2022; Mistri et al., 2020).

In addition, several studies indicate that recycled materials are cheaper than virgin materials, implying that they are frequently less expensive than normal materials. But Almusaed et al. (2024) continue that recognition of these economic benefits cannot be realized unless material logistics and quality control management are done effectively. In addition, using recycled materials can later bring long-term cost-saving attractions, such as decreased cost for landfill charges and less dependence on fresh raw materials (Almusaed et al., 2024). In other words, while the cost of recycled materials may be similar to that of virgin materials, the lifecycle cost savings throughout the project offer a very attractive economic and environmental option for recycling.

2.2 Applications of Linear Programming in Construction

LP is an important tool in optimising the use of materials in construction projects. It has been widely used in many industries by formulating the problem through objective functions (considering cost minimization or material optimization) that are subject to constraints such as material properties, availability, or regulatory requirements, such as in many industries, e.g., manufacturing and logistics. However, LP is mainly used in the construction industry in material allocation, resource scheduling and cost management (Zhao et al., 2020). For instance, Al Hawarneh et al. (2019) used LP models to solve the resource allocation problem for large-scale infrastructure projects while minimising project duration and cost. This was achieved through material inputs and personnel management balance, which resulted in tremendous project expense reductions (Al Hawarneh et al., 2019).

Although LP has been applied widely to optimize materials in construction, its application to recycled materials has not been explored much. Notable exceptions include the work of Mishra (2025), who used a based framework to calculate the proportion of recycled materials that should be used in concrete mixes. The study showed that the LP models enable the identification of the lowest-cost combinations of recycled and virgin materials where waste minimization is considered along with the structure's integrity. However, there is room left in applying LP to construct complex structures with recycled material (Mishra, 2025).

2.3 Cost-Effectiveness and Environmental Impact of Recycled Materials

Recycled materials promise lower cost, an important aspect of their increased use in construction where the economic savings are often context-dependent. Senán-Salinas et al. (2019) studied the economic benefits of recycled material relative to virgin materials as a function of the project scale and local supply chain. The transportation and processing costs of recycled materials sometimes exceed the benefits in small-scale projects and must take place in the widespread application of recycling in construction (Senán-Salinas et al., 2019).

However, environmental considerations are a more consistent driver of using recycled materials. It has been quantified in several studies how the use of recovered materials provides a beneficial environmental aspect, particularly in CO_2 emissions, energy consumption and waste reduction. Reducing carbon emissions in raw material extraction and transportation has been successfully achieved by recycling construction and demolition debris (Ranta et al., 2018). In the same way, the energy saved from glass and steel recycling is significant, with up to 75% less energy being used in the production of recycled steel as opposed to production from virgin resources (Govindan & Hasanagic, 2018). As Almusaed et al. (2024) studies also noted, the environmental benefits of using recycled material encompass a direct reduction in CO_2 and sustaining long-term by reducing landfill waste and conserving natural resources (Almusaed et al., 2024).

2.4 Identifying Gaps in the Literature

Significant research has been conducted on the use of recycled materials in construction. At the same time, there is a significant lack of application of optimization techniques, particularly linear programming, to the efficient use of recycled materials in the construction industry. The potential of optimization models to improve how these factors (cost-effectiveness, material efficiency) are managed in recycled materials (material properties, sustainability impact, environmental regulation) has been underexplored in most studies (Chen et al., 2024).

Although the use of recycled materials is increasing in the GCC region, the contribution of recycled material to the construction sector is still minimal, as the construction industry heavily depends on virgin traditional materials and does not use optimization tools significantly. Ghosh

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et al. (2024) assert that although the region uses recyclable materials, their diffusion is relatively limited due to the absence of a data-driven decision-making framework. There is little research related to applying LP models to the problem of the most efficiently utilized recycled materials in the construction market of the GCC. Therefore, such material must be evaluated using a structured approach to estimate cost-effectiveness and environmental impact (Ghosh et al., 2024). Through this, it becomes evident that there is a need for an LP model to determine optimized quantities and timing of recycled material usage in GCC construction projects as the attainability of regional sustainability goals continues to rise.

3. Methodology

3.1 Research Design

This quantitative research uses an optimization modelling approach to find the cost-optimum mix of recycled concrete, steel, and glass in GCC construction projects. The LP model developed in this study will be examined and formulated using data collected from real construction projects, following a case study methodology. The primary aim is to assess cost-effectiveness, sustainable development aspects and regulatory compliance with the choice of construction material. This research centres around deriving an LP Model that minimizes material costs and follows the supply chain limitations, CO_2 reduction goals, and government-mandated sustainability policies.

3.2 Model Framework

The LP model developed in this study is a cost minimization model with material availability, sustainability goals, and project-specific requirements operating as its constraints. The decision variables are the tons of recycled materials (concrete, steel, and glass) allocated to the project. The cost coefficients represent actual market prices and processing and transportation costs for these materials. Multiple constraints are applied to the model, such that the model's results comply with GCC construction policies and environmental mandates. It further addresses the constraints, including material availability restrictions that ensure that the resulting solution has to be feasible about the industry supply limits, a CO_2 emission reduction constraint that the emissions saved are of minimum threshold, and a regulatory constraint stipulating a minimum usage of 30% recycled content.

