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Research Article

Environmental Sustainability in Piping Systems: Exploring the Impact of Material Selection and Design Optimisation

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Abstract

As the world embraces sustainable Piping systems, improving their environmental, economic, and social performance has become fundamental). This paper will analyse the importance of material selection and design optimisation in the sustainability of piping systems: environmental issues related to conventional piping system materials and their installation. This calls for development of options that help decentralise energy demand, emissions and impact on ecosystems. The study also considers highly developed design optimisation techniques that can significantly enhance the main parameters of piping systems, including the use of genetic algorithms and Computational Fluid Dynamics CFD. Furthermore, the paper focuses on the main technical and economic barriers encountered in the course of implementing sustainable practices, such as the high cost of investment, lack of materials, and the suitability hurdle. Ways of addressing these barriers are suggested, particularly in the selection of cheaper and environmentally sound materials and in engineering design. Lastly, this work provides useful information about future piping systems' development as well as the role of sustainability in urban and industrial development towards SDG achievement.

Keywords: *Piping Systems, Sustainability, Material Selection, Design Optimization, Environmental Impacts.*

Introduction

Sustainability in engineering has emerged as one of the utmost areas of concern while delivering infrastructure systems, especially in piping systems that are used in water distribution systems for both urban and industrial applications. Due to the push towards more sustainable designs, engineers are tasked with the responsibility of determining feasibility for environmental, economic, and social factors for what they build [1]. Comprising of piping systems installed in steel industries and building areas, pipes are mostly from materials like PVC, ductile iron and concrete and have high life cycle effects since they involve high energy effects and produce greenhouse gases. Hence, new piping construction materials and techniques that can minimise the environment impact have emerged as crucial for consideration.

The choice of materials used in the construction of piping systems is one of the most critical success factors for sustainability. Conventionally used construction materials still have steep drawbacks in terms of their environmental friendliness since their preparation requires much energy and they have a low rate of recycling.

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Newer and advanced materials and coatings are seen as providing potential value-add as far as durability, energy, and the environment are concerned [2]. However, the decision on which material to use depends on other factors such as cost, durability, behaviour under load and resistance to corrosion. This decision making process is complex and is the key to institutionalising the processes required to support the longevity of water distribution networks.

Besides the choice of material for constructing the piping systems, the factors that influence the optimisation of the design of the piping have been described as being very effective in improving the sustainability of the piping. Such tools as finite element analysis (FEA) and computational fluid dynamics (CFD), along with the more recent genetic algorithms, are being used widely to generate the optimum layout of the piping system that elicits minimal energy losses, frequency of maintenance requirements and durability of the system [3]. They also assist the engineers in establishing, for example, the roughness of the pipe, the corrosion allowance, and the effects of the environment and hence design good piping solutions that are sustainable.

However, there are some barriers to sustainable material selection and material optimisation or lightweight. Intensive initial investment costs, availability of few sustainable materials, and absence of positive signals for green technologies introduce considerable barriers to their utilisation. Furthermore, the challenge of integrating environmental objectives with the issue of efficiency and cost is still apparent [4].

Significance and Contribution of the Paper

Sustainability in piping systems has a greatest value of cutting down on the destruction of the earth's natural endowment in support of water distribution networks that are central to urban and industrial developments. Therefore, through the implementation of sustainable material and better designs of piping system energy utilisation, greenhouse gas emissions, as well as the waste production during whole life cycle of the piping systems, can be reduced. It not only assists in decreasing the impacts of climate change but also greatly assists in achieving sustainable development of economic perspective infrastructure. Sustainable piping systems also enhance effective ways of the usage of water, minimise the use of funds in the process, and conserve the supply of water for future generations. Contained in the following are the contributions that they discuss below:

- Enumerates the environmental costs of conventional piping materials and cautions on the need to find better solutions.
- Focused on aspects such as energy efficiency, durability of materials, and their further recyclability, it is devoted to the investigation of the role of the choice of material.
- Investigates the applicability of new methods, including CFD and genetic algorithms, in enhancing the efficiency of piping systems and sustainability.
- Summarizes major issues that need to be addressed regarding the choice of materials for piping systems, with emphasis on corrosion, mechanical characteristics and operating parameters of temperature and pressure.
- Discusses the economic barriers to adopting sustainable practices and provides insights into overcoming challenges related to cost, availability, and market competition.
- Sustainability In Engineering Systems: Sustainability is a complex systems problem with interconnected environmental, social, and economic components. Advancing sustainable infrastructure is partly the responsibility of engineers. However, engineering practice for sustainability often works to reduce complexity by creating linear lists and processes and even neglects the dynamic relationship between these systems components. For example, rating systems like Leadership in Energy and
- Environmental Design (LEED) which provide engineers and project teams a checklist of individual parts in design without consideration of connections and holism (Azhar et al. 2011). However, this linear, rational and well-structured design approach in LEED might not be able to address the complex and ill-structured design problems for sustainability (Chance 2010).

Sustainability is a multifaceted issue with interrelated social, economic, and environmental elements. Engineers have a role to play in promoting sustainable infrastructure. In engineering practice for sustainability, which usually aims to reduce complexity by creating linear lists and procedures, the dynamic relationship between the components of these systems is usually ignored. For example, LEED (Leadership in Energy and Environmental Design) certification programs, The complex and poorly organised design difficulties for sustainability may be beyond the scope of LEED's linear, rational, and well-structured design approach. Without considering links and holistic design, this method provides engineers and project teams with a checklist of discrete design elements.

Environmental Impact of Traditional Piping Systems

Traditionally, the conventional pipe structures are fabricated from PVC, ductile iron or concrete. These systems are large in their impact on the environment for their entire life cycle of the system. You know, it requires a lot of energy and emissions lots of greenhouse gases to come up with these things. An energy of 68.30 MJ/kg is required to manufacture PVC pipes, which in turn emits 4.860 kg of CO_2. In contrast, the production of ductile iron pipes requires 19.55 MJ/kg and emits 1.430 kg of CO_2 per kg of the pipe [5]. Additionally, Standard pipe systems also pose threat to the environment during installation and maintenance of the systems. Current methods of installing open-cut pipelines harm ecosystems and worsen soil erosion and sedimentation in water structures.

Reduction of these impacts on earth requires the adoption of environmentally friendly materials and new technologies. As with all issues related to embodied energy and carbon footprint, life cycle assessment has demonstrated that in terms of some materials, such as PVC, the earth may actually be better off.

Some of the ways of decreasing the environmental impacts of piping systems is by using trenchless technology methods of installation which disturbs the surface to a lowest level possible.

For a comprehensive analysis of the environmental impacts of various, the resources listed below offer comprehensive information on pipe materials and installation techniques:

Environmental Effects of Trenchless Technology Techniques and Traditional Open-Cut Pipeline Installation: A State-of-the-Art Review.

Life Cycle Assessment of PVC Water and Sewer Pipes and Comparative Sustainability Analysis of Pipe Materials.

The Role of Sustainable Practices in Global Environmental Goals

Growth is anticipated to be slowed by changes in the global environment as well as local communities' current inability to adapt to the demanding and quickly changing environment [6]. The methods used for expansion frequently have nothing in common with the policies and actions required for sustainable development. Therefore, it is crucial to conduct study on the behaviour and attitudes of the local population. An approach that will handle the community's poor development path and ensure future generations are adopted and routed as a result of the overwhelming necessity to identify and rectify the aforementioned differences. The urgent need to identify the crucial elements is highlighted by the continuous research on the sustainable development process. In terms of technical, socioeconomic, and environmental concerns, it also strikes a balance between the needs of the present and future generations.

Material Selection for Piping Systems

The choice of materials is essential to engineering design. It is a complicated matter where a decision-maker may come across several opposing or conflicting characteristics, such as the fact that materials' functional and economic performance may not always coincide [7]. In essence, the materials are chosen to satisfy the design specifications. Mercer explained that choosing pipe materials required consideration of longevity and dependability, with internal pressure and exterior loads serving as the main performance evaluation criterion.

