Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA
Published: February 18, 2025

DOI: 10.46254/AN15.20250190

Logistics Optimization for the Use of Solid Urban Waste as Fuel in Cement Production: An Approach Based on Operations Research

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Abstract

The cement industry is a significant contributor to global carbon dioxide (CO_2) emissions. To reduce these emissions, the industry is increasingly utilizing municipal solid waste (MSW) and turning it into Refuse-Derived Fuel (RDF) as an alternative fuel source in cement kilns. This initiative not only seeks to reduce the need for traditional fossil fuels but also addresses critical waste management challenges. This paper develops a mixed integer programming (MIP) model to optimize the cost-benefit ratio associated with processing, transporting, and utilizing MSW as fuel across multiple cement plants. The model aims to minimize logistics costs while addressing the complexities of waste processing and transportation, offering a systematic approach to decision-making.

The collaboration with a cement company, which receives urban waste from the government for use as fuel, highlights the importance of efficient operations. While the plants have the capacity to process the waste, logistics have historically been managed manually. To improve efficiency, a mathematical model was created to minimize both logistics costs and CO_2 emissions through deterministic multi-objective optimization.

The results demonstrate that the optimized process significantly reduces operating costs and CO_2 emissions. A key finding is that, under the current constraints, CO_2 emissions are less sensitive to optimization, meaning that the primary focus should remain on cost reduction. When RDF plants operate at higher utilization, emissions decrease with a slight increment in costs, showcasing the environmental benefits of waste-to-fuel practices. Validation of the model confirmed its effectiveness, with real-world data showing improved efficiency, reduced truck requirements, and optimized processing capacities. These improvements lead to lower operational costs and more efficient resource utilization.

Keywords
Alternative Fuel, Carbon dioxide (CO_2) Emissions, Clinker, Municipal Solid Waste (MSW), Landfill, Refuse-Derived Fuel (RDF), and Waste Logistics.

1. Introduction
The rapid growth of urbanization, industrialization, and population over recent decades has led to an uncommon increase in the consumption of natural resources, with corresponding environmental consequences. One of the most significant concerns is the consumption of resources, which has now surpassed the planetary boundaries needed to sustain ecosystems vital for climate regulation, agriculture, and biodiversity (Rockström et al., 2009). Among the many industries contributing to resource consumption and environmental deterioration, the construction sector stands out, responsible for approximately half of global resource usage (De Wit et al., 2018). Specifically, the cement industry is a major contributor to CO_2 emissions, which leads to pollution and negatively impacts both ecosystems and human health.

To address these challenges, the cement industry is increasingly exploring innovative approaches to reduce its carbon footprint. One such strategy is the utilization of municipal solid waste (MSW) as an alternative fuel in cement kilns. This not only helps in reducing CO_2 emissions but also provides a solution to the growing issue of waste management. This paper focuses on developing a logistics optimization model to improve the efficiency of processing, transporting, and utilizing urban waste as fuel across a network of ten cement plants. By integrating additional facilities into the logistics network, the model aims to maximize the reduction of CO_2 emissions and improve operational efficiency.
To convert solid waste into Refuse-Derived Fuel (RDF), a series of treatment is required, including separation, compaction, and shredding. These processes take place in RDF formulation plants and aim to increase the calorific value of the material, enabling its use in cement plant kilns. However, many of these facilities deliver as a product the Inorganic Fraction of Municipal Solid Waste (IFMSW) instead of RDF. IFMSW, essentially RDF before shredding, has a larger particle size and must undergo a final treatment in cement plants to be considered suitable fuel. The final output of this entire process is the production of clinker, a key component in cement manufacturing. The quality and composition of the clinker, which are influenced by the properties of the RDF or IFMSW used as fuel, directly affect the strength and performance of the resulting cement. This underscores the importance of efficiently processing and transporting these alternative fuels to ensure both environmental and operational benefits in the cement production cycle.