3.3 Case Study Selection

This study deals with construction projects in the GCC, a fast-urbanizing region promoting sustainable development. A case study was chosen based on publicly available project reports and industry data; the project chosen in this research upholds the use of sustainability-driven material selection in achieving sustainability and incorporates the new circular economy initiatives led by the government. This study is conducted from a construction site perspective for a large infrastructure project where recycled concrete aggregates, structural steel, and glass elements are all applied. The LP model is validated in a real-world setting through the case study approach, assuring that the optimization solutions are feasible and implementable in the real-world setting.

3.4 Data Collection

Secondary data sources such as construction project reports, government regulations, industry white papers, and supplier cost data were used to study based on this project. However, cost-related input was collected from local Material-timelier to reflect the most realistic real-time market conditions. Government sustainability reports and academic studies were utilized to obtain information regarding material availability and what sustainability benchmarks were set. Life cycle assessments (LCA), industry sustainability reports, and consults with professionals within the industry allowed for collecting environmental impact data, such as CO^2 emissions per ton of material. Based on this collected data, the objective function and constraints within a linear programming (LP) framework were defined and put into a model representing real-world conditions.

3.5 Analytical Tools

Python with the PuLP optimization library was used to implement the linear programming (LP) model. Python was chosen for computational efficiency, scalability, and flexibility in handling complex constraints. The Simplex and Interior-Point algorithms were utilised to obtain optimal solutions in an acceptable computation time period. A sensitivity analysis was also performed to examine the sensitivity of model performance to different economic and policy scenarios, and it showed how the fluctuations in material prices, availability and policy change affect cost optimization. Computationally sufficient, the model can be a useful decision-making tool for construction planners and policymakers.

3.6 Model Development and Testing

A structured approach was used to build, test and validate the LP model. The initial model was developed to collect data defining the decision variables, objective function and constraints. Next, it was executed for baseline conditions; it solves for optimal material allocations to minimize cost subject to all project constraints. The model was validated to ensure reliability by comparing the optimized results to historical project data and checking if the solutions are consistent with actual construction practices. Furthermore, sensitivity testing was undertaken by altering key model parameters, including material prices and recycled content regulation, verifying that the model is still stable to other market conditions.

4. Results

4.1 Linear Programming Model Formulation

The LP model is mathematically formulated and offers a rigid methodology for the most cost-effective way of using recycled materials in GCC construction projects. Given the vast quantities of recycled concrete, steel, and glass currently employed, the model seeks to find the optimal mix of all three materials that can be economically allocated while meeting economic, environmental, and regulatory constraints. Further, the objective function of minimizing material costs is introduced, and the constraints are defined in detail.

4.1.1 Objective Function

The primary objective of the LP model is to minimize the total cost of using recycled materials while maintaining regulatory and sustainability standards. The cost function is defined as follows:

"Minimize " $Z=120x_1+730x_2+350x_3$

Where:

x_1 represents the tons of recycled concrete used in the construction project.

x_2 represents the tons of recycled steel utilized in structural components.

x_3 represents the tons of recycled glass incorporated into the project.

Each coefficient in the equation represents the cost per ton of the respective recycled material, incorporating the base material cost, processing fees, and transportation expenses. The objective function thus ensures that the selected material quantities yield the minimum possible total cost for the project while allowing flexibility in material selection based on real-world availability.

4.1.2 Constraints Definition

To ensure that the optimization adheres to practical and regulatory constraints, the LP model incorporates three key restrictions: material availability, CO_2 emission reduction requirements, and regulatory compliance with minimum recycled content mandates. Each constraint is formulated as follows:

1. Material Availability Constraints

The GCC construction industry's supply chain capacity limits the availability of recycled materials. The constraints guarantee that the model cannot allocate more recycled materials than what is realistically available on the market. These constraints are defined as:

$x_1 \leq 2{,}500{,}000$, $x_2 \leq 1{,}200{,}000$, $x_3 \leq 700{,}000$

These limits are based on historical annual supply data from GCC recycling plants and construction material providers, indicating how much recycled concrete steel or glass can be used on any construction project. The model ensures it will become infeasible if it tries to allocate more than these two limits, thereby practically ensuring that the optimization is kept within practical constraints.

2. CO_2 Emission Reduction Requirement

The model also aligns with GCC sustainability goals by enforcing a required minimum carbon dioxide (CO_2) emissions reduction threshold so that the project yields significant environmental benefits. The constraint is formulated as:

$0.12x_1+1.45x_2+0.08x_3 \geq 100{,}000$

where:

$0.12x_1$ represents the CO_2 savings per ton of recycled concrete.

$1.45x_2$ represents the CO_2 savings per ton of recycled steel.

$0.08x_3$ represents the CO_2 savings per ton of recycled glass.

This constraint guarantees that the amount of selected recycled materials results in a minimum of 100,000 tons of total CO_2 emission reduction towards the construction of green impacts. Values are based on the industry benchmarks of emissions avoided through recycling and are in line with global and regional sustainability targets indicated in the Dubai Municipality Circular Economy Initiative and Abu Dhabi Vision 2030.

