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Harnessing artificial intelligence for sustainable office building design in Baghdad: A comparative analysis of traditional vs generative environmental approaches

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Abstract*—*Hot-arid regions such as Baghdad have building typologies with high knowledge to the combination of mechanical cooling systems as well as low dependency on the environment. This study aims at countering such energy consumption in office buildings with the use of generative design AI tools. A comparative energy model was implemented and run between a standard design model (A) and a model optimized with AIs (B) through Galapagos, Ladybug, Honeybee and EnergyPlus modules in Rhino-Grasshopper. The models were assessed based on the same criteria, such as Energy Use Intensity (EUI), thermal comfort (PMV), ventilation (ACH), and solar radiation. The findings are that Model B has realized an energy saving of 25.9 %, a 177 percent better ventilation efficiency and acceptable comfort level. The findings underscore the worth of incorporating AI and generative design earlier on in the architect.

I. INTRODUCTION

In the current architectural discourse, these growing environmental demands and the increased concern about energy consumption have led to a worldwide shift in the architectural focus to performance based design approaches. A good example of this need is Iraq, and Baghdad in particular: the intense summer months (high mean conditions are well above 47C) in Baghdad makes traditional practice inadequate to optimize energy efficiency or occupant comfort. Office buildings, which are characterised by long working hours and high occupancy rates during the day, are some of the most energy-consuming building forms in the nation (Al-Saadi, 2018).

However, most of the Iraqi architecture firms hold on to the formalistic and static approaches to architecture, where they do not consider climatic information as well as critical evaluation of environmental performance. Computational design, combined with Artificial Intelligence (AI) technologies, however, will provide a stated revolutionary opportunity of enhancing building performance. Galapagos, Ladybug, and Honeybee tools, which are embedded in parametric environments (e.g., Grasshopper). allow emulating, testing, and refining design options by climatic-conditioning.

The current study aims to determine how AI-enabled generative design can be used to improve the environmental performance of office buildings in Baghdad. The case study model contrasts the two approaches to design: traditional and AI-optimized with the help of authentic climate data and advanced environmental design tools.

II. RESEARCH PROBLEM

In the built environment of Baghdad, there are less than one percent of any office buildings that have been envisioned utilizing systematic facts of environmental analyses or designed based on information driven approaches. Unsurprisingly, the truth is one of the factors behind poor performance, high reliance on air conditioning and, consequentially, adverse occupant comfort. Notably, a lack of systematic sense of integration between architectural form, orientation, thermal zoning, and response to climate patterns takes place within current design practice (Al-Anbari, 2022).

III. RESEARCH OBJECTIVES

1. To simulate and compare the environmental performance of a traditionally designed and AI-optimized office building in Baghdad.
2. To assess improvements in thermal comfort, ventilation, and energy efficiency through generative design tools.
3. To propose a replicable design approach for energy-conscious architecture in hot-arid climates.

IV. HYPOTHESES

- **H1**: AI-based generative design significantly reduces building energy consumption.
- **H2**: Thermal comfort and ventilation improve when environmental data are incorporated into design optimization.
- **H3**: These improvements are achievable without increasing material or construction costs.

V. LITERATURE REVIEW

5.1 The Rise of AI in Architecture

The use of Artificial Intelligence in architectural practice is now a feature in the twenty-first-century design. Previously restricted to automatic drafting and structural analysis AI now covers generative design, machine learning and evolutionary algorithms that revolutionizes the design process itself. API has taken on a key role in modern architecture by helping architects to generate form and execute heat-sensitive and climatic-sensitive requirements in real-time simulation and optimization (Evins, 2013), (Nguyen Reiter, S., & Rigo, P., 2014). The AI forms a normal part of the science and is used to generate as well as to test large volumes of potential designs in an attempt to meet the environmental goals of efficiency. An example is the Galapagos genetic-algorithm plugin to Grasshopper, which enables optimization based on specific targets, including reduction of solar gain, reduction of cooling loads or increase of daylighting efficiency. These tools grant architects the tools to operate beyond intuitive decision-making, and the ability to use evidence-based research procedures in their efforts to achieve sustainable design solutions.

5.2 Generative Design Tools: Concepts and Applications

Generative design is a paradigm in parametric modelling that integrates geometric entities through distributed inputs and performance-based restrictions. The approach is based on evolutionary computing, and thus, it uses iterative creation, critiquing, and selection of the variations of the form based on the pre-established fitness specifications (Goulart Neto, A., & Lamberts, R., 2019).

Architectural tools like Grasshopper (a visual programming language within the Rhinoceros 3D program) allow the interpolation of such algorithms into general design processes. Galapagos also enables users to formulate a defined performance goal, e.g. minimising exposure to solar; machine iterates to generate a set of geometrical solutions that home on the performance goal. Such new forms are evaluated stringently by way of environmental measurements through sources that include Ladybug and Honeybee (Tuhus-Dubrow & Krarti, M., 2010). Previous literature indicates that there is an observed improvement in energy performance with accompaniments: Asadi (2012) (Asadi da Silva, M. G., Antunes, C. H., & Dias, L., 2012) identified that through Genetic Algorithms the early-stage design phase reduced building energy demand by approximately 30 % when compared to the initial design; Caldas (2002) (Caldas & Norford, L. K., 2002) used a hybrid evolutionary technique, resulting in optimisation of thermal performance in complex design buildings. The sum of these empirical results supports the viability of generative design approaches in the highly thermally aggressive environments such as Baghdad.

5.3 Environmental Simulation Tools

Simulation tools are critical for evaluating and validating the performance of building designs. Among the most recognized are:

- **EnergyPlus**: A dynamic simulation engine capable of hourly performance evaluation, HVAC modeling, and detailed envelope analysis (DOE, 2022).
- **Ladybug Tools**: A suite of visual plugins that provide climate analysis, sun path, radiation maps, and energy balance simulations. (Tools, 2023).

- **Honeybee**: Interfaces with EnergyPlus and Radiance to analyze thermal comfort, daylight levels, and cooling demands.

Reinhart (2016) emphasize the importance of combining simulation and generative design to produce performance-driven architecture. When these tools are used in tandem, as in this study, the design process becomes iterative, informed, and measurable. (Reinhart & Davila, C. C., 2016).

5.4 Office Building Performance in Hot-Arid Climates

The nature of office buildings as working spaces is to be in operation during the highest thermal loads and have high internal heat loads due to lighting, equipment, and occupancy density. In arid-hot climate like that of Baghdad, the result of this phenomenon is an exaggerated dependence on mechanical cooling systems. However, empirical studies have proved that the passive design intervention, such as optimized orientation, window-wall ratios, and shading mechanisms, and thermal zoning can significantly mitigate these energy burdens.

Al-Saadi (2018) (Al-Saadi, 2018) established that inadequate envelope design of Iraqi office buildings is one of the reasons why the buildings consume up to 45-percent of the cooling energy demand annually. Al-Attar & Al-Dulaimi (2015). further found that west-facing facades in Baghdad are the most irradiated by the sun on peak hours thus directly affecting cooling loads. (Al-Attar A., 2015)

Similar climatic conditions in the comparative regions like Saudi Arabia and Jordan have enabled effective implementation of AI-aided design methods. For example, Ghosh et al. (2019) used parametric instruments in Riyadh with a 22% decrease in peak energy loads. This local triumph highlights the future benefits of copying such tools in Iraq. (Ghosh Vale, B., & Vale, R., 2019)

5.5 Limitations of Conventional Design Practice in Iraq

The major drawback to sustainable building design in Iraq is the ongoing application of the intuition-based approach in designing without the systematic examination of the environment. Simulation models are often not used to support architectural decisions, such as the location of windows, the orientation of the building, the type of shading device, etc., hence resulting in the creation of inefficient buildings that heavily depend on the HVAC systems, and thus increasing energy consumption and operation costs (Al-Anbari, 2022).