Due to the challenges and limitations of adopting a systematic decision-making approach, many companies in this field rely on empirical methods, leveraging their expertise to determine logistical factors such as transportation quantities and the number of trucks required to meet demand efficiently. To address this, a deterministic mathematical model is proposed to minimize logistics costs while addressing the complex requirements of waste processing and transportation. By considering the capacities of both Waste Treatment and Cement Production Plants, as well as the fleet logistics involved, the model looks to provide a sustainable and economically viable solution to optimize the use of urban waste as a fuel source. This research not only contributes to improving the cement industry's sustainability but also aligns with global efforts to reduce the environmental impact of industrial practices.

1.1 Objectives
This paper aims to develop an efficient logistics system that optimizes the cost-benefit of processing, transporting, and utilizing urban solid waste as fuel in cement production through a deterministic model.

The objectives of this research are as follows:

1. Develop a mathematical model that minimizes costs and minimizes CO_2 emissions associated with clinker production.
2. Conduct scenario analyses to evaluate the process against the company's sustainable goals and variations in demand, fleet availability, and plant downtime.
3. Design a practical tool for the company to facilitate decision-making in logistics.

By addressing these objectives, this research seeks to increase the company's sustainability initiatives while improving operational efficiency in the cement production process. The key unique contributions of this research include the formulation of a logistics model tailored to the specific needs of the company, the identification of critical variables impacting cost and efficiency, and the development of actionable insights to inform strategic decision-making in waste utilization.

2. Literature Review

The utilization of MSW as fuel in cement production represents a critical intersection of environmental sustainability and industrial efficiency. While there is a growing body of literature addressing various aspects of this topic, a comprehensive investigation that integrates all components: logistics optimization, circular economy strategies, and emissions reduction, remains largely absent. The transition to a circular economy is vital for minimizing resource consumption and mitigating environmental impacts. NoParast et al. (2021) explored a non-dominated sorting genetic algorithm designed to implement circular economy strategies in the concrete industry. This research emphasizes the integration of recycled materials, such as aggregates derived from solid waste, into concrete production processes. Despite its valuable contributions, the study falls short of addressing the logistics involved in processing MSW as fuel across multiple cement plants. Specifically, it does not consider how varying capacities and operational efficiencies of different plants could affect the overall logistics framework required for optimal waste utilization.

Research in Sustainable Supply Chains (SSC) is significant for industries with substantial environmental footprints. Memari et al. (2015) addressed the integration of sustainability into supply chain planning through a multi-objective evolutionary approach, illustrating how optimizing both environmental and economic objectives can lead to meaningful reductions in emissions and costs. However, their approach does not specifically target the logistics challenges associated with using MSW as fuel in cement production, particularly when considering the dynamic nature of waste availability and processing needs. While significant progress has been made in individual research areas related to circular economy strategies, SSC, and logistics optimization techniques, there remains a notable gap in comprehensive studies that address the logistics of solid urban waste utilization as fuel in cement production. Existing literature lacks the integration of these components into a single framework that can effectively optimize the supply chain while minimizing environmental impact. Therefore, this study aims to bridge this gap by developing a holistic approach to logistics optimization, providing a valuable contribution to both the academic field and the practical implementation of sustainable practices in the cement industry.

2.1 Municipal Solid Waste as an Alternative Fuel

The use of MSW as an alternative fuel in cement production has been the subject of various studies. According to Gendebein et al. (2003), co-processing waste in cement kilns not only reduces greenhouse gas emissions but also decreases the volume of waste destined for landfills. The European Cement Association (CEMBUREAU) reported in 2019 that alternative fuels accounted up to 43% of the energy used in European cement plants, with some facilities achieving substitution rates exceeding 90%.

Moreover, MSW is typically processed into Refuse-Derived Fuel (RDF) through separation, compaction, and shredding, which increases its calorific value and makes it suitable for cement kilns. Studies such as those by Reguera et al. (2018) have shown that RDF offers a comparable energy output to traditional fossil fuels, making it a viable alternative for energy-intensive industries. However, challenges such as variability in waste composition and logistical inefficiencies remain significant barriers to worldwide adoption.

2.2 Logistics Optimization in Waste Management

Logistics plays a critical role in the efficient utilization of MSW as an alternative fuel. Beullens et al. (2004) applied vehicle routing and scheduling models to optimize waste collection systems, highlighting the potential for cost savings and emission reductions. More recently, Aljohani et al. (2020) developed a supply chain model for the transportation of municipal solid waste, demonstrating the benefits of integrating location-allocation models with transportation optimization.