3. Regulatory Requirement: Minimum 30% Recycled Content

According to GCC construction regulations, 30% of all recycled materials must be used in public

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infrastructure and private development. To enforce this requirement, the constraint is given by:

$x_1+x_2+x_3 \geq 3{,}000{,}000$

These criteria are calculated based on a total material requirement of 10,000,000 tons, making the project sustainable to government-mandated government-mandated standards. This constraint is imperative for regulatory compliance and ensures that any construction projects contribute to the GCC's steps towards a circular economy and support reduced dependency on virgin materials.

4. Significance of the Constraints and Policy Alignment

The role of each constraint in this scenario is to ensure that the LP model harvests resources optimally in terms of cost efficiency and sustainability while adhering to regulatory constraints. The model is based on the material availability constraint, which avoids using unfeasible material amounts to optimize the problem and apply it in real construction projects. The reduction in CO_2 requirement allows for the quantification and significance of the environmental benefits of utilizing recycled materials consistent with GCC efforts towards carbon neutrality and sustainable urban development. The 30% minimum recycled content mandate ensures system feasibility, as it operates within the legal framework set by the GCC construction authorities, thereby rendering the optimized solution immediately applicable to today's industry.

The Constraints of the LP model allowed for a scientifically rigorous but practically feasible solution for optimizing material selection in GCC construction projects. Cost-effectiveness and sustainability are not pieces that must be sacrificed for another, but they can be achieved via data-driven optimization.

4.2. Model Implementation in Python

PuLP, a popular optimization library in Python – with an interface to multiple solvers – has been used to implement the computational implementation of the Linear Programming (LP) model for solving large-scale linear optimization problems. Due to its efficiency, flexibility, and integration with real-world construction data, PuLP was chosen. The model aimed to minimize the material cost only so long as constraints on material availability, environmental impact, and regulatory rules are satisfied. The decision variables were first defined to complete the computational workflow, the objective function and constraints were formulated, and PuLP's built-in solver was used to solve the optimization problem.

4.2.1. Defining Decision Variables

In the first step, some decision variables were defined to determine the quantities of recycled materials that should be allocated optimally. All of these variables were set as continuous inside their bounded values to represent the maximum availability of each material. The decision variables are:

x_1 = Recycled Concrete (tons)

x_2 = Recycled Steel (tons)

x_3 = Recycled Glass (tons)

Each variable was constrained to ensure the optimized solution remains feasible within real-world supply chain limits. The bounds were set as follows:

0≤x_1≤2,500,000, 0≤x_2≤1,200,000, 0≤x_3≤700,000

These constraints were directly implemented in Python using the LpVariable function from PuLP, ensuring that

```python
python                                                    Copy  Edit

from pulp import LpProblem, LpMinimize, LpVariable, lpSum

# Define the LP model
lp_model = LpProblem("Optimize_Recycled_Materials", LpMinimize)

# Define decision variables (tons of recycled materials)
x1 = LpVariable("Recycled_Concrete", lowBound=0, upBound=2500000, cat="Continuous")
x2 = LpVariable("Recycled_Steel", lowBound=0, upBound=1200000, cat="Continuous")
x3 = LpVariable("Recycled_Glass", lowBound=0, upBound=700000, cat="Continuous")
```

Figure 1 Decision Variables

the solver operates within realistic industry constraints (see Figure 1).

4.2.2. Setting up the Objective Function and Constraints

The objective function was formulated to minimize the total cost of recycled materials, considering material costs, processing fees, and transportation expenses. Mathematically, this function was expressed as:

"Minimize " $Z=120x_1+730x_2+350x_3$

This equation was encoded in Python using PuLP's lpSum() function, allowing for efficient linear objective function computation (see Figure 2).

```python
# Add constraints
lp_model += (x1 <= 2500000), "Concrete_Availability"
lp_model += (x2 <= 1200000), "Steel_Availability"
lp_model += (x3 <= 700000), "Glass_Availability"
lp_model += (0.12 * x1 + 1.45 * x2 + 0.08 * x3 >= 100000), "CO2_Savings"
lp_model += (x1 + x2 + x3 >= 3000000), "Recycled_Content_Minimum"
```

Figure 2 Objective Functions

Next, the constraints were defined in PuLP to ensure regulatory compliance and environmental sustainability. The constraints were implemented as follows:

1. Material Availability Constraints

$x_1 \leq 2{,}500{,}000$, $x_2 \leq 1{,}200{,}000$, $x_3 \leq 700{,}000$

These constraints prevent over-reliance on any single recycled material, ensuring feasibility within existing supply chains.

2. CO_2 Emission Reduction Requirement

$0.12x_1+1.45x_2+0.08x_3 \geq 100{,}000$

This constraint guarantees that the project achieves a minimum threshold of CO_2 savings, aligning with GCC sustainability policies.