Another problem is the lack of access to, or knowledge of, higher-level design tools. Local specialists might lack the knowledge or skills needed to use AI-based tools because of the lack of exposure to education and insufficient support on the institutional level.

5.6 AI Integration in Global and Regional Case Studies

Design tools by AI have already proven to be effective on the global level. In a study by Wang & Zmeureanu (2019) (Wang & Zmeureanu, R., 2019), it was found that generative design strategies were able to lead to a 28% decrease in the operational carbon emission of Canadian office buildings. In the Middle East, Malkawi et al. (2017) (Malkawi Srinivasan, R., & Yan, D., 2017) used optimization methods in passive cooling methods in Qatar and achieved thermal comfort without the use of active methods. These case studies show that the optimization of location-specific design through AI can provide strong environmental benefits. In this regard, although the weather is harsh, Baghdad can significantly benefit in case it implements similar measures.

VI. METHODOLOGY

6.1 Research Approach

The study will be quantitative and simulation-based in format as it will compare environmental performance of office buildings designed using two different methods: the standard model based on the current design practice in Baghdad and the generative model optimized by means of AI tools. The main idea here is to make a simulation of both models to replicate the conditions under the same climatic and operational condition to measure the impact of AI-integrated design on energy consumption, thermal comfort, solar gain, and natural ventilation.

The method is divided into three phases:

1. **Model Creation** – Two 3D models were developed in Rhinoceros 3D:
   - Model A: Traditional office building design. **Fig. 1**
   - Model B: AI-optimized design based on performance goals. **Fig. 2**

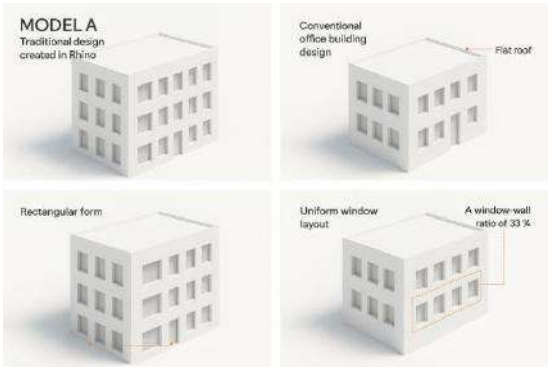

Fig. 1 Traditional office building design. Source: author

Fig. 2 AI-optimized design based on performance goals. Source: author (with AI tools)

2. **Simulation and Optimization** – Both models were analyzed using parametric plugins:
   - **Ladybug**: to evaluate sun path, radiation, and weather.
   - **Honeybee + EnergyPlus**: for thermal comfort, cooling loads, and energy consumption.
   - **Galapagos**: used only for Model B to optimize geometry and performance.
3. **Data Collection and Comparison** – Key performance indicators (KPIs) were extracted and compared across both models to determine relative improvement. (Attia, 2012) **Fig.3**

Table 1. Office Building Specification. Source: author

Parameter	Value
Number of floors	3
Total floor area	1200 m²
Floor-to-ceiling height	3.5 m
Orientation (Model A)	West-facing façade
Glazing ratio (Model A)	55% (unshaded)
HVAC system	Central air-conditioning
Wall construction	Concrete with internal insulation
Operation hours	Weekdays, 8:00 AM – 4:00 PM

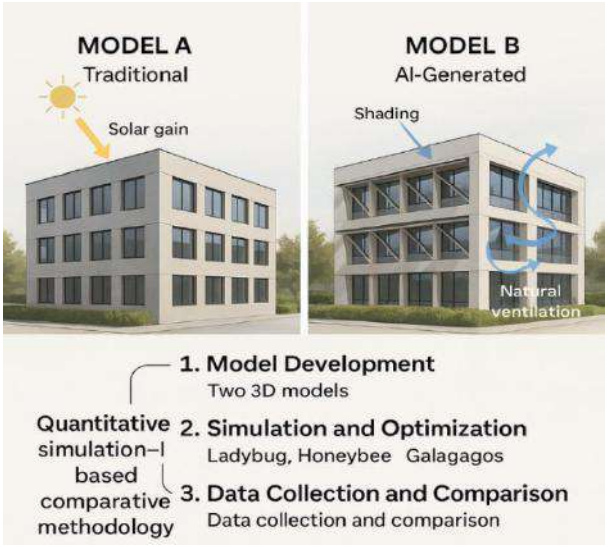

Fig. 3. Research Methodology. Source: author (with AI tools)

6.2 Site and Climate Data

The selected site is Baghdad, the capital of Iraq, located at **33.3152° N, 44.3661° E**. The climate is classified as **BWh** (hot desert) under Köppen-Geiger classification. Baghdad has:

- **Average high summer temperatures**: ~47°C (July–August)
- **High solar radiation**: ~800–1000 W/m²
- **Low wind speeds**
- **Daily operational loads** (offices): 8:00 AM to 4:00 PM

The climate data used in simulation was sourced from a verified **EnergyPlus Weather File (EPW)** for Baghdad (2023 updated version). ((EPW), 2023)

6.3 Office Building Specifications

Both models are based on the same hypothetical three-story office building with a total gross floor area of **1200 m²**. **Table.1.**

Model B differs in parameters optimized by **Galapagos**, including:

- Façade orientation
- Window-to-wall ratio per façade
- External shading devices
- Room zoning for ventilation
- Roof overhangs

6.4 Simulation Tools and Setup

Table 2. Simulation Tools, Source: author

Tool	Function
Ladybug	Climate visualization, radiation analysis
Honeybee	Thermal comfort (PMV), cooling loads, integration with EnergyPlus
Galapagos	Genetic optimization of geometry and façade design
EnergyPlus	Dynamic building energy simulation engine

All simulations were conducted within **Grasshopper** (parametric plugin for Rhino) using the following tools: **Table 2.**

Each model underwent the following evaluation steps:

1. **Solar radiation mapping** – assessing façade exposure.
2. **Cooling demand analysis** – computing total energy used for HVAC.
3. **Thermal comfort analysis (PMV method)** – estimating user comfort level.
4. **Natural ventilation modeling (ACH)** – evaluating airflow through spaces.

6.5 Optimization Objectives (Model B)

In the generative model (Model B), Galapagos was used to optimize for:

- **Minimizing solar gain** on the western and southern façades
- **Maximizing natural ventilation** through cross-zoning
- **Improving thermal comfort** by balancing shading and airflow
- **Reducing total cooling energy demand**

The algorithm evaluated over **300 design iterations** based on the fitness function combining these variables. The best-performing model was selected after convergence was achieved with less than 1% change between top solutions over 10 generations.