Common Materials Used in Piping Systems

PIPE materials which are used in China pipeline construction consist of Concrete, cast iron, PVC, PE, steel belts, and composite pipes made of hole mesh steel tape and plastic [8]. In recent decades, the scheduling restraints, differences in construction environments and the need for maintenance have contributed to pipeline construction utilising multiple materials and connection methods. For example, metal pipes are usually joined by welding and are connected to PVC pipes. Nevertheless, mixed material joints themselves present difficulties when attempting to locate the water supply pipelines because conventional metal pipe detectors do not efficiently distinguish between joined pipes and non-metal sections thereof.

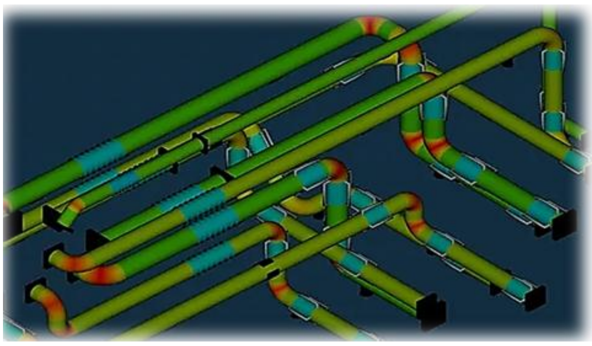
Environmental Impacts of Material Choices

The criteria that should be used in economic evaluation of available plastics in selection of plastic pipes must also include factors like cost of purchasing or acquiring the plastic, cost of processing the plastic and percentage market share of the plastic. Combined with new generations of environmental design guidelines for lean production, material choice turns into a distinct focus on reducing the ecological footprint throughout the lifecycle of a product.

Research has been done on different types of pipes to establish their effect on environmentally sustainable using their lifecycle for selection. Comparing four typical sewage pipe materials, researchers chose the material with the least environmental burden during the whole lifecycle while meeting the basic utilitarian requirement.

Design Optimization in Piping Systems

Some of the most sophisticated metrics technology include profilometry, which has been useful in pairing system designs in that it can pinpoint the degree of roughness of the internal surface [9]. Which depends on the effective flow area, ϵ, and results in changes to the flow efficiency as well as pressure losses. Corrosion, which contributes to the roughness, decreases flow rates and costs, thus advancing alloy pipes and internal coatings. These innovations help to increase useful life, facilitate the pipe flow, and enhance pipe durability. Eliminating errors in roughness measurement through profilometry, therefore, allows accurate estimations of friction pressure losses that form the basis of appropriate piping designs in the chemical and Petroleum industries. Figure 1 depicts the piping layout seen below:



Optimisation of piping layout

Principles of Sustainable Design in Piping Systems

The sustainable design of Piping systems basically aims at attaining effectiveness, reliability and eco-friendly paving systems. Key principles include:

Energy Efficiency: Engineering mechanisms that reduce energy needs based on calculated design and by using the right materials.

Water Conservation: Measures for using and conserving water should be put in place.

Material Selection: Selecting environmentally sensitive products, long-lasting products, recyclable, and products with minimal emission.

Lifecycle Assessment: Assessing effects of the environment at every stage in the life cycle of the system from manufacturing to disposal.

Waste Reduction: Evaluating construction and operational wastage and enhancing the efficiency of their management.

Computational Tools for Piping Design Optimization

Optimisation in piping systems focuses on design improvement by means of computational redesign techniques to increase effectiveness and decrease expenses[10]. The key techniques include:
CFD and FEA: Study the characteristics, that is, movements and forces within fluids and their containers.
Optimization Algorithms: Instruments like genetic algorithms find out optimal design parameters.
Adjoint Methods: Accomplish the steps for getting gradients for optimisation of the network speed.
Simulation-Based Metaheuristics: They use an iterative or cyclical approach when solving problems.
Spanning-Tree Matrix Approach: Use a systems approach to create changes for big water systems.
Challenges In Achieving Sustainability
In constructioning projects, industrial development, water channelling or alterations in or near freshwater sources cause piping for freshwater systems to have shorter or reduced pipe lifespan or pipe stability [11]. It alters the water level as well as temperature and sediment in pipe systems and qualitative flow, thus posing a challenge to sustainability. These materials all have minimal conducting of harm, such as not causing rust, low frictional losses or fears with their surroundings.