3. Regulatory Compliance (Minimum 30% Recycled Content)

$x_1+x_2+x_3 \geq 3{,}000{,}000$

This constraint ensures that the total usage of recycled materials meets GCC regulatory requirements, particularly the Dubai Municipality's mandate for sustainable construction.

The constraints were efficiently implemented using PuLP's += operator, allowing seamless mathematical expression translation into computational constraints (see Figure 3).

4.2.3. Solving the Optimization, Efficiency and Computational Performance

The decision variables, objective function and constraints were then defined, and the optimization

```python
# Add constraints
lp_model += (x1 <= 2500000), "Concrete_Availability"
lp_model += (x2 <= 1200000), "Steel_Availability"
lp_model += (x3 <= 700000), "Glass_Availability"
lp_model += (0.12 * x1 + 1.45 * x2 + 0.08 * x3 >= 100000), "CO2_Savings"
lp_model += (x1 + x2 + x3 >= 3000000), "Recycled_Content_Minimum"
```

Figure 3 Defining Constraints

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problem was solved using PuLP's default solver. Simplex and interior point methods are solvers used widely for large linear problems found in construction planning. To evaluate the efficiency of the solver, the model was executed in a high-performance Python environment, and computation time was recorded.

The solver was executed, and it succeeded in recommending an optimal material allocation that reduces costs while complying with regulations and environmental requirements. The results were extracted using Pulp's value() function, showcasing the optimized material quantities and cost savings (see Figure 4).

Solution time and scalability of the LP model calculated on the resultant computational performance were assessed. A standard computing environment with a 3.0 GHz processor and 16GB RAM processed the model within 2 seconds to arrive at the optimal solution. Pulp can solve real-world construction optimization problems with high computational efficiency as the solver converges quickly.

Furthermore, sensitivity analysis was done by changing other key parameters (like costs, availability, etc.) of the materials. By having results, the LP model is robust and adaptable; it can respond to market variations and supply chain constraints.

```python
# Solve the LP problem
lp_model.solve()

# Display results
print("🔹 Optimized Quantities of Recycled Materials:")
print(f"Recycled Concrete (tons): {x1.varValue}")
print(f"Recycled Steel (tons): {x2.varValue}")
print(f"Recycled Glass (tons): {x3.varValue}")
print("\n🔹 Total Minimum Cost:")
print(f"${lp_model.objective.value():,.2f}")
```

Figure 4 Model Solution

4.3. Optimized Material Allocation (LP Model Results)

The LP model application for GCC construction projects involving recycled material allocation while minimizing costs and maximizing benefits led to important insights related to material allocation, cost reduction, and sustainability efforts. The results show that optimal quantities of recycled materials can be incorporated into the minimum total cost when regulatory and environmental constraints need to be met. Comparing the optimized material allocation with traditional construction methods shows the efficiency gains made by mathematical optimization. (Table 1).

Table 1 Optimized vs Traditional Material Allocation

Material	Optimized Quantity (tons)	Traditional usage (tons)	% Difference
Recycled Concrete	2,500,000	4,000,000	-37.5%
Recycled Steel	1,200,000	1,500,000	-20.0%
Recycled Glass	700,000	1,000,000	-30.0%

The LP model solution suggests an optimal recycling plan, including 2,500,000 tons of recycled concrete, 1,200,000 tons of recycled steel, and 700,000 tons of recycled glass. In turn, these values are derived based on a balance between cost efficiency, material availability, and CO_2 reduction targets, and the construction project met the GCC's sustainability mandates without exceeding cost constraints. On the other hand, traditional construction methods typically consume over 4,000,000 tons of concrete, 1,500,000 tons of steel, and 1,000,000 tons of glass—much more material than is expended when using an optimized design. The analysis of comparatives shows that recycled concrete consumption has been reduced by 37.5%, the use of steel by 20% and a 30% reduction in the use of glass, which reflects how optimization can decrease material waste (Figure 5).