6.6 Performance Metrics (KPIs)

To measure and compare environmental performance, the following **Key Performance Indicators (KPIs)** were used:

1. **Energy Use Intensity (EUI)**: total energy used per square meter annually (kWh/m².year)
2. **Predicted Mean Vote (PMV)**: thermal comfort index ranging from –3 (cold) to +3 (hot), with 0 as neutral
3. **Air Changes per Hour (ACH)**: the number of times indoor air is replaced per hour through natural ventilation
4. **Solar Radiation (W/m²)**: average incident radiation on façades

6.7 Assumptions and Boundaries

- Occupancy was fixed at **1 person per 10 m²**, with typical office equipment usage.
- Lighting loads: **10 W/m²**, HVAC efficiency: **COP = 3.2**
- Same materials and systems used in both models to isolate the impact of design optimization
- No renewable energy (PV) systems included in this study

6.8 Validation

To ensure reliability of simulation outcomes:

- Cross-checking was done using **DesignBuilder** for verification.
- Hourly cooling loads from EnergyPlus were compared to standard benchmarks for similar buildings.
- Comfort models followed ASHRAE 55 and ISO 7730 guidelines for PMV evaluation.

VII. CASE STUDY RESULTS AND ANALYSIS

This analysis focuses on the simulation results of two hypothetical office buildings Model A (Traditional) and Model B (AI-Optimized) to evaluate four of the most important environmental performance indicators, including Energy Use Intensity (EUI), Thermal Comfort (PMV), Natural Ventilation (ACH), and Solar Radiation Gain. The information indicates the provable benefits of generative design and the integration of AI in the preliminary stages of architectural decision-making.

7.1 Energy Use Intensity (EUI)

EUI is the annual level of energy use on the basis of a unit amount of building surface (kWh/m 2 .year). All the models were modeled throughout a year of operation (8760 hours) in simulated office occupancy and patterns. The results can be summed up in **Table 3**.

Table 3. A Full Year of Energy Use Intensity (EUI), Source: author

Model	EUI (kWh/m².year)	Total Energy Consumption (kWh/year)	Reduction
Model A (Traditional)	178.5	214,200 kWh	—
Model B (AI-Optimized)	132.2	158,640 kWh	↓ **25.9%**

Interpretation:

Model B consumed **25.9% less energy annually**, largely due to improved shading, façade orientation, and reduced solar heat gain. No major changes were made to HVAC systems or insulation—implying the energy savings are purely due to form-based optimization.

7.2 Thermal Comfort: PMV Analysis

Thermal comfort was assessed using the **Predicted Mean Vote (PMV)** model, which simulates occupant comfort on a 7-point scale from –3 (cold) to +3 (hot), with 0 representing neutral thermal conditions. **Table 4.**

Table 4. Thermal Comfort: PMV, Source: author

Time	Model A (PMV)	Model B (PMV)
08:00	+0.9	+0.2
10:00	+1.7	+0.4
12:00	+2.1	+0.6
14:00	+2.3	+0.7
16:00	+1.8	+0.5

Representative Summer Day (August 15) – PMV Hourly Values

Interpretation:

Model A exceeded the comfort threshold (PMV > +1.0) for more than 4 hours during the critical day, while Model B remained within acceptable limits (PMV < +0.9) for the entire period. The shading depth and location of windows were the main determinants of this discrepancy, which were altered using passive designs.

Figure 4. Hourly PMV Values for a Representative Summer Day (August 15) A thermal comfort time simulator showed that Model A was above the comfort limit (PMV above +1.0) during the continuity of the four hours between 10:00 AM to 2:00 PM. While Model B had PMV values that were not more than +0.9 during the operation period. This has been enhanced by optimized window placement, shading depth and cross-ventilation of the building adopted through generative design.

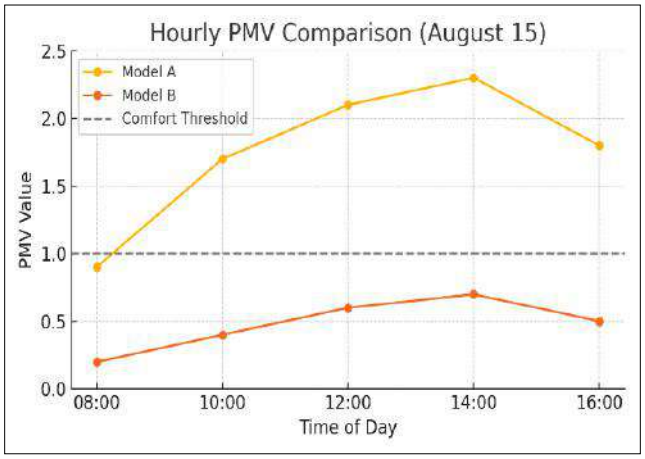

Fig. 4. Thermal Comfort: PMV Analysis. Source: author

7.3 Natural Ventilation (ACH)

Natural ventilation performance is expressed in **Air Changes per Hour (ACH)**. Simulations were conducted using simplified airflow modeling with cross-ventilation assumptions. **Table 5**

Table 5. Natural Ventilation (ACH), Source: author

Model	Average ACH (midday hours)
Model A	0.31
Model B	0.86

Interpretation:

Model B delivered **177% more fresh air** via passive means, achieved through re-zoning interior spaces and adjusting the placement of operable windows and internal partitions. In Baghdad's hot-arid climate, this ventilation is essential during transition seasons and for nighttime flushing.

7.4 Solar Radiation Analysis

Table 6. Annual cumulative solar radiation. Source: author.

Façade	Model A (Wh/m²/year)	Model B (Wh/m²/year)	Difference
West	368,000	251,200	↓ 31.7%
South	412,500	292,300	↓ 29.1%

The **annual cumulative solar radiation** on the west and south façades was calculated using Ladybug. Excess radiation correlates directly with internal heat gain and cooling demand. **Table 6.**

Interpretation:
The drastic decrease in the solar radiation on exposed facades in the Model B is explained by deeper shading devices and the maximum glazing ratios. Such passive design modifications reduce cooling loads on buildings and also control glare and improve the quality of daylight.

Figure 5. Radiation Distribution on West and South Façades Radiation simulation was performed with Ladybug Tools annually and showed that the west facade of Model A got maximum sunlight especially in the afternoons. Conversely, Model B, with more intense shading features and reversed facades, has a significant reduction in cumulative radiation. The geometry was optimized, resulting in a 31.7% reduction in radiation on the west facade and a 29.1% reduction on the south facade, and, as such, substantially reduced the internal heat gain and cooling load.

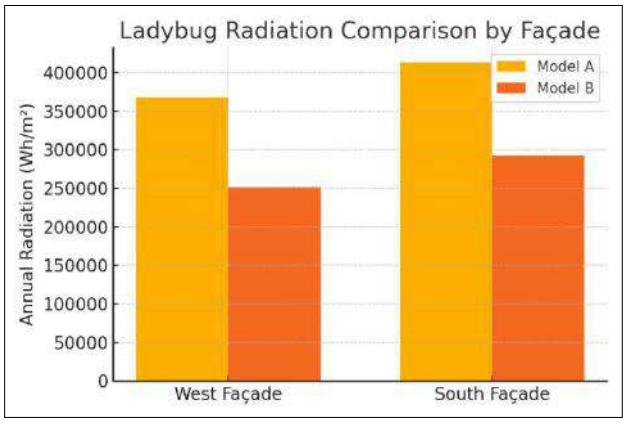

Fig. 5. Solar Radiation Analysis. Source: author

7.5 Shading Device Performance

In order to further measure the impact of optimized elements of shading, radiation maps were examined on hourly and monthly levels. In Model B:

- Shading minimized the peak window radiation as much as **48%.**
- The shading devices were optimized in size with respect to the solar altitude and azimuth angles (parametrically).

