<u>MM 656 Case Study Report</u>

Energy Cost Optimization Using Linear Programming For Process Industry

Submitted

by

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Abstract

Addressing the increasing expenses associated with energy, particularly in energy-intensive sectors like textile manufacturing, is increasingly crucial for maintaining competitiveness in both local and global markets. This study proposes a novel method employing linear programming (LP) to model and optimize energy consumption within textile processing. The LP model is designed to ensure that production meets quality standards while minimizing energy costs, considering various operational constraints. Data necessary for model development are generated from thorough energy audits conducted at manufacturing facilities, enabling the identification of constraints and product specifications. These constraints are integrated into the model as material and energy balance equations, alongside production requirements. By calculating optimal values for process design variables, the LP model aims to achieve optimized cost efficiency. This systematic approach, leveraging LP, offers a strategic means to enhance energy management within textile manufacturing, aiding industries in navigating the challenges posed by escalating energy expenses.

Introduction

Industries, facing escalating energy demand and costs, prioritize energy conservation and optimal utilization. Energy management is vital for profitability and competitiveness, especially in sectors like textiles. Effective management ensures efficient resource usage, minimizing expenses and enhancing sustainability. By adopting sound energy strategies, industries can navigate global competition and contribute to a more sustainable energy landscape, securing their place in the market while reducing environmental impact.

Energy management involves tracking and controlling energy and material use to achieve goals with minimal power consumption. It includes monitoring and analyzing resource allocation, supply, and conversion. By finding the most efficient ways to meet demands using available resources and technologies, energy management helps reduce costs and environmental impact over time.

Textile manufacturing is intricate due to diverse substrates, processes, and machinery. Various yarns, fabric production methods, and finishing steps contribute to energy intensity. Energy models aid decision-makers by offering insights into the consequences of their choices, improving decision-making. These mathematical tools, grounded in the system approach, help tackle complex issues. Selecting the most suitable model depends on the specific problem decision-makers aim to address.

Linear programming finds extensive applications in business, engineering, transportation, energy, telecommunications, and manufacturing. It's valuable for modeling planning, routing, scheduling, assignment, and design problems. Commonly used in management for profit maximization or cost minimization, it serves as a fundamental technique for optimization. Linear programming involves an objective function and a set of linear constraints.

The textile manufacturing plant industrial model aims to reduce energy costs by analyzing the production of yarn, grey fabric, and finished fabric. It considers equipment powered by electricity, wood fuel, and fuel oil. The goal is to create mathematical models ensuring product requirements are met while minimizing energy expenses, subject to operational constraints.

Brief Study On Production Process

Textile manufacturing involves five key stages: spinning, sizing/preparation, rewinding, weaving, and wet processing (finishing). Each stage comprises various machines serving distinct purposes. The process begins with yarn production in spinning, proceeds to weaving for woven fabric (grey fabric), and culminates in wet processing for finished fabric.