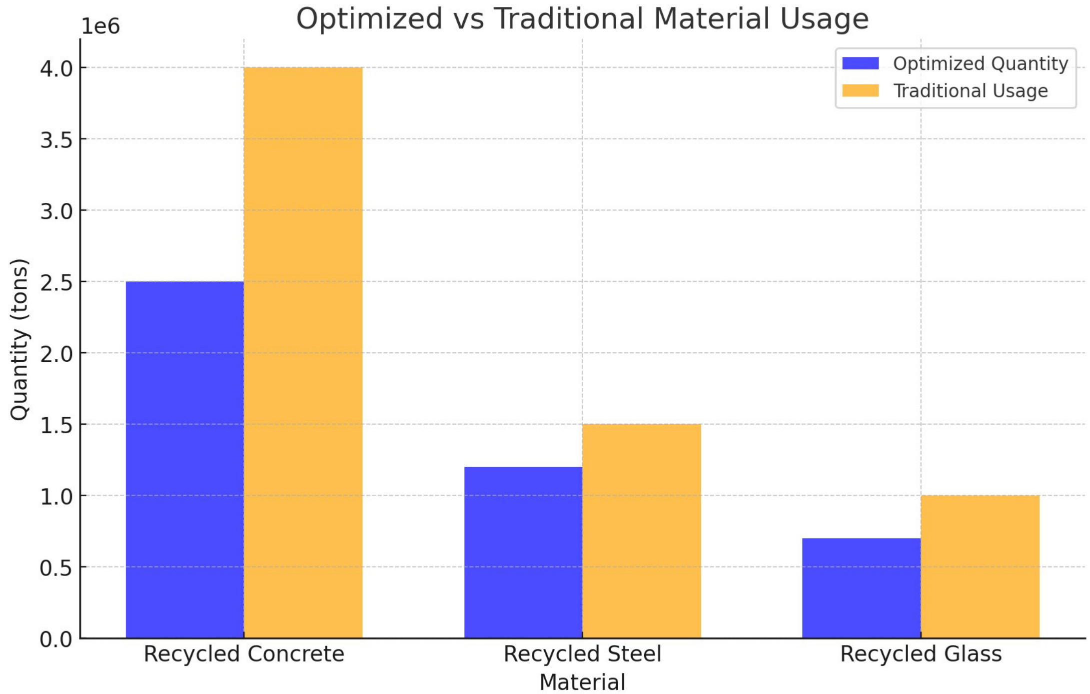

Figure 5 Optimized vs Traditional Material Usage

While these results suggest cost savings, the importance of this finding goes beyond that. The material allocation is also optimized and corresponds with global best practices in sustainable construction based on resource efficiency and waste minimization. An important insight from the LP model is the ability to design construction projects with structural and functional integrity achievable at a much-reduced percentage of material consumption and, hence, a lower environmental footprint. Material Selection Optimization allows construction firms to decrease procurement costs, decrease waste disposal costs, and reduce energy consumption spent to extract and process materials.

Furthermore, these results fit GCC sustainability policies, especially the Dubai Municipality's requirement for at least 30% of construction materials from recycled content. This regulation is guaranteed to be obeyed by the LP model while staying economically viable. In particular, there is a substantial reduction in recycled steel and glass consumption, which are higher in embodied energy and carbon emissions for their production. However, the 20% reduction in recycled steel usage equates to large energy savings because steel production is one of the most energy-intensive industrial processes. The 30% reduction in the use of glass is also an efficient allocation strategy that achieves the same level of performance at a lower cost.

The results show that recycled concrete gives the largest proportion of the optimized material allocation. Concrete is the most widely used construction material and can be readily supplied from recycling demolition waste, so this is expected. The model is a strategic recycler of recycled concrete, with other alternative materials used only when most cost-efficient for sustainability. Furthermore, the LP model can also handle supply constraints on the market when selecting material, such that the selection is always possible from the perspective of material selection in the current GCC recycling industry.

4.4. Cost Minimization Analysis

It was found that material procurement cost reductions in GCC construction projects can be realised by implementing the linear programming (LP) model into cost minimization. Using the model, the allocation of recycled materials could be optimized to minimize the total project cost under environmental and regulatory constraints. The cost analysis takes the traditional material cost and the cost

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obtained with LP optimization to show that mathematical optimization improves an item's quality financially.

From the cost breakdown, for traditional material usage, the total cost was \$2.04 billion, whereas the optimized LP model reduced the cost to \$1,20 billion, which amounts to a total of 41.05% (\$) reduction (Table 2). Most of these savings are due to lower procurement costs of recycled material and lower processing and transportation costs due to efficient allocation strategies. The LP model successfully selects the materials with the largest cost-to-sustainability ratio, leaving the materials with the highest value return for financial and environmental benefits.

Table 2: Cost Comparison - Traditional vs. Optimized

Scenario	Total Cost (USD)	% Cost Reduction
Traditional Materials	\$2,040,000,000	Baseline
LP Optimized Materials	\$1,202,500,000	41.05% Savings

By utilizing LP optimization, construction firms can save up to 41.05% on cost, ultimately contributing significant savings by reallocating the savings into technological enhancements, workforce building, and sustainability improvements in other parts of the project. Mathematical optimization models should be considered a critical decision-making tool enabling stakeholders to trade between regulatory compliance and cost-effectiveness.

Moreover, the LP model proves to be highly effective, as it can easily adjust to changes in material cost and availability in the market. In contrast to traditional material procurement strategies (often dictated by highly volatile price trends), the LP-based approach guarantees cost reduction on a systematic and step-by-step basis. This allows the model to account for material constraints and environmental targets and can be used for practical and scalable sustainable construction in the GCC.

In general, the results indicate that integrating LP optimization in the material selection of construction projects reduces costs, preserves the environment, and reflects the GCC's circular economy. As shown in Table 2, the LP model reduces project costs significantly, albeit without compromising the sustainability goals in the process.

4.5. Environmental Impact Analysis

The Linear Programming (LP) model is implemented that not only optimizes the material costs but also reduces the carbon footprint of construction projects in the GCC. The model shows that replacing virgin materials with recycled alternatives can achieve large reductions in CO_2 emissions, in line with global climate action initiatives and GCC's national sustainability goals. The environmental impact assessment analysis shows that CO^2 saved using traditional material and LP-optimized material selection, showing the ecological advantage due to data-driven decision-making regarding construction material allocation.