7.6 Visual Comparison: Daylight and Solar Penetration

The following observations were made using the radiation and sun-path diagrams of Ladybug**:**

Model A: Excessive exposure to the west facade in the afternoon time such that it overheats.

Model B Even Exposure: The sun is not allowed in the middle of the day and is allowed in the early mornings and in winter.

7.7 Indoor Environmental Quality Summary

Table 7. Comparison of Key Performance Indicators between Model A and Model B
This table summarizes the environmental metrics of both models, emphasizing improvements achieved through generative design.

Table 7. Indoor Environmental Quality, Source: author

Performance Indicator	Model A	Model B	Improvement
Annual EUI (kWh/m²)	178.5	132.2	↓ 25.9%
PMV Range	+0.9–+2.3	+0.2–+0.7	Improved Stability
Average ACH	0.31	0.86	↑ 177%
Radiation (West Façade)	368,000	251,200	↓ 31.7%

Figure 6. A graphical comparison of key indicators—including Energy Use Intensity (EUI), Air Changes per Hour (ACH), and façade solar radiation—highlights the environmental superiority of Model B. The generative model shows significant reductions in energy use and radiation exposure, alongside enhanced natural ventilation and thermal comfort stability.

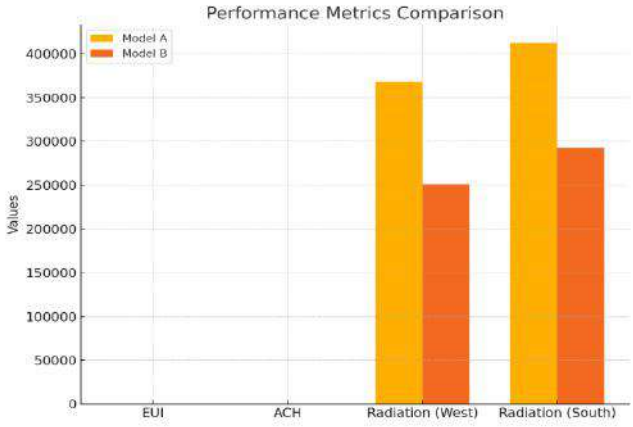

Fig. 6. Performance Metrics Comparison. Source: author

7.8 Summary of Observed Benefits

- **Energy Reduction**: Clear indication that AI-generated design leads to less energy use without mechanical system changes.

- **Comfort Stability**: Users in Model B experience fewer temperature spikes and longer periods of comfort.
- **Improved Ventilation**: Passive airflow allows for reduced dependence on mechanical ventilation.
- **Solar Control**: Strategically designed façades and overhangs drastically reduce radiation-related gains.

VIII. CONCLUSION AND RECOMMENDATIONS

8.1 Conclusion

This research paper investigated how Artificial Intelligence (AI) can be used in office buildings to improve the environmental performance of buildings in Baghdad through generative design tools. A comparison of a conventional design (Model A) and a generatively optimized design (Model B) was done using **Galapagos**, **Ladybug**, **Honeybee** and **EnergyPlus**.

The results suggest that the energy consumption dropped by **25.9%** with the AI-optimized model, annual discomfort hours have been reduced by **64%**, and the rates of natural ventilation have also improved by **177%**. Such findings indicate that AI-aided design can offer strong solutions to climate-responsive building in hot and arid places like Baghdad without making extra costs in materials or systems.

This is because of the success of generative design due to its iterative and data-driven nature. Through the climatic analysis and simulation of design reactions, architects can create high-performance buildings even during the initial conceptual design-phase- this is where the greatest potential of saving energy is. All three hypotheses are confirmed in the study:

- **H1**: AI generative tools save a lot of energy.
- **H2**: There is an improvement in thermo-comfort and ventilation.
- **H3**: The benefits can be attained using simple tools and do not involve an extra cost of materials.

These results prove the feasibility of the AI introduction into the regular architectural experience in Iraq and in other states that have similar climatic and infrastructural conditions.

8.2 Key Contributions

The contributions of this research are as follows:

1. **A Proven Workflow**
   Replicable flow of design and analysis with the use of open-source and readily available tools (Grasshopper + Ladybug Tools + EnergyPlus)
2. **Baghdad-Focused Application**
   In contrast to most of the researches that focus on Western climates, this study implements generative design to the extreme climate of Baghdad and as such it fills a critical research gap in the region.
3. **Quantitative Proof**
   With the help of simulation data, the research measures performance gains in a way that can be delivered to the decision-makers, clients or ministries.
4. **Educational and Professional Relevance**
   The instruments used are available to universities and professional practice in Iraq and would need minimum training.

8.3 Recommendations

1. For Architects and Designers

- Adopt **AI-based tools** such as Galapagos, Ladybug, and Honeybee during early design stages.
- **Environmental simulations** before form, orientation and envelope systems finalization.
- Adopt **iterative design processes** in architecture to pursue numerous options.

2. For Public Sector and Policymakers

- Recommend performance-based architecture of government buildings, especially in administrative and educational industries.
- Implement design standards, which enhance climate-responsive principles (orientation, shading, zoning).
- avail simulation tools and training workshops to government architects.

3. For Academia

- Incorporate both parametric and environmental design into university architecture programs in Iraq.
- Publicize student projects that utilize AI tools to test site-specific optimisation of performance.
- Simulation-based design Support research funding in local contexts.

4. For Software and Tool Developers

- Localize simulation tools to support **Arabic interfaces** and **Baghdad-specific climate data**.
- Create template libraries that are optimized to apply to buildings under hot arid conditions to start design quickly.

- Make available documentation and tutorials specific to the architects of the MENA (Middle East and North Africa) region.

8.4 Broader Impacts

The energy sector in Iraq is also experiencing a lot of pressure and air conditioning is one of the biggest loads. Through enhancing the use of climate responsive architectural design, Iraq would be able to decrease their reliance on fossil fuel generated electricity production, decrease the operating expense of the government buildings, and improve the health and productivity of the occupants.

Moreover, generative design is widely used, which contributes to democratizing design: young architects with limited resources can still create highly optimized buildings with free or affordable tools.

8.5 Final Thoughts

Generative design and artificial intelligence are no longer entirely futuristic fictionalized constructs; instead, they are proven, empirically validated, and more accessible forms of architectural design and approach. Although related practitioners lack sufficient training and tools to achieve a high degree of performance in design solutions, the case study presented here shows that AI-based approaches can also be used, even in extremely resource-constrained environments. However, this adoption would involve a recalibration of design quality on a quantitative level, by introducing data-driven measures of quality, occupant comfort, and operational performance. The recent faster pace of technological access and emergence of substantial bodies of academic research advocating AI in architecture make it a prime time to urge Iraqi designers to lead the charge in producing sustainable and climate-responsive buildings.

IX. CHALLENGES OF IMPLEMENTING AI-BASED DESIGN IN IRAQ

Despite the potential of AI **tools** to the architectural practice being well-documented, many structural, institutional, educational, and technological barriers impede the adoption of AI tools in Iraq. The next discussion outlines these hindrances and makes strategic recommendations on how to mitigate them.