Additionally, the logistics network must account for factors such as vehicle capacities, waste processing facility locations, and transportation costs. For example, studies by Gupta et al. (2019) emphasized the importance of integrating multimodal transportation systems to improve the efficiency of waste-to-fuel supply chains. Furthermore, advanced digital technologies, such as GPS tracking and data analytics, have enhanced the ability to monitor and optimize logistics operations in real time.

2.3 Operations Research in Cement Production

Operations research (OR) techniques have been increasingly applied in the cement industry to address challenges related to production efficiency, cost reduction, and sustainability. Notably, linear programming and mixed-integer programming models have been used to optimize raw material blending, energy consumption, and kiln operations (Kabir et al., 2020). However, the integration of OR techniques into the logistics of MSW utilization remains an underexplored area.

For instance, Moya et al. (2021) proposed a MILP model to optimize the allocation of alternative fuels in cement plants, considering factors such as fuel availability, transportation costs, and emissions. This study highlighted the potential for OR methodologies to enhance decision-making processes and improve operational efficiency. Despite these advancements, further research is needed to address the dynamic and stochastic nature of waste-to-fuel supply chains.

2.4 Gap in Literature

While these studies provide a solid foundation, there is limited research that integrates the principles of operations research, scenario analysis, and logistics optimization for the specific context of MSW utilization in cement production. Existing literature often focuses on individual aspects, such as waste processing or transportation, without addressing the interconnectedness of the entire logistics network. This paper seeks to fill this gap by proposing a comprehensive framework that combines these methodologies to evaluate and optimize logistics strategies under various scenarios.

3. Methods

This study develops a mixed-integer programming (MIP) model to optimize the logistics of using solid urban waste as an alternative fuel in cement production, aiming to minimize logistics costs and CO_2 emissions. This chapter presents the specific case study of the company and details the development of the deterministic model.

3.1 Supply Chain Structure

The supply chain structure illustrated in Figure 1 provides a comprehensive understanding of waste arrival and processing. Municipal Solid Waste (MSW) is delivered by the government to five RDF treatment plants, where it is separated and processed to extract the Inorganic Fraction of Municipal Solid Waste (IFMSW). The processed IFMSW is then converted into Refuse-Derived Fuel (RDF) or remains as IFMSW, depending on the available infrastructure, as shown by the color-coded lines in the figure. The waste processed is then transferred to Cement Production Plants. At these facilities, IFMSW undergoes a final shredding stage to achieve the necessary calorific value for use as fuel. While some cement plants are equipped with shredders to convert IFMSW into RDF, not all have this capability.

The mathematical model includes ten cement plants, expanding the initial focus on the four closest to the treatment facilities. This broader inclusion allows for a more comprehensive representation of the supply chain, optimizing the use of urban waste provided by the government. It also evaluates whether sending alternative fuel to these additional cement plants is justified, given the longer distances travelled.

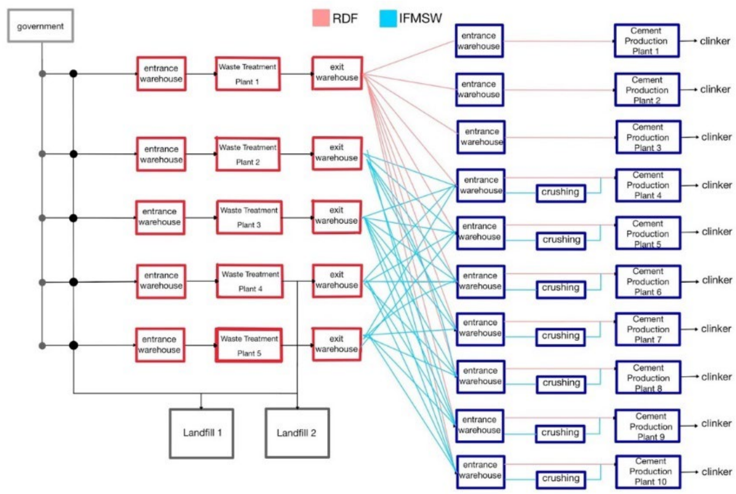

Figure 1. Supply Chain Structure

3.2 Waste Management Process

Upon the arrival of the IFMSW delivered by the government to the five Waste Treatment Plants, waste is managed through a systematic process:

1. Warehouse Capacities: Each Waste Treatment Plant and Cement Production Plant have designated warehouse capacities that dictate the amount of waste that can be stored before and after processing.
2. Processing Capacities: Each Waste Treatment Plant has designated processing capacities that dictate the amount of waste that can be treated and processed.
3. Shredders Capacities: The Cement Production Plant that is equipped with shredders has designated shredding capacities that dictate the amount of waste that can be processed.
4. Conversion Factors: The model includes conversion factors that determine the efficiency of turning waste into usable fuel. This is essential for calculating the effective utilization of RDF and IFMSW.
5. Processing Options:
   i. Shredders: Some Cement Production Plants are equipped with shredding machines, allowing IFMSW to be processed into a suitable form for use as fuel.
   ii. Combustion: Depending on the waste type and processing status, the waste can either be processed through shredding or directly introduced into the kiln for clinker production.

3.3 Transportation and Logistics

Transportation plays a vital role in the logistics of the supply chain. The model considers various transportation modes to move waste from Waste Treatment Plants either to Cement Production Plants or to landfills. Different types of trucks, categorized by weight, are utilized based on the specific requirements of the waste being transported. Also, waste can be sent in various formats, including bulk, single bales, and full bales.

3.4 Mathematical Model Development

The developed mathematical model utilizes a deterministic framework designed to optimize a logistics network within the context of waste processing and fuel conversion. This model is a multi-objective mixed-integer programming (MIP) algorithm aimed at minimizing both operational costs and CO_2 emissions. The model can either evaluate these objectives separately to assess their individual impacts or combine them into a single objective function. In the latter case, the environmental cost of CO_2 emissions is incorporated through a virtual cost, reflecting the company's internal carbon management strategy. The model operates daily, enabling dynamic optimization of waste processing, transportation, and fuel utilization in response to fluctuating demand, fleet availability, and other operational constraints.

The model's structure is composed of several components, including sets, parameters, and decision variables that reflect the real-world logistics system.

The model incorporates two primary objectives:

1. Minimizing logistics costs. The first objective function aims to minimize the total logistics costs associated with waste transportation, treatment, and processing. Key costs include:
    a. Waste disposal in landfills.
    b. Waste treatment and conversion into IFMSW or RDF.
    c. The shredding process to reduce IFMSW into RDF.
    d. The burning process of alternative fuels in cement kilns.
    e. Transportation between treatment facilities, landfills, and cement production plants.
    f. Compacting treated waste into bales for certain types of transportation.
    g. Potential savings from replacing traditional fossil fuels with alternative fuels.
    h. Payments received from the government for waste disposal at treatment plants.
2. Minimizing CO_2 emissions. The second objective function focuses on reducing CO_2 emissions associated with the entire process. It accounts for:
    a. CO_2 emissions from the traditional fuel mix used in cement kilns.
    b. CO_2 emissions from burning RDF in cement kilns.
    c. CO_2 emissions from the transportation of waste between facilities and landfills.
    d. CO_2 emissions from decomposition of waste in uncontrolled landfills.

Additionally, a combined objective function that balances both economic and environmental considerations was developed. This is achieved by converting CO_2 emissions into a cost equivalent using a market-specific virtual cost. The resulting single objective function reflects both logistics costs and environmental impact, incentivizing solutions that reduce both costs and CO_2 emissions. The model introduces a conceptual value C, representing the CO_2 emissions if all waste were directed to landfills without any processing. This value further ensures that the model seeks solutions that minimize both economic and environmental impacts.