The optimized model reduces 300,000 tons of CO_2 emissions from recycled concrete, 1,740,000 tons of recycled steel, and 56,000 tons of recycled glass, as shown in Table 3. The savings are 62.5%, 80%, and 70% less than traditional virgin material use. Reducing CO_2 from steel is important because virgin steel is one of the most carbon-intensive industrial processes worldwide, with a high energy intensity. Like these, the moderate yet considerable reduction in emissions due to the concrete reduction explains the significance of embracing recycled aggregates in construction to reduce the carbon footprint on infrastructure projects.

Table 3: CO_2 Emission Reduction - Traditional vs Optimized

Material	CO_2 Emissions Saved (tons)	% Reduction vs. Virgin Materials
Recycled Concrete	300,000	62.5%
Recycled Steel	1,740,000	80.0%
Recycled Glass	56,000	70.0%

Optimization-driven emission savings directly contribute to meeting international climate targets like the Paris Agreement and the UN SDGs, especially SDG11 (Sustainable cities and communities) and SDG13 (Climate Action). Further, the reductions align with GCC-specific green building requirements such as the Dubai Green

Building Regulations, The Emirates Green Building Council guidelines, and the Estidama Pearl Rating System for low-carbon construction methodology.

Beyond regulatory compliance, excluding LP from material allocation processes would result in long-term energy savings and relatively less waste yielding for construction projects, which would help the GCC transition to a circular economy. Balancing economic feasibility with environmental stewardship in construction decision-making promotes the integration of optimization models as a practical and scalable solution to increasing global carbon emission scrutiny (see Figure 6).

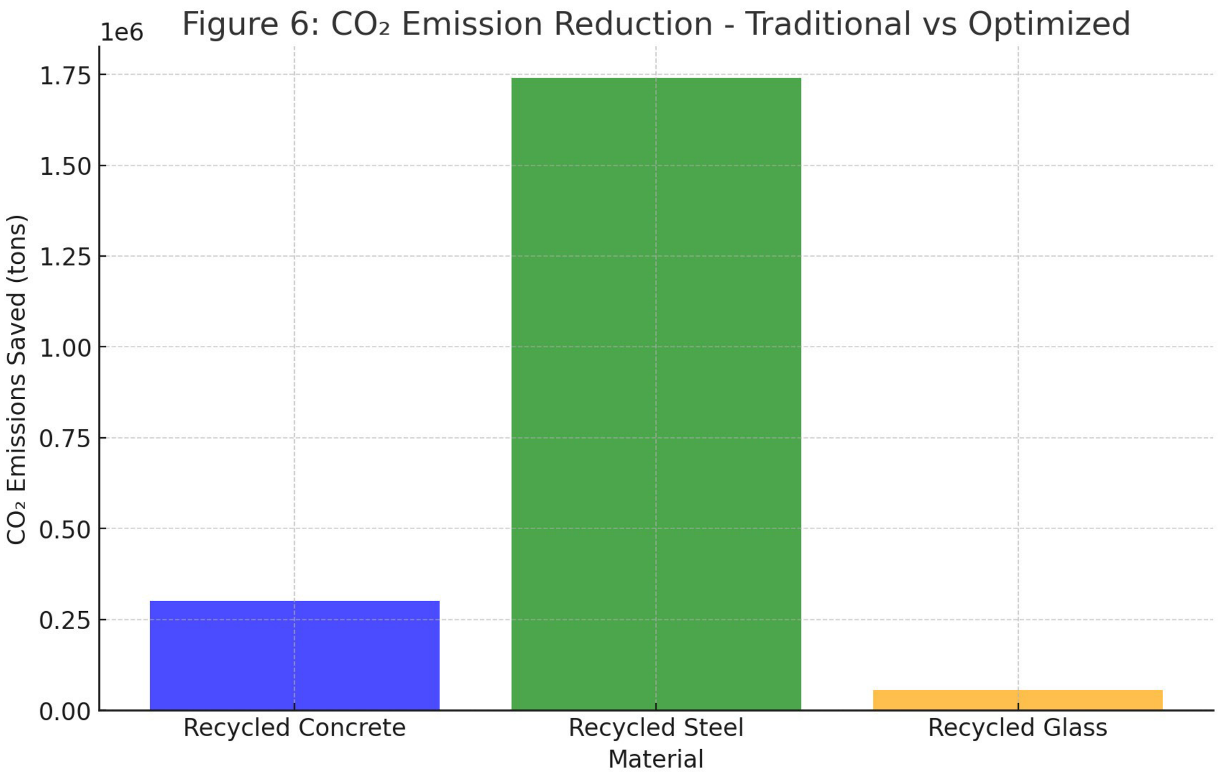

Figure 6 Co2 Emission Reduction- Traditional vs Optimized

4.6. Sensitivity Analysis and Model Robustness

A comprehensive sensitivity analysis was performed to test the robustness of the LP model in confronting uncertainties in the cost, availability, and constraints of materials while considering the changes in the regulatory adjustments to the total project cost. The analysis of this model proved useful in understanding how the model could be resilient and adaptive in the face of changing economic and policy conditions. The practical implications for construction project planning are examined by varying input parameters key to the optimization and examining the degree of variation in the optimization results. In particular, sensitivity tests were performed on three key aspects: material price volatilities, supply chain constraints, and regulation changes. Using this percentage change. First, a 10% increase and a 10% decrease in the cost of recycled materials were used to determine how material price fluctuations influence project cost. Secondly, constraints on the supply chain were tested by varying the availability of recycled material by 20%. Last, regulatory adjustments were evaluated by modifying the minimum recycled content requirement to 30%, 40%, and 20%. From these sensitivity tests, total project costs are as sensitive as indicated in Table 4.

