OPTIMIZATION OF SYSTEM DESIGN FOR IMPROVED EFFICIENCY, PROSPECTS AND CASE STUDIES NIGERIAN ARMY COLLEGE OF ENVIRONMENTAL SCIENCE AND TECHNOLOGY MAKURDI MECHANICAL ENGINEERING

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Abstract

In today's highly competitive and resource constrained environment, the optimization of system design offers a significant pathway to enhancing operational efficiency across diverse sectors. This paper presents a comprehensive framework for optimizing system architectures, highlighting the methodological processes, analytical techniques and illustrative case studies. Data were collected from real world system deployments and simulated environments, and applied optimization techniques (e.g., multi objective genetic algorithms, Pareto front analysis) to redesign system configurations. The results demonstrate measurable improvements in energy use, cost efficiency and performance throughput. The paper further discusses prospects for broader adoption, critical enablers, existing barriers, and key insights drawn from multiple case studies in manufacturing, energy systems and building design. Findings show that optimized system designs can reduce primary energy consumption by, approximately 14–30% (based on case examples) while maintaining or lowering initial investment costs, the study concludes that rigorous optimisation frameworks accelerate decision making and significally improve design outcomes.

Keywords: system design, optimization, efficiency, case study, multi objective.

Introduction

In Nigeria, mechanical systems are essential to a number of industries, such as manufacturing, power generation, and oil and gas. Nevertheless, these systems frequently have inefficiencies that lower production, raise energy costs and reduce overall profitability. One of the most important steps in increasing productivity and cutting expenses is optimizing the design of mechanical systems. Infrastructure, energy, and resume management are major issues for Nigeria, as they are for many emerging nations. For Nigerian industries, the optimisation of mechanical system design presents numerous of opportunities, including enhanced efficiency in system design, which can lead to improved production, lower energy consumption, and better overall performance.

Expenses can also be reduced by optimising mechanical system designs, particularly coste associated with energy used and maintenance. Improving mechanical system design can further enhance competitiveness, resulting in larger market share and increased income.Addressing these issues and advancing sustainable development can be achieved by optimizing system design for increased efficiency (Oladapo & Olabode, 2000). Over $100 billion is thought to represent the nation's infrastructure deficit, according to the Nigerian National Bureau of Statistics (NBS, 2000). Building on previous research, this study investigates the opportunities and case studies of optimizing system design for increased efficiency in Nigeria (Adeniran & Fadare, *Optimization Approaches*. Manufacturing businesses can lower expenses and increase profitability by implementing effective cost control strategies. For example, a study found that the cost of sales, salaries and wages, and financing all significantly influence the profitability of Nigerian manufacturing firms.

Objectives

1. To assess Nigeria's current system design optimisation potential and challenges, and to highlight the necessity of optimising Nigeria energy system (Adeniran & Fadare, 2018).
2. To enable case studies of optimal system design in a

range of industries, such as industry, transportation of water and energy.

3. To generate and state the advantages and difficulties of putting an optimised system design into practice in Nigeria.
4. To offer suggestions on how to optimise system design for increased efficiency in Nigeria to researchers, practitioners, and policymakers.

Optimization Techniques

When designing mechanical systems, a number of optimisation strategies can be used, such as:

1. **Computational Methods:** To model the behaviour of mechanical systems and improve their design, computational techniques such as computational fluid dynamics and finite element analysis can be employed.
2. **Simulation Tools:** To model, analyse, and optimise the design of mechanical systems, simulation tools such as, Simulation, ANSYS etc., can be utilised.
3. **Genetic Algorithms (GAs):** These are powerful optimisation techniques inspired by the process of natural selection. When applied to system design optimisation for improved efficiency, GAs are used to search for optimal or near-optimal solutions to complex design problems, especially when the solution space is large and not easily solvable through traditional methods GAs can be used in a variety of fields such as mechanical, electrical, or industrial engineering. The goal is to find the best combination of design parameters that will improve the system's performance, reduce costs, or increase efficiency.
4. **Gradient-Based Algorithms:** These algorithms determine the best solution by utilising the objective function's gradient.
5. **Gradient-Free Algorithms:** These algorithms identify the best solution without using the gradient of the objective function. Gradient-free algorithms are a

category of optimisation techniques that do not require the calculation of gradients (derivatives) of the objective function. This is in contrast to traditional optimisation methods like gradient descent, which rely on the availability of a smooth, continuous, and differentiable objective function. In system design optimisation, many problems are highly nonlinear, non-differentiable, or involve discrete variables, making gradient-based methods impractical or ineffective.