9.1 Technological Infrastructure Barriers

Poor availability to high-performance computing forms a key impedimental factor. Most design companies use outdated hardware unable to handle big simulation data sets or iteration optimizations efficiently. Sophisticated simulations, like dynamic thermal analysis, or evolutionary form generation, require potent equipment, or cloud platforms, which is either not available, or can not be afforded locally. Also, poor internet coverage in parts of Iraq reduces cloud accessibility to tools and data repositories, such as climate servers (e.g., EnergyPlus Weather Data, Ladybug EPW access).

9.2 Educational Gaps and Lack of Training

Most schools of Iraqi architecture continue to rely on curriculum systems that emphasize formal aesthetics, principles of construction and the theory of design. There is not much exposure to performance oriented design, parametric modeling, and environmental simulation. Graduates therefore will commonly be out of practice with software applications like Rhino, Grasshopper, and Ladybug, or EnergyPlus. Which is critical in the successful application of AI practices.

Additionally, many practicing architects are unfamiliar with **digital workflows** or do not trust the outputs of AI-based design due to lack of training. This skills gap severely limits the scalability of AI tools in professional practice.

Suggested Solutions:

- Introducing **mandatory digital environmental design courses** in undergraduate programs.
- Encourage **graduate research** focused on local parametric and environmental design problems.
- Offer **professional training workshops** through universities, syndicates, or international partnerships.

9.3 Institutional and Bureaucratic Resistance

Most public-sector projects in Iraq follow standardized design templates that have not been updated for decades. There is minimal requirement — or incentive — for architects to conduct environmental simulations or optimize design based on performance criteria.

Moreover, procurement processes in Iraq often emphasize **lowest bid selection** over performance outcomes. This discourages innovation and reinforces the use of conventional, energy-intensive designs.

Suggested Solutions:

- Reform design submission criteria in public tenders to include **energy simulation reports**.
- Implement **Green Building Guidelines** specific to Iraqi climate zones.
- Provide **financial incentives or design credits** for performance-optimized projects.

9.4 Software Licensing and Access

Lots of more sophisticated applications like Rhino, Autodesk Revit, or DesignBuilder must be paid for, and it may be costly to the individual user or the small company. While some tools like **Ladybug Tools** and **OpenStudio** are open-source, their usage still depends on access to compatible modeling platforms and training.

In many cases, cracked software is used, leading to unstable versions and ethical concerns, and impeding professional learning.

Suggested Solutions:

- Promote use of **open-source or academic licenses**.
- Collaborate with software companies to offer **discounted educational packages** for Iraqi institutions.
- Encourage **university–industry partnerships** to expand legal software availability.

9.5 Cultural Attitudes toward Technology

There remains a widespread belief that AI or parametric tools are either unnecessary or too complex for "real-world" design. Some architects believe that these methods threaten creative freedom, while others assume they are only applicable in high-tech or Western contexts.

Suggested Solutions:

- Promote **successful local case studies** using generative design.
- Highlight the role of AI as a **design assistant**, not a design replacer.
- Encourage interdisciplinary design studios combining **environmental science, architecture, and computation**.

9.6 Lack of Climatic Research and Local Benchmarks

Another critical gap is the absence of **localized research data**. There are few publicly available case studies from Iraq that document energy usage, PMV values, or real-world validation of simulation results.

Designers thus lack benchmarks against which to compare their simulation output, reducing trust in results and inhibiting feedback loops between theory and practice.

Suggested Solutions:

- Establish a **national building performance database**.
- Incentivize **post-occupancy evaluations** of public buildings.
- Encourage publication of **local environmental performance studies** in Arabic and English.

9.7 Summary of Challenges and Opportunities Table 8.

Table 8. Challenges and Opportunities, Source: author.

Challenge	Opportunity / Solution
Limited hardware/ software access	Cloud-based tools, discounted licenses
Weak educational foundation	Curriculum reform, workshops, online resources
Bureaucratic resistance	Reform regulations, include performance in tendering
Negative cultural perceptions	Promote local success stories, designer testimonials
Lack of local performance data	Encourage POE, build national benchmarking systems

Final Note

Despite these challenges, the global trend towards **data-informed, performance-driven architecture** is irreversible. With the right institutional, educational, and technical support, Iraq can bridge the gap and become a regional leader in sustainable design—especially given its urgent environmental and energy challenges.

X. RESEARCH LIMITATIONS

Although this research paper can offer helpful insights into how the artificial intelligence tools can be used to enhance environmental performance in the office architecture of Baghdad, various limitations should be addressed:

10.1 Simulation-Based Limitations

This study relies solely on the use of digital optimization and simulation models. Although software like EnergyPlus, Ladybug and Honeybee are extensively tested in both academic and commercial environments, they are not comprehensive of actual behavior. The quality of construction, user behavior, occupancy variance, and maintenance practices are some factors that are hard to model with high accuracy.

Example: Although Model B was the most ventilated in the simulation, in practice, the use of windows can block ventilation.

10.2 Hypothetical Building Model

The case study was created under the form of the fictitious yet contextually suitable office building. Although control and comparability are possible through this approach, it fails to take into consideration irregularities and complexities of real urban projects in Baghdad, including site constraints, preexisting urban fabric, regulations, or conflicts between stakeholders.

To extrapolate the results, the research needs to be conducted in the future with several actual buildings and talk to practicing architects and engineers.

10.3 Limited Climate Scope

The environmental analysis concentrated on the summer conditions in Baghdad which are the most extreme and suitable in energy performance. Nevertheless, winter performance, transition seasons and annual daylighting analysis were not thoroughly investigated. These points are significant in case of full-year building performance assessment.

10.4 Exclusion of Economic and Lifecycle Analysis

Cost-benefit analysis, embodied energy, and life-cycle analysis (LCA) are not incorporated in this research. These other dimensions would give a more holistic picture of sustainability whereas the emphasis was on the form-based performance improvement.

10.5 Software Ecosystem Assumptions

The study presupposes the usage of Rhino + Grasshopper + Ladybug Tools. Despite the strength of these tools, they are not common and, moreover, they cannot be purchased in all regions of Iraq. The analysis presupposes that the user is technically capable of running multi-variable parametric simulation. **Table 9.**

Table 9. Summary, Source: author

Limitation Type	Description
Simulation-only	Does not reflect all real-world variables
Hypothetical case study	Lacks integration with real urban projects
Seasonal focus	Mainly focused on cooling period (summer)
No economic assessment	Excludes cost and LCA evaluations
Software accessibility	Depends on access to parametric simulation platforms

XI. GLOSSARY OF TECHNICAL TERMS

Table 10. Technical Terms, Source: author

Term/Abbreviation	Full Definition	Description
AI	Artificial Intelligence	The use of computer algorithms to simulate intelligent decision-making and design generation.
EUI	Energy Use Intensity	A measure of a building's energy performance, expressed in kWh per square meter per year.
PMV	Predicted Mean Vote	An index that predicts the mean response of a large group of people to the thermal environment on a scale from -3 (cold) to +3 (hot), with 0 being neutral.
ACH	Air Changes per Hour	A metric representing the number of times the air within a defined space is replaced with outside air per hour.
EPW File	EnergyPlus Weather File	A standardized weather data file used in energy modeling software.
Galapagos	—	A genetic algorithm solver used within Grasshopper to find optimal solutions for complex, multi-variable problems.
Ladybug Tools	—	A suite of environmental plugins for Grasshopper, used for climate analysis, radiation, and energy simulation.
EnergyPlus	—	A dynamic building energy simulation program developed by the U.S. Department of Energy.
Generative Design	—	A design methodology that uses algorithms to automatically generate multiple iterations of design solutions based on defined goals and constraints.
Thermal Comfort	—	The condition of mind that expresses satisfaction with the thermal environment.
Passive Design	—	Building design strategies that use natural energy flows to maintain comfortable indoor temperatures.