The constraints of the model address key operational aspects, such as warehouse capacities, processing efficiencies, and transportation limits, ensuring that the scenarios considered are both feasible and realistic. Additionally, certain constraints are designed to maintain consistency throughout the model, ensuring no loss of materials as they flow through the various stages of the process. Some non-negativity constraints are also incorporated into the model to ensure that quantities of waste, both before and after conversion into alternative fuel, and waste sent to landfills, are non-negative. Additionally, the variables representing vehicles are defined as integers to account for the discrete number of trucks required in the model.

The proposed model is specifically tailored to the needs of the company in question, as it encompasses the processes and logistics involved from the moment waste is delivered to the treatment facilities to the burning of alternative fuels in cement kilns, ensuring alignment with the daily clinker production plan. Due to confidentiality concerns, the detailed mathematical formulation of the model is not disclosed in this paper.

3.5 Scenario Analysis

The flexibility to modify input parameters enables a deeper understanding of how specific variables impact the objective functions. For instance, assessing the effects of non-operational facilities can guide decision-making on prioritizing daily operations. Similarly, altering the virtual cost of CO_2 emissions could influence the model's outcomes, highlighting the need for careful evaluation of key operational components.

Beyond adjusting input parameters, new constraints were introduced as part of the scenario analysis. For example, the base model assumes unlimited vehicle availability to avoid potential biases in the results due to artificial constraints. This approach ensures that vehicle availability does not overshadow other operational considerations. However, understanding how an expanded or limited fleet could affect the logistics network is crucial, especially if the network can benefit from new transportation contracts or increased vehicle availability.

Three key constraints were incorporated during the scenario analysis:

1. Vehicle Availability: A limit is imposed on the number of vehicles, reflecting realistic operational conditions.
2. Sustainability Goals: A minimum RDF production requirement is introduced to prioritize sustainability objectives, even at the expense of higher costs.
3. Resource Utilization: A minimum percentage of utilization for each treatment facility is considered.

In addition to the primary scenarios, several other cases were evaluated. These included scenarios where individual plants of both treatment facilities and Cement Production Plants were considered non-operational, allowing for the assessment of their respective impacts on the system's performance. Furthermore, an analysis was conducted focusing on the utilization rates of the treatment facilities, as they represent the primary bottleneck in the process. This analysis aimed to determine whether increased processing leads to higher costs or provides greater environmental benefits.
Another key scenario involved modifying the cost of CO_2 emissions to assess its influence on the model outcomes. For each scenario, graphs were generated, providing a clear visualization of the trade-offs between minimizing costs and reducing emissions, helping to identify the optimal balance between these objectives.

4. Data Collection

For the development of the model, extensive data collection was essential to ensure the accuracy of the logistical, environmental, and economic analyses. The data collected covered several key areas, including plant capacities, energy conversion factors, waste handling, transportation costs, and emission calculations, all of which were crucial for building a comprehensive optimization model, and some of which were retrieved from other scientific papers.

4.1 Data Collected

a) **Plant Capacities:** Data was gathered from the company on the capacities of the warehouses, both at the entry and exit points. This included the quantity of waste received at the entry warehouse, the storage capacities available, and the maximum capacity for waste processing and storage at the exit warehouse. Additionally, information on the available capacity for shredding waste and feeding systems in cement kilns was gathered.
b) **Conversion and Efficiency Factors:** Conversion factors in the treatment plants, specifically related to how much of the incoming waste is processed and converted into Waste-Derived Fuel (RDF). The efficiency of these plants was also measured in terms of the amount of waste that goes in versus what is processed and sent out as usable fuel. In addition, calorific values (the energy produced per unit of waste) were obtained for each treatment plant.
c) **Clinker Demand and Plant Capacities:** The demand for clinker, a key product in cement production, was another critical data point. Data was collected depending on the required clinker for each plant, helping to balance the logistics for transporting waste-derived fuels to plants based on demand.
d) **Transportation Data:** Detailed information was gathered on the transportation aspect of the logistics, including truck capacities and the costs associated with each type of truck. Data was collected on transportation routes, including the distance between treatment plants, cement plants, and landfills, to accurately calculate transportation costs per kilometer. This was crucial for estimating the total cost of transportation in the supply chain.
e) **Cost Data:** Cost data played an important role in the analysis. Information on the costs was collected associated with waste treatment, including treatment and shredding costs per ton. Additionally, data on the costs of transporting waste between different plants was also collected, as well as the costs incurred when waste is sent to landfills rather than being used as fuel.
f) **Emissions Data:** Emission factors were critical for evaluating the environmental impact of the logistics network. The study considered emissions from transportation, waste treatment, and clinker production, referencing scientific articles from various authors, including Nilrit & Sampanpanish (2012), Kristanto & Rachmansyah (2014), Zhang (2017), Nordahl et al. (2020). This was necessary to calculate parameter C, representing CO_2 emissions that would be released if all the material were sent directly to uncontrolled landfills.