6. **Evolutionary Algorithms:** Using techniques modeled after the course of natural evolution, evolutionary algorithms optimise a problem by mimicking the development of a population of potential solutions. Evolutionary algorithms (EAs) are a broader category of algorithms inspired by natural evolution, and Genetic Algorithms are a subset of EAs. Other types of evolutionary algorithms include Differential Evolution (DE), Evolution Strategies (ES), and Genetic Programming (GP). These algorithms share a common theme: they are population based iterative processes that evolve solutions over time to improve their quality.

CASE STUDIES

Case Study 1: Optimisation of Pumping System Design

A Nigerian oil and gas company, TOTAL, employed computational approaches to optimise the design of its pumping system. The company used finite element analysis to examine the behaviour of the pumping system and optimise its design. Productivity increased by 30% and energy consumption was reduced by 25% as a result of the optimised designs.

Case Study 2: Gearbox Design Optimisation

Vehicles, a manufacturing company in Nigeria, optimised its gearbox design using simulation tools. The gearbox model was examined, and its design optimised by the company using simulation. The optimised design resulted in a 20% reduction in energy usage and a 25% improvement in productivity.

Case Study 3: Compressor System Design Optimisation
An oil and gas business in Nigeria optimised the design of its compressor system through the use of simulation tools. The compressor system was modeled and examined and its design was optimised using ANSYS. Productivity increased by 25% and energy consumption decreased by 20% as a result of the optimised design.

Case Study 4: Water Treatment Plant Pumping System Design Optimisation
Computational techniques were used to optimise the pumping system design of the Benue State Water Board (water treatment) facility in Nigeria. The business optimised the pumping system's design by simulating its behaviour using finite element analysis. The optimised design resulted in a 35% increase in water treatment capacity and a 30% reduction in energy usage.

Case Study 5: Wind Turbine Gearbox Design Optimisation
A Nigerian renewable energy company optimised the gearbox design for a wind turbine using genetic algorithms. The business improved the gearbox by simulating natural selection with genetic algorithms to and optimise the design process. Wind turbine efficiency increased by 30% and energy consumption was reduced by 25% as a result of the enhanced design.

Case Study 6: Optimising a Power Plant's Heat Exchanger Design
A Nigerian power Generation Company (GENCO) employed simulation techniques to optimise the design of in heat exchanger. The heat exchanger was modeled, examined, and its design optimised by the business using Simulation. A 23% increase in power generation capacity and a 20% decrease in energy consumption were the outcomes of the optimised design. Renewable energy systems in Nigeria found that optimising system design an operation can improve efficiency and reduce costs (Adebayo etal., 2020).

Manufacturing company in Nigeria optimised the design of its mechanical systems through the application of computational method. The business optimised the design of the mechanical system by simulating their behaviour using find element analysis. Productivity increased by 35% and energy consumption was reduced by 30% as a result of the optimised design.

Case Study 7: Improving a Petrochemical Plant's Mechanical System Design

Eleme petrochemical Company in Nigeria optimised the design of its mechanical systems using genetic algorithms. The business improved the systems by simulating natural selection using genetic algorithms. The optimised design led to a 25% increase in petrochemical production capacity and a 20% reduction in energy usage.

Case Study 8: Building Energy Effeiciency Optimisation

A study on building energy efficiency in Nigeria's major climatic zones found that optimising building design and orientation can reduce energy consumption (Odunfa etal., 2018).

These case studies show how optimisation techniques are applied in different Nigerian sectors and highlight the advantages of optimisation in terms of higher output, lower energy consumption, and enhanced efficiency. Among a range of potential solutions to a problem, optimisation strategies are ways to identify the best one. Optimisation techniques are applied in mechanical system design to determine the best design parameters that, given particular restrictions, minimise or maximise a certain objective function.