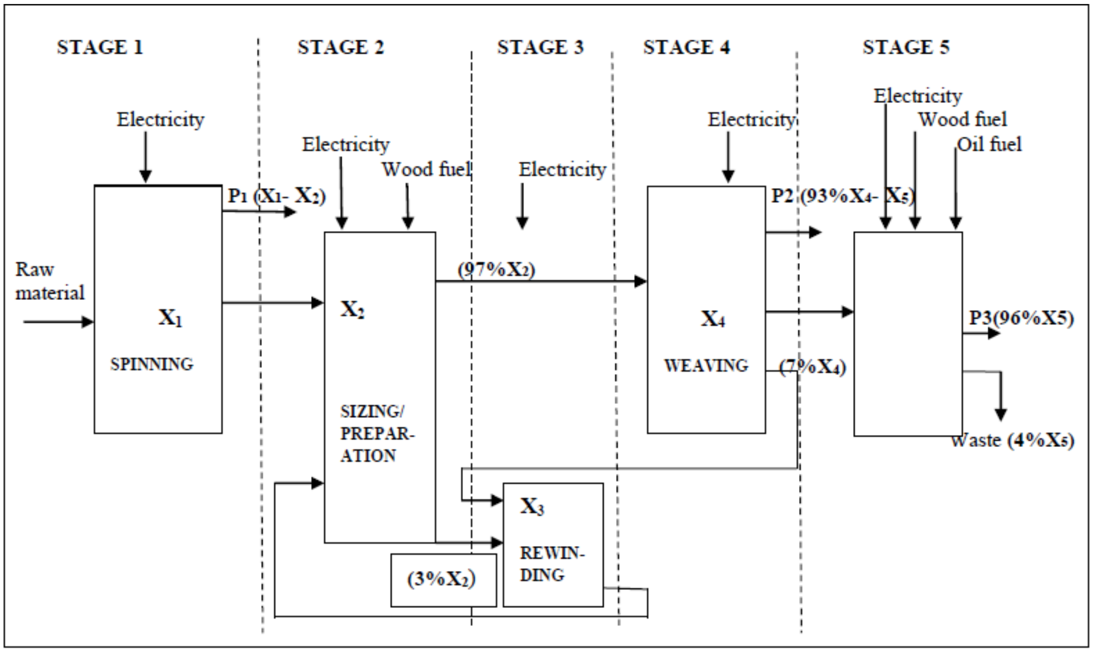

Fig. Textile production Flowchart

1. **<u>Stage 1 - Spinning Process</u>**
   In spinning, cotton, viscose, and polyester turn into yarn, the primary output (X1). Raw materials are the key inputs. Depending on orders or forecasts, some yarn is stored (P1), while the rest moves to the next stage. This stage marks the start of textile manufacturing, where materials are transformed into yarn, a crucial component for subsequent processes. Spinning involves machines like bale breakers, step cleaners, draw frames, carding, and open-end machines, crucial for turning raw materials into yarn.
   The spinning process accounts for 48% of the total electricity consumption in the plant, making it the largest consumer among textile manufacturing processes. The average monthly electricity usage is 43,942 kW.

2. **<u>Stage 2 - Sizing/Preparation Process</u>**
   Stage 2 receives materials from Stage 1 and recycled materials from Stage 3. Its product, depicted as X2, undergoes processing. 3% of Stage 2's output is sent to Stage 3 for recycling, while 97% proceeds to Stage 4. Sizing involves applying substances like starch, gelatin, oil, wax, and manufactured polymers such as polyvinyl alcohol, polystyrene, polyacrylic acid, and polyacetates to warp yarns, enhancing their durability and abrasion resistance during weaving.

Additional objectives of sizing include enhancing the breaking strength, smoothness, and elasticity of yarn, as well as protecting it from abrasion. Moreover, sizing aims to reduce static electricity generation and minimize hairiness in the yarn.
The process utilizes wood fuel in a fire-tube boiler to produce steam for yarn sizing, involving treatment with starch solution. Electricity powers the warping machines. The boiler operates at 17.35% efficiency, generating steam at a rate of 3TPH. Stage 2's average monthly electricity consumption is 5,400 kW.

3. **Stage 3 - Rewinding Process**
   Stage 3 functions as a recycling unit, processing waste materials from Stage 2 and Stage 4 to be reused in Stage 2, represented by X3. Waste materials include remnants of yarn during the transfer from cones to warper beams and from weavers' beams during weaving. This stage solely consumes electricity, averaging a monthly consumption of 4,147 kW.

4. **Stage 4 - Weaving Process**
   Weaving, the fourth stage, uses treated yarn from Stage 2 to produce grey fabric, illustrated as X4. Some products from this stage go to storage (P2), while the rest move to Stage 5. Main weaving machines like Projectile, Rapier, Air-Jet, or Water-Jet are used depending on the fabric needed. Stage 4's energy input is mainly electricity (14,428 kW).

5. **Stage 5 - Wet Processing (Finishing Process)**
   The final textile manufacturing stage includes singeing, washing, de-sizing, scouring, bleaching, mercerizing, stentering, curing, and dyeing. It transforms grey fabric into finished fabric (X5), with 96% stored as finished products (P3) and 4% wasted. This stage demands thermal energy from thermo boilers and fire-tube boilers burning heavy fuel oil and wood fuel. Electricity powers machines like thermostenters and jiggers. The thermo boiler operates at 86.1% efficiency, outputting 1860 kW, with a monthly electricity consumption of 20,608 kW.