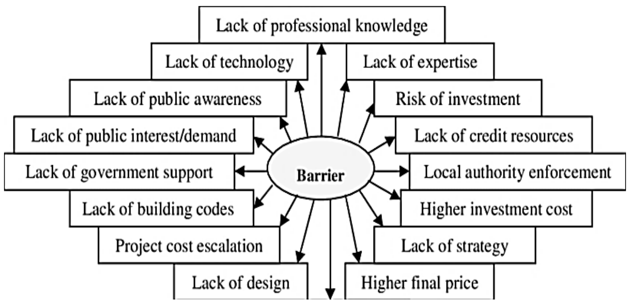
Two new piping system sustainability issues are microplastics that clog pipes and antimicrobial resistance that corrodes pipes. Design optimisation can provide powerful and cost-effective sustainable, efficient freshwater resources management solutions to these challenges.

Technical Challenges in Material Selection

Material selection for piping systems involves several technical challenges:
Corrosion Resistance: Materials used should be resistant to corrosion due to the aggressive environment in order to avoid failure of complex systems.
Mechanical Properties: Achieving the right tensile modulus which would result in high flexibility and adequate strength and toughness to withstand operational loads that undermine performance.
Temperature and Pressure Resistance: The most critical decision, since it defines the overall performance and stability of the system, is to select materials that do not weaken upon changes in temperature and pressure.
Cost-Effectiveness: Assessing the efficiency of resource costs versus the characteristics of materials in order to find an optimal solution.
Environmental Impact: Anticipating material choices in order to meet sustainability and legal compliance objectives.

Economic Barriers to Adopting Sustainable Practices in Piping Systems [12]

High Initial Costs: Sustainability materials and designs repeatedly require considerable initial investment, and that can be a problem for SMEs.
Limited Availability: Carbon-friendly products and technologies may be a problem in procurement, hence increasing the costs of acquiring them.
Maintenance Expenses: However, sustainable systems may entail one-time or lower installation and maintenance costs than conventional systems but inferred the recurring general operating costs and sometimes specialised maintenance costs.
Lack of Incentives: Lack of financially attractive prices or subsidies for sustainable solutions and policies prevent companies from adopting sustainable practices.
Market Competition: Self-interests can create an environment in which organisations will strive to achieve greater efficiency in the short term without regard for the future.



Barriers to sustainable practice.

Figure 2 illustrates the various barriers to implementation, categorised into factors such as lack of professional knowledge, technology, and expertise. It highlights challenges like insufficient government support, public awareness, and building codes. Economic constraints, including higher investment costs, credit resource limitations, and project cost escalation, are also emphasised. These barriers collectively hinder progress and require strategic interventions for resolution.

Literature Review

This section provides literature review with specific emphasis on sustainability trends and practices in piping systems with special reference on materials, design techniques and technologies. In Table I, a brief synthesis of main outcomes is presented:
This study, Dawood et al. (2020) goal is to create a regression analysis-based risk of failure model. The model was built using seven years' worth of historical

data collected from the Peruvian city of El Pedregal. When the regression analysis-based model was tested against several statistical indicators, the results showed that it was coherent, with an R2 of 98%. As a decision support tool, the suggested model is anticipated to help civil engineers and infrastructure managers with their planning and decision-making. Urban populations suffer serious repercussions when water distribution networks deteriorate and fail [13].

Wibowo and Grandhi (2017) formulates the challenge of evaluating the sustainability performance of urban water services as a multicriteria group decision making problem and provides a new multicriteria group decision making technique for effectively assessing the sustainability performance of urban water services. Interval-valued intuitionistic fuzzy numbers are used to reflect the imprecision and subjectivity of the decision-making process. An interval-valued intuitionistic fuzzy weighted averaging operator is used to aggregate fuzzy data. A distance-based knowledge measure is utilised to provide positive and negative interval-valued knowledge measure values, which are then utilised to determine the final decision [14].