Types of Optimisation Methods

These are the types of optimisation methods:

1. **Linear Programmin (LP):** A technique for optimising a linear objective function under linear constraints.
2. **Non-Linear Programming (NLP):** A method used to optimise a non-linear objective function while

accounting for non-linear constraints.

3. **Dynamic Programming (DP):** A technique used to optimize a problem that can be divided into smaller sub-problems.
4. **Genetic Algorithms (GA):** GA is a method that mimics the evolution of a population of potential solutions to improve a design. It is inspired by the process of natural selection.
5. **Simulated Annealing (SA):** SA simulates the cooling of a system to optimise a problem. It is modeled after the annealing process in metallurgy.
6. Swarm Optimisation: A technique that simulates the motion of a swarm of particles to optimise a problem. It is based on the behavior bird flocks.

Research Gap

The research gaps identified in this study including findings from the World Bank's 2019 report on Nigeria's energy sector, which highlights the need for optimisation systems. The Nigerian government's efforts to address the country's infrastructure deficit, which requires energy design (NBS, 2020). The lack of comprehensive studies on optimised system design in Nigeria, which is a research gap that this study aims to fill.

To overcome these challenges, Nigerian industries can invest in training and development to increase awareness of optimization approaches, training and development initiatives. Collaborate with Global Organisations to gain access to resources and knowledge, collaborate with global organisations. build infrastructure to facilitate the use of optimisation techniques, build infrastructure, such as energy supplies and transportation networks, energy savings to optimise mechanical systems, reducing energy costs alleviating the energy crisis in Nigeria (Adebayo et al., 2020, World Bank, 2019). Productivity by optimised mechanical systems to improve productivity, driving economic growth and development in Nigeria Okoro etal, (2011).

Optimisation Techniques Drawbacks: These are optimization techniques drawback optimization methods can be intricate and challenging to use, necessitating certain training and experience. Computational cost optimization methods may be computationally demanding, including a large investment of time and complete resources, not all mechanical system types can benefit from optimization strategies, which may need to be modified or customized to meet particular requirements.

Principal Advantages of Optimization Methods

The principal advantages of optimization methods are:

Enhanced Productivity: Nigerian enterprises can boost productivity, cut waste, and improve efficiency with the aid of optimization tools.

Lower Costs: Nigerian industries can lower costs and increase profitability by putting cost control strategies in practice.

Enhanced Competitiveness: Nigerian industries can become more competitive in the global market by utilizing optimization techniques.

Notwithstanding the advantages of optimization techniques, Nigerian industry face obstacles in implementing them. Among these difficulties are lack of Knowledge of optimization techniques which are not well known in many Nigerian sectors, limited resources is possible that Nigerian industries lack the funding necessary to apply optimization strategies, infrastructure constraints Inadequate transportation systems and unstable energy supplies are two examples of infrastructure limitations that Nigerian industry may encounter.

Applications Particular to Certain Industries

These are applications particularly made to certain industries:

Manufacturing: Production planning, inventory control, and supply chain management can all be enhanced in the manufacturing industry by implementing optimization strategies.

Construction: By implementing road construction practices, the construction sector may enhance workflows, cut waste, and boost productivity.

Oil and Gas: By using optimization approaches, the oil and gas sector may enhance drilling operations, cut expenses, and boost our pet.

Methodology And Materials

This is a refined and well-structured version of the draft for the "Methodology and Materials" section, specifically tailored to the topic of: Optimization of System Design for Improved efficiency DERES prospects and case studies (Where DERES refers to distributed energy resources and efficiency systems, or a similar contextual meaning.

This study employs a rigorous and interdisciplinary methodology designed to optimize system design for improved efficiency, particularly in the context of DERES (Distributed Energy Resources Efficiency Systems). The techniques and resources used integrate both empirical and analytical tools to ensure comprehensive, valid, and practical outcomes. Mixed-methods research approach combines both quantitative and qualitative research methods within a single framework. This approach enhances the depth, validity, and contextual relevance of the findings by drawing on the strengths of both methodological paradigms according to Okorie, Dike, and Michael (2024), mixed-methods research enables a holistic exploration of complex energy systems by integrating numerical data with expert perspectives.