4.2 Model assumptions:

1. Waste Treatment Plants
    a. Some treatment plants consistently produce RDF, while the others only produce IFMSW.
    b. The amount of waste arriving daily at the input warehouse is known, and these transportation costs are covered by the government.
    c. Incoming waste has the same composition across all plants.
    d. Efficiency factors for converting waste into IFMSW and RDF remain constant, regardless of the incoming waste.
    e. Plants begin with zero utilized capacity at the start of the shift.
    f. IFMSW and RDF stored in output warehouses must be fully transported to cement plants.
2. Transportation

   a. All material movements, treatment, shredding, and burning in kilns occur on the same day, with no time gaps between processes.
   b. Trucks are operated in three predefined sizes: the smallest transports bulk material, and the other two only transport bales.
   c. Truck capacities are defined by weight in tons, without considering material volume.
   d. The routes between locations remain constant, so distances do not vary.
   e. Truck availability is known at the beginning of the shift.
3. Landfills
   a. Waste sent to landfills is not properly managed and results in the release of toxic gases into the atmosphere.
   b. Landfills are considered to have unlimited capacity.
4. Cement plants
   a. The demand for clinker is measured daily.
   b. IFMSW is shredded, and the resulting RDF achieves the same calorific value as when processed in treatment plants.
   c. Fuel mix proportions are represented as a weighted average across the target cement plants.
   d. The fuel mix consists of RDF, petroleum coke, natural gas, other solid and liquid fossil waste, fuel oil, and tires.
   e. Shredders and cement kilns start with zero utilized capacity at the beginning of the shift.
5. Costs
   a. The payment from the government to Cement Production Plants for handling waste is calculated per ton received.
   b. Operating costs are divided into treatment costs at Waste Treatment Plants, shredding costs at cement plants, and consumption costs in kilns.
   c. Transportation costs are based on the distance traveled, calculated as a cost per kilometer depending on the vehicle type.
   d. The virtual cost of CO_2 emissions is not currently incurred as an actual expense but is used to guide strategic decisions.

5. Technology Transfer

To facilitate the company's adoption of the model, two Excel files were developed to streamline the input of data and collection of output results. The optimization software, General Algebraic Modeling System (GAMS), is integrated with these files to determine the optimal arrangement of daily operations, minimizing costs and emissions.

5.1 Excel Files and GAMS Integration

The first Excel file contains all the necessary parameters for each plant. Fixed data that remains constant is locked, while editable cells—such as the daily amount of waste received at each plant—are highlighted in a different color for easy identification. These inputs are used to organize waste distribution and operational planning.

The Excel file is fully linked to the GAMS model. Any changes made to the editable cells are automatically detected when the file is saved, allowing the model to run with updated data. The output results are returned to the Excel file in pre-designated cells, which are linked to separate, user-friendly result templates. These templates are designed for a professional and presentable format, ensuring the results are clear and executive ready.

5.2 Power BI Integration

To provide a more synthesized and actionable overview, Microsoft Power BI was chosen as an additional tool for visualization and decision-making support. Power BI's dashboard offers a daily snapshot of the key metrics, such as:

- Volumes processed by each Waste Treatment Plant and Cement Production Plant.
- Truck movements, including types, starting points, destinations and volumes.
- Emissions data and cost breakdowns.
- Savings and other critical indicators.

Users can filter the dashboards by specific plants or view aggregated data for the entire operation. The Power BI interface is intuitive and requires only a simple "Update" click to refresh the data, making it ideal for daily decision-making without needing to navigate through detailed Excel sheets.