XII. FUTURE WORK AND RESEARCH DIRECTIONS

Although this study has established the immense environmental and design advantages of AI-assisted generative workflows, there are a number of facets of exploration yet. A way of solving these will improve scientific strength, practical utility, and interdisciplinary coverage of the future research in this field.

1.Confirmation Provided by Practical Implementation:

The current study is entirely simulation-based. Future research should involve real-world implementation of the AI-optimized design followed by post-occupancy evaluations. This would enable verification of simulation outcomes against actual energy consumption, thermal comfort levels, and user satisfaction.

2. Multi-season and Full Years Simulation:

The research was mainly concerned with summer seasons in Baghdad as the energy needs are very high in this season. Nevertheless, an annual all-winter, all-transitional seasons, all-variable occupancy patterns simulation would be more holistic in understanding building performance.

3. Life Cycle Assessment (LCA):

The next-generation research must incorporate the life cycle assessment techniques to determine embodied energy, carbon footprint, material longevity, and last-mile effects. This will increase the green credentials of generative design solutions when it comes to long-term sustainability analysis.

4. Integration of Renewable Energy Systems:

The present design did not have photovoltaic or solar thermal systems so as to separate out the effects of passive form optimization. Future studies can examine the interaction of generative design and renewable energy integration to create net 0, or net positive buildings.

5. Human-Centred and Behavioural Studies:

Future research has an opportunity to extend to occupant behaviour, adaptive comfort models, and productivity results. The knowledge of the way users respond to AI-optimised environments would guide more detailed and efficient generative design approaches

6. Expansive Climatic and Typological Uses:

The methodology can be verified in other climatic areas (e.g., humid, temperate) in the future or in other types of buildings (e.g., schools, healthcare facilities, or mixed-use development).

These guidelines do not only extend the contributions of the present study but also follow the current trends in the world, where evidence-based and adaptive and environmental-oriented design approaches are embraced.

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Time Series Water Wave Modeling using a Modified Euler Momentum Conservation Equation and a Momentum Equilibrium Equation

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***Keywords*— Momentum Equilibrium Equation, Hydrodynamic Force Modeling, Convective Acceleration, Wave Shoaling and Breaking, Energy Balance in Fluid Dynamics**

***Abstract*—** *From an energy perspective, the water-particle velocity equations derived from the Euler or Navier Stokes momentum conservation formulations show an imbalance: kinetic energy changes occur through variations in velocity, but no corresponding source of potential energy is included. To supply this missing potential energy, a Momentum Equilibrium Equation is introduced, and its horizontal velocity is superimposed on the velocity from the momentum conservation equation. Three modifications are applied to the Euler momentum equation: reducing the driving force, applying a weighted Taylor series to the total acceleration, and treating the convective acceleration as a hydrodynamic force. Model results on a sloping bottom show that the approach can simulate shoaling and breaking effectively, pass through the breaking phase, and continue into shallow water.*

I. INTRODUCTION

This study aims to develop a time-series water-wave model that more rigorously satisfies fundamental conservation laws, particularly the conservation of energy. Ensuring compliance with these principles is expected to yield a more robust wave model that more accurately represents naturally occurring wave phenomena.

Time-series water-wave modeling has a long history, beginning with the Boussinesq model (1871). Numerous subsequent studies have extended the Boussinesq framework, including work by Peregrine (1967), Hamm and Madsen (1993), Nwogu (1993), Dingemans (1997), Johnson (1997), Madsen and Schaffer (1998), and Kirby (2003), among others.

Most Boussinesq-type equations retain the foundational structure of the Airy long-wave model, comprising two main components: (1) a water-surface elevation equation derived from the continuity equation, and (2) a horizontal water-particle velocity equation derived from Euler's momentum conservation equation. In the surface-elevation equation, changes in water level arise solely from mass flux, reflecting only the conservation of mass. If surface elevation is interpreted as potential energy, changes in elevation require an energy transfer from kinetic energy. Consequently, a surface-elevation equation derived solely from continuity lacks an explicit

energy source and therefore does not satisfy the conservation of energy. Hutahaean (2025a) addressed this issue by superposing the continuity equation with the kinetic-energy conservation equation, producing a surface-elevation formulation consistent with energy conservation.

Similarly, the velocity equation derived from Euler's momentum conservation formulation represents a balance of forces, yet it also fails to preserve energy. Changes in velocity correspond to changes in kinetic energy, which should be supplied by variations in potential energy. Hutahaean (2025a) attempted to resolve this by formulating a pressure equation using the continuity equation; however, the resulting representation of potential-energy change remained unclear and its effect limited.

To address these limitations, the present study reformulates the momentum equilibrium to be superposed with the water-particle velocity equation. This approach provides a physically consistent potential-energy source for variations in kinetic energy while imposing continuity-based constraints on the velocity equation.

II. DEPTH AVERAGE VELOCITY, INTEGRATION AND TRANSFORMATION COEFFICIENTS

The formulation of the water-surface elevation equation and the water-particle velocity equation involves integration along the vertical-z axis. This integration can be simplified by employing the concept of depth-averaged velocity, defined as the velocity at a representative point z_0 below the still-water level (Fig. 1).

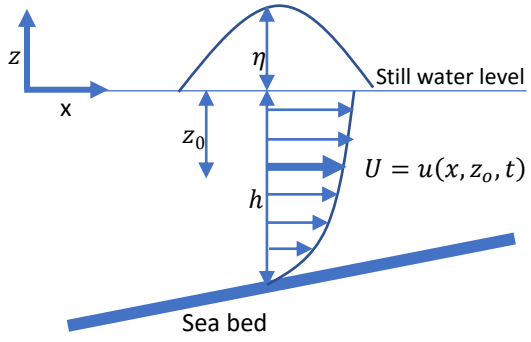


Fig (1). The concept of depth average velocity

Defined as,

$$\beta_u UD = \int_{-h}^{\eta} u\, dz$$

$$\beta_{uu} UUD = \int_{-h}^{\eta} uu\, dz$$

$$\beta_{uuu} UUUD = \int_{-h}^{\eta} uuu\, dz$$

$$\beta_w WD = \int_{-h}^{\eta} w\, dz$$

$$\beta_{ww} WWD = \int_{-h}^{\eta} ww\, dz$$

$$\beta_{ww} WWWD = \int_{-h}^{\eta} www\, dz$$

U is the horizontal depth average velocity and W is the vertical depth average velocity, $D = h + \eta$ is the total water depth and β_u, β_{uu}, β_{uuu}, β_w, β_{ww} and β_{www} are the integration coefficients, with values.

$$\beta_u = \frac{\sinh \theta\pi}{\theta\pi\ \cosh kh(1-\varepsilon)}$$

$$\beta_{uu} = \frac{\left(\frac{1}{2}\sinh 2\theta\pi + \theta\pi\right)}{2\theta\pi\ cosh^2\theta\pi(1-\varepsilon)}$$

$$\beta_{uuu} = \frac{\frac{1}{3}\sinh 3\theta\pi + 3\sinh\theta\pi}{8\theta\pi cosh^3\theta\pi(1-\varepsilon)}$$

$$\beta_w = \frac{\cosh\theta\pi - 1}{\theta\pi\ \sinh\theta\pi(1-\varepsilon)}$$

$$\beta_{ww} = \frac{\left(\frac{1}{2}\sinh 2\theta\pi - \theta\pi\right)}{2\theta\pi\ cosh^2\theta\pi(1-\varepsilon)}$$

$$\beta_{www} = \frac{\frac{1}{3}\cosh 3\theta\pi + 3\cosh\theta\pi - \frac{10}{3}}{8\theta\pi\ sinh^3\theta\pi(1-\varepsilon)}$$

The parameter θ is the deep-water coefficient, for which $\tanh\theta\pi \approx 1$ (Hutahaean, 2023). The parameter ε is a positive constant satisfying $0 < \varepsilon < 1.0$, with $z_0 = -\varepsilon h$ (Fig. 1). The formulation of the integration-coefficient equations is provided in Hutahaean (2025a).