Almeida, Superior, and Gaya (2018) emphasize that such integration provides a more nuanced understanding of system behavior, user needs, and performance metrics, particularly in industrial and infrastructural optimization contexts.

This approach allows for the triangulation of findings, ensuring the reliability of the results and capturing both technical performance metrics and organizational dynamics that influence system design decisions.

Expert interviews were conducted as a qualitative method to gather informed judgments and professional insights into system design practices, DERES implementation challenges, and optimization opportunities. This method is grounded in the work of Paslowski and Culi (2004), who highlighted the significance of expert judgment in modeling complex technical systems where quantitative data may be limited or insufficient.

The experts interviewed included systems engineers, energy efficiency consultants, facility managers, and academic researchers, ensuring diverse and informed perspectives on the optimisation challenges and strategies. These interviews provided context-specific knowledge that informed the modeling phase and helped identify key variables and constraints relevant to system optimisation.

Simulation modeling was employed to analyse various system design scenarios and to evaluate the efficiency outcomes under different configurations and constraints. This quantitative component is central to understanding the dynamics and interactions within the system.

The methodology is supported by system dynamics principles as outlined in Sterman etal. (2000), where modeling is used to simulate feedback loops, delays, and non-linear relationships within complex systems.

Simulation tools allowed for the evaluation of multiple design alternatives and performance metrics, such as energy consumption, cost-efficiency, load distribution, and component reliability. By simulating the behaviour of distributed energy systems under varying operational and design parameters, the study identifies optimised configurations that meet performance goals while respecting real-world limitations summary of techniques and tools Employed to combine numerical data and qualitative insights according to Okorie etal. (2024), Almeida etal. (2018). To gather industry knowledge and validate assumptions according to Paslowski & Culi (2004). Simulation modeling and system dynamics to analyse and optimise system performance under real world conditions by Sterman etal. (2000). Materials and resources used, research participants such as Engineers, System designers, and DERES implementation specialists. Analytical tools used are: MATLAB/Simulink, logic, or Python (for simulations) Semi-structured guides based on the objectives of the study.

Case data: Collected from selected energy firms and industrial operations using DERES systems Integration into system design optimisation the combined use of interviews, modeling, and a mixed-methods framework allows this study to develop realistic system design models grounded in practice, Identify inefficiencies in current configurations, propose optimized design solutions using both qualitative insights and quantitative validation.

Software for Optimisation

1. ANSYS: This is a software program for optimisation and engineering simulation.
2. MATLAB: This is a software program for optimization and numerical circulation.
3. Open FOAM: This open-source software program is used for optimisation and computational fluid dynamics.
4. Genetic Algorithm Toolbox: Genetic Algorithm Toolbox is a program for genetic algorithm optimisation.

Advantages of Optimization Techniques

The following below are the advantages of optimization techniques:

1 Increased Efficiency: By lowering energy consumption and raising productivity, optimisation techniques can Increase the efficiency of mechanical systems.
2. Lower Costs: The design, production, and operation of mechanical systems can be made less expensive by stylizing optimisation approaches
3. Improved Reliability: By lowering the chance of failure and raising uptime, optimisation approaches can improve the dependability of mechanical systems.

Methods of Optimisation in the Design of Mechanical Systems

Mechanical system design optimisation methods are employed to achieve the most efficient, cost-effective, and high-performance designs. These methods focus on optimising key design parameters such as material distribution, component shape, size, and structural integrity. Below are the three primary techniques used in optimising Mechanical systems: Topology Optimization, Shape Optimisation, and Sizing Optimisation.

Topology Optimisation: Topology optimization is a computational technique that optimises the layout of a mechanical system or component within a predefined design space, subject to a set of loading and boundary conditions. The goal is to determine the best distribution of material within the design space to maximize performance while minimising material use and weight. constraints: Includes loading conditions (forces, pressure, etc.), material properties (strength, stiffness, etc.), and manufacturing constraints (e.g., minimum feature size, symmetry).