Equations And Constraints

Based on the flowchart and the material balance equations based on the demands and forecasts from the marketing department, the objective function for cost minimization with the necessary constraints is formulated.

Decision Variables
X (Decision Variable Vector) = [X_1,X_2,X_3,X_4,X_5]
Here,

X_1 = Weight of product processed at stage 1 in a month in Kgs
X_2 = Weight of product processed at stage 2 in a month in Kgs
X_3 = Weight of product processed at stage 3 in a month in Kgs
X_4 = Weight of product processed at stage 4 in a month in Kgs
X_5 = Weight of product processed at stage 5 in a month in Kgs

<u>Objective Function</u>

The objective function is to minimize total energy costs.

Minimize $\mathbf{Z = C_1X_1 + C_2X_2 + C_3X_3 + C_4X_4 + C_5X_5}$

Here,

C_1 = Energy cost per unit of product to be produced in spinning
C_2 = Energy cost per unit of product to be produced in sizing/preparation
C_3 = Energy cost per unit of product to be produced in rewinding
C_4 = Energy cost per unit of product to be produced in weaving
C_5 = Energy cost per unit of product to be produced in wet finishing

<u>Constraints</u>

Based on the material balance equations, we get 2 equality and 3 inequality constraints.

Inequality Constraints

1) $\mathbf{X_1 - X_2 \geq P_1}$
2) $\mathbf{0.93X_4 - X_5 \geq P_2}$
3) $\mathbf{0.96X_5 \geq P_3}$

Here,

P_1 = Weight of demand for product produced in stage 1 in a month (Yarn)
P_2 = Weight of demand for product produced in stage 2 in a month (Grey Fabric)
P_3 = Weight of demand for product produced in stage 3 in a month (Finished Fabric)

Equality Constraints

1) $\mathbf{0.97X_2 - X_4 = 0}$
2) $\mathbf{0.07X_4 + 0.03X_2 - X_3 = 0}$

Non Negativity Constraints

$\mathbf{X_i \geq 0 \ \ \forall\, i \in [1,5]}$

Time Constraints

$\mathbf{X_1t_1 + X_2t_2 + X_4t_4 + X_5t_5 \leq T}$

t_i is the required processing time to produce a unit of the product in i^{th} stage.
T = available processing time in a month
X_3 is not included in the constraint because it does not produce any valuables, it recycles output back to X_2.

The data for the model came from energy audits, historical records, and information provided by the production process and manager. It includes the amount of electricity, wood fuel, and oil fuel used for each product at each stage. Electricity is measured in kWh, oil fuel in liters, and wood fuel in kilograms.

Code and Result

The goal of the linear programming model is to minimize production energy expenses. Cost coefficients, expressed in Ksh (Kenyan Shillings) per kilogram, are multiplied by variables measured in kilograms, yielding a total objective function in Ksh. By optimizing resource allocation and cutting costs, the model aims to reduce overall energy expenditures.
Based on the material balance equations and the time constraint, we created a linear programming solver model using Scipy, a very popular library of Python used for statistical analysis and solving complex maths problems.