5.3 Documentation

To ensure smooth implementation, a step-by-step instruction manual with visual aids was created. This manual guides users through operating the Excel files, GAMS integration, and Power BI dashboards. The Power BI tool also allows users to download daily executive reports for company records, which consolidate critical insights, such as daily expenses, emissions, truck schedules, and savings, into an easy-to-understand format for easier decision-making.

6. Results and Discussion

To evaluate the effectiveness of the model, data from the company's operations for the most recent month was requested. This enabled the model to be run using real-world inputs, allowing a comparison between the results and the decisions made by the company during that period. By analyzing the discrepancies between the company's current logistical approach and the outcomes suggested by the optimization model, potential improvements were assessed in terms of cost reduction, emissions minimization, and overall efficiency. This comparison provides a foundation for evaluating the practicality and effectiveness of the proposed model in optimizing the logistics of solid urban waste utilization as fuel in cement production.

6.1 Verification

To validate the numerical results, all previously defined input data were utilized, including sets, parameters, variables, constraints, and equations tailored to meet the company's requirements. Key factors influencing the results include the amount of waste received, clinker demand, distances between plants and landfills, production capacities, and the efficiency of each plant. These factors ensure the model aligns with the company's operational realities.

The results provide insights into critical decisions, such as determining the number of trucks and the volume of waste to send to each destination, based on criteria such as costs, emissions, or volumes. The model's outputs are consistent with its objective of optimizing logistics while minimizing costs and emissions.

Given the dynamic nature of waste arrival at the plants, the model is designed to be updated daily. Using the current input data, the results indicate total costs and CO_2 emissions, with emission-related costs serving as a decision-making tool to evaluate environmental and economic trade-offs, though these costs are not directly incurred. Due to confidentiality requirements, specific numerical results and data points have been generalized or omitted.

Based on the model's recommendations:

- A specific number of trucks were assigned to transport waste from the Waste Treatment Plants to landfills.
- Another group of trucks were designated for transportation to Cement Production Plants.

The results reveal that some plants transported RDF, while others moved IFMSW, and some sent all waste to landfills. This distribution reflects the infrastructure and constraints of each plant, including shredding capabilities and specific truck requirements.

The analysis indicates that 45.65% of the incoming waste was processed, factoring in the efficiency of each treatment plant. Additionally, the plants operated at 79.82% of their total capacity, which is a higher utilization rate compared to their actual, real-world operational levels. The model provides precise recommendations regarding the type of truck and volume to be transported, enabling cost and emission reductions.

6.2 Validation

To validate the effectiveness of the optimization model and ensure its practical utility for the company, the Cement Production Plants were tasked with providing necessary data for October 2024. During this period, the model was used to generate the most efficient routes, including the type and number of trucks required, while minimizing both costs and emissions. The validation process replicated the same operational conditions, such as plant shutdowns, to allow for a direct comparison between the model's predictions and actual results.

The results accurately reflected the real-world scenario, with a 5.08% difference between the real data and the mathematical results under the same conditions. Additionally, the model predicted a lower overall cost compared to the actual data, requiring fewer trucks than were used and demonstrating a more efficient solution in terms of cost and waste processing. While the RDF volume in the model was slightly higher than the actual volume, the model achieved a much higher waste processing efficiency compared to the real scenario. This suggests that the model optimizes resource utilization, reduces landfill costs, and improves overall operational efficiency, making it a valuable tool for the company to enhance both cost-effectiveness and environmental sustainability.

6. Conclusion

With increasing concerns about achieving sustainability in highly polluting industries like cement manufacturing, it becomes crucial to incorporate these aspects into daily operations. Moreover, implementing semi-automated decision-making processes is essential for companies with complex operations, as finding optimal solutions without optimization tools can be extremely challenging. This is particularly relevant when evaluating economic and environmental impacts in scenarios involving numerous variables.