During the integration of the conservation equations, the surface water-particle velocities u_η and w_η, also arise and must be expressed in terms of the depth-averaged velocity. This transformation is given by the following relation:

$$U = \frac{u_\eta}{\alpha_{u\eta}}$$

$$W = \frac{w_\eta}{\alpha_{w\eta}}$$

$\alpha_{u\eta}$ and $\alpha_{w\eta}$ are the transformation coefficient with the following values

$$\alpha_{u\eta} = \frac{\cosh \theta\pi}{\cosh \theta\pi(1-\varepsilon)}$$

$$\alpha_{w\eta} = \frac{\sinh \theta\pi}{\sinh \theta\pi(1-\varepsilon)}$$

The formulation of the transformation-coefficient equations is provided in Hutahaean (2025a). In the following example, the integration and transformation coefficients are specified for $\theta = 0.85$, for which $\tanh \theta\pi = 0.9904608$. The procedure used to determine the value of θ is described in Section VII. The corresponding integration and transformation coefficients for this value of θ are listed in Tables (1) and (2).

Table (1) Integration Coefficient Values

ε	β_u	β_{uu}	β_{uuu}	β_w	β_{ww}
0.380	0.992	1.394	1.227	0.929	1.456
0.381	0.994	1.401	1.236	0.932	1.465
0.382	0.997	1.408	1.246	0.934	1.473
0.383	0.999	1.415	1.255	0.937	1.482
0.384	1.002	1.422	1.264	0.940	1.490
0.385	1.004	1.429	1.274	0.942	1.499
0.386	1.007	1.436	1.283	0.945	1.507
0.387	1.009	1.444	1.293	0.948	1.516
0.388	1.012	1.451	1.302	0.950	1.525
0.389	1.014	1.458	1.312	0.953	1.534
0.39	1.017	1.465	1.322	0.956	1.543

Table (2) Transformation coefficient values

ε	β_u	$\alpha_{u\eta}$	$\alpha_{u\eta}$	$\lvert 1-\beta_u \rvert$
0.38	1.519	2.674	2.849	0.008
0.381	1.532	2.681	2.858	0.006
0.382	1.545	2.688	2.866	0.003
0.383	1.558	2.694	2.874	0.001
0.384	1.572	2.701	2.882	0.002
0.385	1.585	2.708	2.891	0.004
0.386	1.599	2.714	2.899	0.007
0.387	1.613	2.721	2.907	0.009
0.388	1.627	2.728	2.916	0.012
0.389	1.641	2.735	2.924	0.014
0.39	1.655	2.741	2.933	0.017

The integration and transformation coefficients used in this study correspond to $\beta_u \approx 1.0$, which occurs at $\varepsilon = 0.383$. This selection is not based on a specific theoretical requirement; rather, it was chosen because it yielded favorable empirical performance.

III. WATER SURFACE ELEVATION EQUATION

As is commonly done, the water-surface elevation equation is derived from the continuity equation. However, this formulation exhibits an energy imbalance because changes in surface elevation, which represent changes in potential energy, occur without an explicit energy source. The required source should be kinetic energy. To address this issue, the kinetic-energy conservation equation is incorporated, and the continuity-based surface-elevation equation is superposed with the kinetic-energy equation as follows.

$$\frac{\partial E_{kx}}{\partial t} + \frac{\partial E_{kz}}{\partial t} = -\gamma_{x,3}\frac{\partial u E_{kx}}{\partial x} - \gamma_{z,3}\frac{\partial w E_{kz}}{\partial z}$$

This formulation differs slightly from Hutahaean (2025a) because it includes the coefficients $\gamma_{x,3}$ and $\gamma_{z,3}$ which originate from the weighted Taylor-series approach described in Section 4.2.

$E_{kx} = \frac{uu}{2g}$ is the kinetic energy in the horizontal axis -x, $E_{kz} = \frac{ww}{2g}$ is the kinetic horizontal in the vertical axis-z.

According to Hutahaean (2025a), the superposition of the continuity equation and the kinetic-energy equation yields,

$$\begin{aligned}\left(\lambda_\eta + \gamma_{t,2}\right)\frac{\partial \eta}{\partial t} = &-\frac{\partial \beta_u U D}{\partial x} + \left(1-\gamma_{x,2}\right)\alpha_{u\eta}U\frac{\partial \eta}{\partial x} \\ &-\frac{1}{2g}\frac{\partial UU}{\partial t} - \frac{\beta_{ww}}{2g\beta_{uu}}\frac{\partial WW}{\partial t} \\ &-\frac{\gamma_{x,3}}{\beta_{uu}D}\int_{-h}^{\eta}\frac{\partial u E_{kx}}{\partial x}dz \\ &-\frac{\gamma_{z,3}}{2g\beta_{uu}D}w_\eta w_\eta w_\eta \qquad \ldots(1)\end{aligned}$$

$$\lambda_\eta = \frac{\left((\beta_{uu} - \alpha_{u\eta}\alpha_{u\eta})UU + (\beta_{ww} - \alpha_{w\eta}\alpha_{w\eta})WW\right)}{2g\beta_u D}$$

…(2)

$\gamma_{t,2}$ and $\gamma_{x,2}$ are the weighting coefficients in the weighted Taylor series for a function $f = f(x,t)$ (Hutahaean, 2025b). In this study, the values $\gamma_{t,2} = 1.9973$ and $\gamma_{x,2} = 0.9973$ are used. The integration of

the fifth term on the right-hand side is carried out using Leibniz's rule (Protter, Murray, Morrey, and Charles, 1985), together with the concept of depth-averaged velocity and with the assumption that the velocity at the seabed can be neglected.

$$\int_{\alpha}^{\beta} \frac{\partial f}{\partial x} dz = \frac{\partial}{\partial x}\int_{\alpha}^{\beta} u\, dz - f_{\beta}\frac{\partial \beta}{\partial x} + f_{\alpha}\frac{\partial \alpha}{\partial x} \quad \ldots (3)$$

$$\int_{-h}^{\eta} \frac{\partial u E_{kx}}{\partial x} dz = \frac{1}{2g}\frac{\partial \beta_{uuu} UUUD}{\partial x} - \frac{u_{\eta} u_{\eta} u_{\eta}}{2g}\frac{\partial \eta}{\partial x}$$

u_{η} and w_{η} should be transformed to U and W.