In [13]:
```python
import numpy as np
import ast
from scipy.optimize import linprog
import pandas as pd

# X (Decision Variable Vector) = [X1,X2,X3,X4,X5] all are in Kgs
# Objective function = Minimize Z = C1X1 + C2X2 + C3X3 + C4X4 + C5X5
# Cis are the cost coefficients, units are in Ksh/Kg

cost_coeff = np.array(ast.literal_eval(input('Enter The Energy Costs for the processes 1 to 5: ')))

# Inequality Constraints, here Pis are the demand values
# 1) X1 - X2 ≥ P1 , Yarn
# 2) 0.93X4 - X5 ≥ P2 , Grey Fabric
# 3) 0.96X5 ≥ P3 ,  Finished Fabric
inequality_coeff = np.array([[1, -1, 0, 0, 0], [0, 0, 0, 0.93, -1], [0, 0, 0, 0, 0.96]])
demand_products = np.array(ast.literal_eval(input('Enter The demand for the products: ')))

# Equality Constraints
# 1) 0.97X2 - X4 = 0
# 2) 0.07X4 + 0.03X2 - X3 = 0
equality_coeff = np.array([[0, 0.97, 0, -1, 0], [0, 0.03, -1, 0.07, 0]])
equality_balance = np.zeros(2)

# Time Constraints, here
# X1t1 + X2t2 + X4t4  + X5t5 ≤ T, here ti are fixed for the processes, T is total available time
# t1 = 0.007, t2 = -0.007, t3 = 0 , t4 = 0.013, t5 = 0.0062
time_coeff = np.array([0.007, -0.007, 0, 0.013, 0.0062])
T = int(input('Enter The total Available time here per month: '))

# Non-Negativity Constraints
# Xi ≥ 0  ∀ i ∈ [1,5]
bounds = [(0, None)] * 5

# creating the data for the model, scipy takes only upper bound inequalities,
# so to convert lower bound inequalities into upper bound, multiply entire inequality by -1
total_inequality_constraints = np.vstack((-1 * inequality_coeff, time_coeff))
total_demand_const = np.append(-1 * demand_products, T)

# creating the solver
res = linprog(cost_coeff, A_ub=total_inequality_constraints, b_ub=total_demand_const,
              A_eq=equality_coeff, b_eq=equality_balance, bounds=bounds, method='simplex')

# Storing the output in the dataframe
df = pd.DataFrame(index = ['X1','X2','X3','X4','X5', 'Minimal Energy Cost'],data = {'Optimal Values':np.append(res.x,res.fun)})
pd.options.display.float_format = '{:.2f}'.format
print(df)
```

Full Code Link: https://drive.google.com/file/d/18t18B9XVKOQp0cXO5xscq1ld6rMt5ezV/view?usp=sharing

The process parameters that might change are Demand values C_iS, P_iS, and T based on the market requirements, etc. The rest of the parameters are more or less fixed due to the material balance equations and the property of yarn.
For the particular case: ***Minimize*** $\boldsymbol{Z = 50X_1 + 7X_2 + 40X_3 + 15X_4 + 48X_5}$
The monthly production demands are as follows: Yarn (P_1) requires 400 kg, Grey Fabric (P_2) requires 600 kg, and Finished Fabric (P_3) requires 20,000 kg. Additionally, the available processing time in a month (T) is 720 hours.

Output of the code along with the parameters:

```
Enter The Energy Costs for the processes 1 to 5: [50,7,40,15,48]
Enter The demand for the products: [400,600,20000]
Enter The total Available time here per month: 720
                    Optimal Values
X1                        24159.38
X2                        23759.38
X3                         2326.04
X4                        23046.59
X5                        20833.33
Minimal Energy Cost     2813025.09
```

The model has 5 variables and 11 Constraints. We used the Simplex Method to solve the optimization problem though there are other methods as well. The Optimal solution is X_1 = 24159.38 Kg , X_2 = 23759.38 Kg, X_3 = 2326.04 Kg, X_4 = 23046.59 Kg, and X_5 = 20833.33 Kg and the minimal value of the energy cost is 2,813,025.09 Kenyan Shilling per Month.

Conclusions

Our study aimed to utilize linear programming techniques to optimize energy utilization within the textile manufacturing industry, with the goal of reducing energy expenses. To achieve this, a linear programming model employing the simplex algorithm was developed using Scipy.

	Cost Percentage
Spinning	42.94
Sizing	5.91
Rewinding	3.31
Weaving	12.29
Wet Processing	35.55

Spinning and wet processing contribute significantly to energy costs in textile manufacturing. Output of the model indicated that spinning accounts for 42.9% and wet processing for 35.5% of the total energy cost (optimal value). Implementing energy-saving measures in spinning and wet processing is crucial for reducing energy costs in textile manufacturing.
This research holds significance as it enables timely corrective decisions for the company through linear programming methods. It guides future production strategies, potentially leading to the establishment of new production units while prioritizing energy cost reduction.

References

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