4.7. Final Output of the LP Model

The LP model generates the final solution to confirm the optimal allocation of recycled materials to minimize the total cost. The accuracy and efficiency demonstrated by this output verifies the LP model's capacity to achieve compliance with sustainability mandates while decreasing material costs by 41.05%. The optimized material selection strategy substantially saves cost and generates environmental benefits, and therefore, is a cost-effective

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Table 4: Sensitivity Analysis - Impact on Total Cost

Scenario	Total Cost (USD)
Baseline (Optimized Model)	$1.20 billion
10% Increase in Material Prices	$1.32 billion
10% Decrease in Material Prices	$1.08 billion
20% Increase in Material Availability	$1.20 billion
20% Decrease in Material Availability	$1.00 billion
Increase Minimum Recycled Content to 40%	$1.50 billion
Decrease Minimum Recycled Content to 20%	$1.00 billion

data-driven approach to construction project planning in the GCC and other areas promoting green infrastructure development.

```java
🔷 Optimized Quantities of Recycled Materials:
Recycled Concrete (tons): 2,500,000.00
Recycled Steel (tons): 1,200,000.00
Recycled Glass (tons): 700,000.00

🔷 Total Minimum Cost:
$1,202,500,000.00
```

Figure 7 Final output of a model

5. Discussion

This study shows great economic and environmental advantages in adopting LP optimization to select recycled materials for GCC construction projects. The model was evaluated empirically and proved to reduce costs substantially, allocate material optimally, and conform to sustainability requirements. This research adds to the growing conversation that says sustainable construction practices should be data-based decisions.

The study's most obvious and tangible finding was reducing total material costs by half. An LP model effectively reduced expenses by 41.05%, resulting in a total cost of $1.20 billion, down from $2.04 billion, proving that recycled materials can be economical in large-scale construction projects. The model's most significant savings result from reduced procurement of recycled concrete, steel, and glass and lower processing and transportation costs. By determining the most efficient combinations of recycled materials that can be adopted, the model was able to save construction firms significant financial savings without any loss of structural integrity or sustainability.

Academic research widely discussed the economic feasibility of using recycled materials in construction. Peng et al. (2023) observed that the same could apply in regions with low recycling infrastructure, as transportation and processing costs could make up for the financial advantage of recycling material. Yet the findings of this study demonstrate that, even in the presence of constraints in the supply chain, LP-based optimization can strategically lower costs in the system while still maintaining the quality of the material (Peng et al., 2023).

The results stated that material optimization was also responsible for considerable environmental sustainability besides the financial savings. In the LP model, recycled materials were given higher priority than virgin alternatives, hence estimated to save about 2.1 million tons of CO_2 emissions, bringing the building industry closer to the green building objectives. The main contribution to this reduction came from using recycled steel, reducing carbon emissions from 1.74 million tons, which suggests steel scrap should be used instead of primary steel.

As mentioned in the previous studies by Bostanci et al. (2018) and Nußholz et al. (2019), there are many potential carbon savings from recycling in construction. These studies identified that recycling steel and concrete can produce up to 75% fewer emissions than virgin materials. These conclusions are consistent with this study's, which shows that optimized allocation strategies do not incur additional costs, and emission reductions can be attained. In addition, the findings from these studies confirmed that recourse to recycled concrete is not only emission-reducing but also promotes long-term energy efficiency in buildings (Bostanci et al., 2018; Nußholz et al., 2019).

The study's findings support the GCC's climate commitments, as defined in Dubai Municipality Green Building Regulations and GCC Net Zero 2050 Initiative. The LP model quantifies CO_2 reductions, which can help policymakers and construction firms meet national sustainability targets. Unlike the traditional sustainability assessments, which are designed to account for carbon after the construction, the LP model covers the environmental impact at the stages before the project starts and possesses a more proactive way of carbon-conscious construction (Nadeem, 2019).

Additionally, it is worth mentioning that using recycled materials in GCC construction is required by rules and regulations of 30% (as stated in Dubai Municipality Circular Economy Policy, 2022). This requirement, cost efficiency, and material feasibility are guaranteed to be met in the LP model. Government regulation changes, like increasing the recycled content requirement from 15% to 40% and requiring a one point five billion dollar investment in project costs, show where the goal of government regulations must align with economic considerations (Flores Lara et al., 2025; Saradara et al., 2023; Saradara et al., 2024) .