George and Binulal (2016) carried out to examine how well a closed loop pulsing heat pipe transfers heat when filled at various filing ratios, inclination angles, and heat inputs with pure water and an aqueous solution of butanol (a self-rewetting fluid). The surface tension of self-rewetting fluids increases with temperature, which is one of their properties. Butanol is added to pure water at weight percentages of 0.1 and 0.5 to produce a self-rewetting fluid. The PHP is made of copper tubing with inner and outer dimensions of 2.0 mm and 3.0 mm, respectively. It has been discovered that utilising pure water produces a higher thermal resistance than using an aqueous solution of butanol. Also, as to the dependence on the orientation angle, the butanol aqueous solution behaves better than pure water up to the horizontal orientation [15].

This research, Ramli, Hamid and Mokhtar (2017) specifically focuses on analysing the efficiency differences between the application of glass reinforced plastic (GRP) force mains pipelines and ductile iron (DI) force main pipes. Subsequently, a network pump station is made more efficient in energy consumption by acting on the variable speed drive (VSD) on the speed range. By using new Total Head of Force Main it is clear that the VSD is more consistent in terms of speed to optimise energy consumption. Applying this method, the energy of a network pump station can be expanded, and consequently, the power use, electricity expense, and carbon discharge will be reduced. Therefore, there will be considerable ROI savings, and this proposal will have some other advantages in the long run [16].

Zeng et al. (2019) offer a comprehensive review of all significant research on the optimisation of district cooling/heating pipe networks in three areas: network operation, pipeline dimensions, and network design. The characteristics and range of uses of several optimising methods are analysed. Since the district heating and cooling system's pipe network system is its most important component, pipe network optimisation is necessary for the system to function successfully and effectively[17].

Table 1 Presents the summary of literature review based on Sustainability in Piping Systems with material selection

References	Focus Area	Key Findings	Challenges	Key Contribution
Dawood et al. (2020)	Modelling the risk of failure in water distribution networks	Developed a regression analysis-based model with 98% R^2 for predicting the possibility of water delivery networks failing.	Need for accurate historical data and model validation.	Infrastructure managers and civil engineers can use this decision support tool to help with planning and decision-making.
Wibowo and Grandhi (2017)	Sustainability performance evaluation of urban water services	Introduced a multicriteria group decision-making approach using interval-valued intuitionistic fuzzy numbers to evaluate sustainability performance.	Handling subjectivity and imprecision in decision-making.	An Innovative Method for assessing sustainability in Urban Water Supplies .
George and Binulal (2016)	Heat transfer performance of pulsating heat pipes with self-rewetting fluids	Self-rewetting fluids (butanol-water mixture) showed improved heat transfer performance and lower thermal resistance compared to pure water in closed-loop pulsating heat pipes.	Limited studies on the impact of self-rewetting fluids and their practical applications.	Investigated the performance of self-rewetting fluids in enhancing heat transfer in pulsating heat pipes.
Ramli, Hamid and Mokhtar (2017)	Comparison of ductile iron and glass reinforced plastics force mains pipelines.	Variable speed drives (VSD) improved energy efficiency by optimising the Total Head of Force Main, reducing power consumption and electricity bills.	Ensuring long-term reliability and ROI from energy optimisation.	Demonstrated energy optimisation in pump stations, reducing costs and carbon emissions.
Zeng et al. (2019)	Optimisation of district cooling/heating pipe networks	Reviewed various optimisation algorithms for pipe network layout, diameter, and operation to enhance the efficiency of district cooling/heating systems.	Balancing the complexity of optimisation algorithms and practical implementation in real-world systems.	Comprehensive review of pipe network optimisation in district cooling/heating systems.

Conclusion and Future Work

Sustainability in piping systems is crucial for reducing environmental impacts, with advancements in material selection, sustainable practices, and design optimisation playing key roles. Traditional piping materials have significant environmental footprints, but new technologies like trenchless installation and eco-friendly materials offer solutions. Despite technical challenges such as corrosion resistance and cost barriers, sustainable practices are essential for long-term infrastructure development.

Future research should focus on developing cost-effective, durable materials and exploring advanced computational tools for design optimisation. Addressing economic barriers through policy changes and incentives will help accelerate the adoption of sustainable piping systems. Long-term studies on the lifecycle costs and environmental benefits will guide future practices.

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