In this study, a mathematical model was developed to address both economic and environmental factors. A significant focus was placed on the practical application of the research, analyzing a cement company's operations and its integration of circular economy principles by repurposing waste as an alternative fuel. Key findings from the model's use and validation include the following:

- The model effectively reduces costs, demonstrating that a well-optimized process with designated software could lower operational expenses compared to current practices. This was especially true when RDF plants operated at a higher utilization.
- The optimization of the current operation successfully reduces the CO_2 emissions throughout the complete process, highlighting the environmental benefits of these practices.
- The model´s results indicate that under current constraints, CO_2 emissions are not highly sensitive to the optimization process, so the primary focus should remain on minimizing costs, as this approach has the biggest impact.
- Validation results showed that the model's results were consistent with actual outcomes but with higher efficiency. For example, the model's optimization in transportation and processing capacities led the company to reduce the number of trucks required, which translates to significant cost savings and improved resource utilization.

Acknowledgements

The authors would like to express their gratitude to Cemex for their valuable support in providing essential data and insights for this study. Their collaboration and contribution were instrumental in the development of this research.

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Biographies

Virgilio S. Acosta Villarreal is currently pursuing a bachelor's degree in Industrial and Systems Engineering from the University of Monterrey, where he developed a strong foundation in process optimization, supply chain management, and quality assurance. As one of the authors of the paper titled "Logistics Optimization for the Use of Solid Urban Waste as Fuel in Cement Production: An Approach Based on Operations Research and Scenario Analysis," Virgilio focuses on developing innovative logistics solutions that utilize solid urban waste as an alternative fuel in the cement industry. This research aims to address the challenges of waste management and carbon emissions reduction, working in collaboration with a leading cement company in Mexico. Virgilio is committed to sustainability and wants to implement eco-friendly practices within industrial systems. As he advances in his academic and professional career, Virgilio aspires to drive positive changes in the industrial sector, utilizing his expertise to contribute to sustainable practices and contribute to a more environmentally responsible future.

Mariana Dingler Villarreal is a student in her final semester, pursuing a degree in Industrial and Systems Engineering, where she developed expertise in project management, logistics, and quality control. Mariana is one of the authors of the paper titled "Logistics Optimization for the Use of Solid Urban Waste as Fuel in Cement Production: An Approach Based on Operations Research and Scenario Analysis." This research focuses on creating effective logistics systems to utilize solid urban waste as an alternative fuel in the cement industry. Collaborating with a cement company, she aims to minimize landfill waste and reduce CO_2 emissions through innovative approaches. Her commitment to sustainability inspires her to look for solutions that build up operational efficiency while promoting eco-friendly practices within industrial settings. Mariana actively engages in projects that align with her values of innovation and environmental stewardship. As she progresses in her academic and professional journey, Mariana aspires to develop her skills and knowledge to contribute to the industrial sector's sustainable development, making a meaningful impact on both organizations and the environment.

Emilia Montes is a student in her final semester, pursuing a degree in Industrial and Systems Engineering. She is currently working on her thesis titled "Logistics Optimization for the Use of Solid Urban Waste as Fuel in Cement Production: An Approach Based on Operations Research and Scenario Analysis." This research focuses on developing effective logistics systems for utilizing solid urban waste as an alternative fuel in the cement industry, aiming to minimize waste and reduce CO_2 emissions. Emilia has collaborated with a cement company that receives urban waste from the government to transform it into fuel, thus contributing to sustainable practices in waste management and cement production. Her efforts involve creating a mathematical model to optimize logistics costs and emissions reduction, considering demand fluctuations and processing capacities. In addition to her academic pursuits, Emilia is preparing a paper for the IEOM conference in Singapore in 2025, based on her thesis analysis. She is passionate about applying engineering principles to address environmental challenges and is committed to contributing to a sustainable future through her work in industrial engineering.

Jenny Díaz Ramírez is an accomplished industrial engineer, professor, and researcher with extensive expertise in applied research and optimization of productive systems. Her work focuses on logistics, supply chain management, mobility and transportation solutions, as well as the design of eco-efficient alternatives and air quality improvement strategies. She is passionate about applying data-driven methods to address real-world challenges and drive sustainable innovation in industrial and urban systems. Professor Díaz Ramírez has a proven track record of advancing practical and impactful solutions through her academic and professional contributions.