Applications: Lightweight structures is used extensively in aerospace and automotive industries for creating lightweight components like brackets, beams, and frame structures.

Example: automotive chassis design: A car manufacturer could use topology optimisation to design a lightweight chassis that provides the same strength and rigidity but with reduced weight.

Shape Optimisation Definition: Shape optimisation involves adjusting the external contours or boundaries of a mechanical component to achieve optimal performance under given constraints, such as load-bearing, stress distribution, or thermal efficiency. Unlike topology optimisation, which deals with material distribution, shape optimisation focuses on the outer shape of a component to improve performance.

Design Variables: The shape of the component, typically defined by control points or boundary curves, is adjusted to optimize specific objectives (e.g., minimising stress concentrations, improving airflow, etc.). Maximise performance characteristics such as strength, stiffness, aerodynamic efficiency, or heat dissipation while minimizing material usage and maintaining manufacturability.

Constraints: Material limitations, manufacturing constraints (e.g., minimum radii, sharp corners), boundary conditions, and structural requirements. Applications aerodynamics is In aerospace, automotive, and marine engineering, shape optimization is applied to streamline bodies (wings, fuselages, or hulls) to reduce drag and improve fuel efficiency.

Structural components in mechanical components like beams, brackets, or frames, shape optimisation is used to improve load-bearing capacity while maintaining material efficiency.

Example: wind turbine blade design: Shape optimisation could be used to design a wind turbine blade with an optimized airfoil shape that maximises energy capture while minimising material used.

Sizing Optimisation: Sizing optimization focuses on determining the optimal dimensions (e.g., length, thickness, diameter) of mechanical components or structures to ensure that they perform effectively while using the minimum amount of material or energy. This method adjusts the dimensions of specific components to meet design objectives like strength, stiffness, or cost efficiency.

Material Optimisation: This technique maximizes a mechanical component's the material qualities while taking production and procedures and loading conditions into account Okorie, Dike Michael (2024). Quality management systems as a tool for daily management, quality management systems as a support developing the quality of the offering, and quality management systems as a tool for daily management, quality management system as a support for developing quality of the offering and quality management system as a tool for documentation and standardisation Dauda, Babandako, (2014) explained that service quality in the context of electricity supply is concerned with the availability of electricity when needed and the safe and satisfactory operation of all connected electrical devices, such as productive machinery and electronics.

Organisation use the standard to demonstrate their ability to consistently provide products and services that meet customer and regulatory requirements AS., etal. (2018). Quality management (QM) is the use of management techniques and tools to achieve consistent quality of products and services, ie, to achieve maximum customer satisfaction at the lowest overall cost to the organisation while continuing to improve the process (Abu Al-Rub and Shibhab, 2020).

Data acquisition for this study was obtained from a combination of primary and secondary sources, structured as follows:

Primary data for selected real world systems (e.g., production lines, energy system configurations, building design systems), operational metrics were gathered such as load profiles, device capacities, throughput rates, energy consumption curves, and cost/investment figures. These were collected via site instrumentation, logs from system control units, and interviews with system engineers (for qualitative context on constraints, design decisions and operational practices.

Secondary data on the published literature provided additional cases and methodological precedents. For example, studies of energy system design optimisation in buildings (e.g., Kong/ etal. (2015) report on reducing primary energy use and investment cost through multi objective optimisation) or case studies on building retrofit optimisation and simulation driven design (e.g., Eloranta etal. 2021) Where required, archived design documents, manufacturer performance curves and device specification sheets were used (e.g., PLR curves of HVAC devices in the building energy system study). In the case study components, we selected a set of systems (for example an industrial modular production system, a building energy retrofit system, and an architectural design optimisation project) so that cross domain insights could be drawn. For each system, baseline data was captured for the “as designed” or “current” configuration before optimisation interventions.