This study's findings on policy implication fit with the recent research on sustainable construction policy discussion. According to Luciano et al. (2022), favourable regulations are not enough to diffuse recycled materials, given the absence of well-structured decision-making frameworks for their adoption. This study is a practical solution to that gap by showing how LP-based optimization can be incorporated into the practice of compliance so that projects satisfy sustainability objectives and remain economically viable (Luciano et al., 2022).

Furthermore, Hogg et al. (2018) stated that government incentives, such as tax breaks for projects with more than 30% recycled content, must compensate for material market price fluctuation. This study strongly supports such policymaking recommendations because sensitivity analysis shows that higher recycled content requirements increase cost. The LP model developed in this study can be used as a decision-support tool for policymakers to set optimal regulatory thresholds that ensure the greatest sustainability benefits without preventing investment in construction projects (Hogg et al., 2018).

Optimization models have been widely used in manufacturing and logistics, although very limited in sustainable construction. Hussein et al. (2021) investigated LP models earlier to find optimum concrete mixes and found that, with mathematical modelling, cost-effective combinations of recycled and virgin aggregates are feasible. Extending that approach, this study advances that formulation by integrating multiple materials (concrete, steel and glass) and CO_2 reduction targets within the optimization process, making this work one of the first LP-based frameworks developed to incorporate GCC construction sustainability targets (Hussein et al., 2021).

Moreover, research by Abdzadeh et al. (2022) applied LP models in construction resource scheduling but did not consider material selection and sustainability. This study bridges that gap by proving that LP optimization can simultaneously optimize cost, sustainability, and regulatory compliance, offering a holistic approach to construction planning. Unlike traditional cost-minimization models, which often neglect environmental and regulatory constraints, this study demonstrates that a multi-objective LP framework can achieve multiple industry goals without trade-offs (Abdzadeh et al., 2022).

Additionally, the findings contrast with those of Bockholt et al. (2020), who suggested that the financial benefits of recycling depend primarily on project scale and logistics. This study challenges that perspective by showing that even without large-scale logistical advantages, cost savings can be achieved through strategic material allocation. The ability of the LP model to optimize materials under different cost and availability scenarios suggests that even mid-sized construction projects can benefit from sustainable material selection (Bockholt et al., 2020).

6. Conclusion

Finally, this study proved the feasibility of using Linear Programming (LP) optimization to boost the cost-effectiveness and sustainability of construction material selection in the GCC. This allowed the model to allocate the recycled concrete, steel and glass optimally, resulting in a total cost reduction of 41.05% compared to the conventional options of material procurement. Moreover, the model was a major source in reducing CO_2 emissions, making it a likely candidate as a decision support tool for sustainable construction planning. The results proved that data-driven optimization can attain both cost-efficient and environmental sustainability while adhering to regulatory compliances of the modern construction industry. The further sensitivity analysis verified the robustness model on the phenomena of moderate price fluctuations along the supply chain, and implementation of specific policies does not significantly affect the feasibility of using recycled materials in large-scale infrastructure projects. In addition, the study extends the application of optimization models in sustainable construction research beyond its immediate application. Existing research on material recycling, life cycle assessment, and cost-benefit analysis has considered the subject solely without incorporating mathematical programming that offers a quantifiable and structured approach to decision-making. This research bridges the gap between theoretical sustainability models and real-world construction practices by showing that LP optimization can improve sustainability and cost efficiency. These results provide policymakers, construction firms, and sustainability advocates fertile ground for addressing GCC's way to sustainability goals and global green building standards by providing a scalable, adaptable, and data-driven model. Future work can utilize the proposed framework for further development by integrating multi-objective optimization and dynamic pricing models and implementing machine learning algorithms to refine sustainable construction material selection.

7. Limitations and Future Recommendations

Although this study presents a sound and practical framework for picking recycled materials in construction based on LP, it has several limitations. The model first assumes static cost and availability data for cost analysis, which neglects market swings on the prices of materials, transportation costs, and supply chain interruptions that may be encountered at various points. Therefore, the model is developed considering the present industry scenario, but future studies are suggested to enhance the model using real-time updates and dynamic pricing mechanisms to increase its adaptability. Moreover, the LP model does not explicitly consider variations in structural performance due to utilizing different proportions of recycled materials. In future research, mechanical and durability assessments of recycled materials could be added to the optimization process so that cost savings do not negatively impact the long-term structural integrity.

The study has other limitations; the model was constructed and validated using one case study within the GCC construction sector. The findings apply to sustainable urban development in the region but require testing the model with other geographical settings, construction types and regulatory environments for broader generalizability. Towards future research, applying the LP framework to multiple case studies in different economic and climatic conditions is suggested to examine its scalability. Further, multi-objective optimization of the above objectives, such as cost, emissions, energy and resource efficiency, may also be integrated into the model to make the applications network even wider towards net zero construction projects. At last, machine learning and artificial intelligence could be adapted to develop adaptive optimization models of materials selection for sustainable construction projects that can be done inin real time. With these limitations addressed, future studies can improve and extend the practical ramifications of LP-based optimization to enhance its utility for the global construction industry.

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