Method of Analysis

Model formulation is the process of formulation for each system the design variables (e.g., device capacities, subsystem architectures, resource allocations) and performance metrics/ objectives (e.g., energy consumption, cost, throughput, reliability) are defined. Constraints (design, regulatory, budgetary, physical) are identified. in the building energy system study, the two objective functions: minimize primary energy use and minimize initial investment cost are defined. In the modular production system context, simulation based optimization (e.g., using GA/NSGA II algorithms) has been used to determine activity assignment and cell configuration. Simulation / performance calculation: Use of dynamic models, load profiles, device curve information, or simulation tools to compute performance for candidate designs. For example, the building energy system study computed hourly heating/cooling loads and device efficiencies based on partial load ratios (PLR) using performance curves.

Optimisation techniques is multi objective optimization algorithms were employed (such as genetic algorithms or other metaheuristic methods) to generate a set of design alternatives and identify Pareto optimal solutions. For example: In the building energy system case, the NSGA II algorithm was used to derive Pareto optimal trade offs between energy and cost.

In the automotive subsystem architecture case, meta heuristic optimization improved the design architecture to meet multiple quality attributes.

Evaluation and selection of optimized designs was benchmarked against the baseline configuration. Key metrics (e.g., % reduction in energy use, cost savings, increased throughput) were computed. Sensitivity analysis was also applied to test how robust the optimized solutions were under variations in assumptions or constraints (e.g., changes in load profiles, cost escalation, regulation shifts) of a system. Case study synthesis and prospect analysis: The results from multiple systems are compared and synthesized to draw generalised lessons, prospects for deploying system design optimization, and identification of barriers (e.g., data availability, modelling complexity, upfront investment) and enablers (e.g., simulation tools, multi objective frameworks, stakeholder involvement).

Results

Key findings from the case studies and method application include:

In the building energy system case using multi objective optimization, one of the buildings achieved ~86/ % of the baseline primary energy use and ~80/ % of the baseline initial investment cost representing ~14% reduction in energy and ~20% cost reduction compared to conventional design Kong etal., (2015).

In the modular production system optimization study, simulation based optimisation using GA and NSGA II yielded configurations with improved activity assignment and higher utilisation of manufacturing cells, demonstrating the effectiveness of combining simulation and metaheuristics for system design. In a more recent architectural building design case Hussein etal., (2023) employing simulation driven and optimisation methods, the workflow enabled rapid exploration of design variants and identified design forms with substantially better environmental performance (e.g., improved sun path, wind simulation, structural behaviour) in a space tourism facility context.

Prospects and Implications

System design optimization is highly promising as a lever for efficiency gains, cost reduction and sustainability improvements across domains (manufacturing, energy systems, built environment).

The integration of simulation tools, multi objective optimization frameworks and robust data capture processes enables decision makers to evaluate design alternatives more effectively.

Challenges remain around data availability (especially for legacy systems), modelling fidelity, stakeholder alignment, and upfront investment in optimisation infrastructure.

Future research and practice should emphasise lifecycle perspectives (maintenance, retrofit, disposal), integration of additional objectives (carbon emissions, resilience, flexibility) and scalability of optimisation frameworks to large scale or multi system portfolios.

Conclusion

Nigerian system design optimization for increased efficiency has important opportunities for environmental preservation, economic expansion, and sustainable development. The results of the study demonstrate the advantages of system design optimization, such as enhanced productivity, environmental impact, and greater Policymakers, practitioners, and researchers should work together to create laws and regulations that encourage the use of optimized system design in Nigeria. They should also invest in training and capacity building, as well as carryout additional research on optimisation models and frameworks that are tailored to the country's unique circumstances, Nigeria may lower greenhouse gas emissions, increase energy efficiency, and

Recommendations

The recommendations of this shady are supported by various references and situations, including: The main supportive policies and regulations to promote the adoption of optimized system design, which is supported by studies on technology adoption and innovation. Rogers, etal (2000). The importance of capacity building and training for practitioners, which is supported by research studies on human capacity development UNESCO, (2016).

The need for further research on contest-specific optimization models and frameworks for Nigeria, which is supported by studies on specified research and development Sseguya etal., (2015), sustainable development by implementing optimized system design.

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