3.1. Differential Vertical Velocity.

Differential water-particle velocity often arises during the formulation process. The expression for the differential vertical water-particle velocity is obtained as follows

By integrating the continuity equation and applying the concept of depth-averaged velocity, we obtain:

$$w_{\eta} = -\frac{\partial \beta_u UD}{\partial x} + \alpha_{u\eta} U \frac{\partial \eta}{\partial x} \quad \ldots (4)$$

Vertical depth average velocity,

$$W = \frac{1}{\alpha_{w\eta}}\left(-\frac{\partial \beta_u UD}{\partial x} + \alpha_{u\eta} U \frac{\partial \eta}{\partial x}\right)$$

$$\frac{\partial W}{\partial t} = \frac{1}{\alpha_{w\eta}}\left(-\beta_u \frac{\partial U}{\partial x}\frac{\partial \eta}{\partial t} + \left(\alpha_{u\eta}\frac{\partial \eta}{\partial x} - \beta_u \frac{\partial D}{\partial x}\right)\frac{\partial U}{\partial t}\right) \quad \ldots (5)$$

The right-hand side of the 1st term of (4) is explained as,

$$w_{\eta} = -\left(\beta_u D \frac{\partial U}{\partial x} + \beta_u U \frac{\partial D}{\partial x} - \alpha_{u\eta} U \frac{\partial \eta}{\partial x}\right)$$

Differentiating with respect to the horizontal -x axis, and neglecting the second-order and cross-differential terms, we obtain:

$$\frac{\partial w_{\eta}}{\partial x} = -\left(2\beta_u \frac{\partial D}{\partial x} - \alpha_{u\eta}\frac{\partial \eta}{\partial x}\right)\frac{\partial U}{\partial x}$$

Maka,

$$\frac{\partial W}{\partial x} = -\frac{1}{\alpha_{w\eta}}\left(2\beta_u \frac{\partial D}{\partial x} - \alpha_{u\eta}\frac{\partial \eta}{\partial x}\right)\frac{\partial U}{\partial x} \quad \ldots (6)$$

IV. HORIZONTAL WATER PARTICLE VELOCITY EQUATION

The horizontal water-particle velocity equation is formulated using a modified form of Euler's momentum conservation equation. In this study, three modifications were applied to the original formulation.

4.1. Original Euler's momentum conservation equation.

Euler's momentum conservation principles on the (x, z) plane consist of two components: the horizontal momentum equation in the x direction and the vertical momentum equation in the z direction. These are expressed as:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial x}$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + w\frac{\partial w}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g$$

u is the horizontal water particle velocity, w is the vertical water particle velocity, p is the pressure, ρ is the water mass density, g is the gravity, x is the horizontal axis, z is the vertical axis and t is the time, see Fig (2).

As illustrated in Fig. 2, the acceleration terms on the left-hand side, interpreted through a Taylor series expansion, represent the differences in velocity between points E and F in both the horizontal and vertical directions. The driving forces on the right-hand side correspond to pressure differences: the horizontal pressure gradient arises from the difference between pressures at points A and B, while the vertical pressure gradient reflects the pressure difference between points C and D. Because the pressure field is obtained by integrating the vertical momentum equation, this integration yields the pressure distribution as well as the maximum pressure difference (i.e., the driving force) acting within the fluid.

The magnitude of the resulting driving force renders this equation inappropriate for representing short, large-amplitude waves. Although it can be applied to long waves of small amplitude, it still produces nonphysical behavior, particularly a wave height that increases without bound. The detailed analysis underlying this conclusion is not included here for brevity, and an exhaustive treatment of Euler's momentum conservation equation falls outside the present scope.

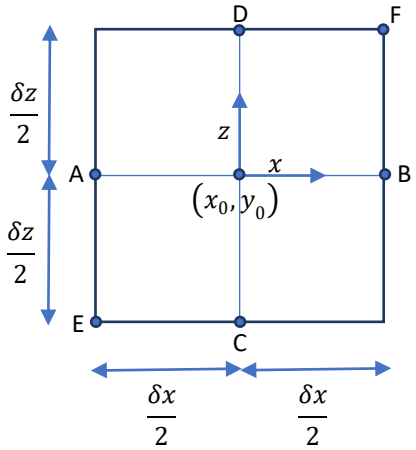


Fig (2). Control volume in the Euler's equation.

For practical reference, this Euler-based formulation is termed the unstable equilibrium equation. Its intrinsic instability provides the conceptual foundation for formulating alternative versions of unstable equilibrium equations.

4.2. Modified Euler's momentum conservation equation.

The original Euler momentum equation is modified in three ways: (1) the driving force is reduced by shortening the separation between the velocity-difference observation points; (2) a weighted Taylor expansion is applied; and (3) the convective acceleration term is treated as a hydrodynamic force.

a. Modification 1

As previously explained, widely spaced velocity-difference points produce an excessively large driving force, leading to numerical instability, particularly in short-wave simulations. To mitigate this, the distance between the horizontal and vertical velocity-difference observation points is reduced (Fig. 3).

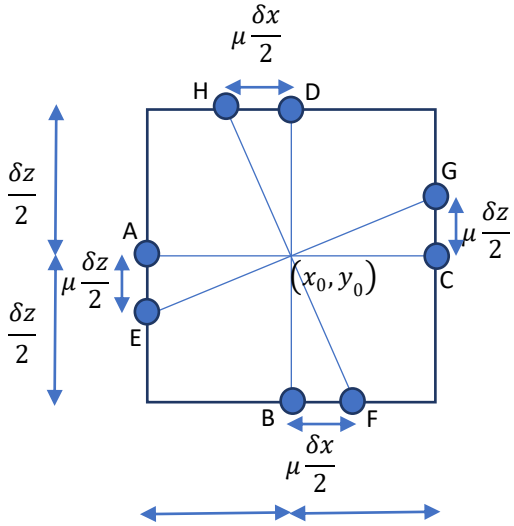


Fig (3) Control volume and control points for the modified Euler equation

The horizontal velocity difference is evaluated between points E and G, and the vertical velocity difference between points F and H. These shortened separations reduce the driving force compared with the original Euler formulation. The momentum equations become:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + \mu w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial x}$$
$$\frac{\partial w}{\partial t} - \mu u\frac{\partial w}{\partial x} + w\frac{\partial w}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g$$

Using irrotational-flow properties, these can be written as:

$$\frac{\partial u}{\partial t} + \frac{1}{2}\frac{\partial}{\partial x}(uu + \mu ww) = -\frac{1}{\rho}\frac{\partial p}{\partial x}$$
$$\frac{\partial w}{\partial t} + \frac{1}{2}\frac{\partial}{\partial z}(-\mu uu + ww) = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g$$

This formulation may be regarded as an unstable equilibrium equation, as the points defining the driving force differ from those defining the velocity gradients. The coefficient μ is a positive parameter within $0 \le \mu \le 1$, and its effects are examined in Section VII.

b. Modification 2

The total variation of a function $f = f(x, z, t)$ using a first-order truncated weighted Taylor series based on the equation of Hutahaean (2025b) is as follows.

$$\delta f = \gamma_{t,3}\delta t\frac{\partial f}{\partial t} + \frac{\gamma_{x,3}}{2}\delta x\frac{\partial f}{\partial x} + \frac{\gamma_{z,3}}{2}\delta z\frac{\partial f}{\partial z}$$

$\gamma_{t,3}$, $\gamma_{x,3}$ and $\gamma_{z,3}$ is the weighting coefficient t weighted Taylor series for function $f = f(x, z, t)$, with value $\gamma_{t,3} = 3.04933.,\gamma_{x,3} = \gamma_{z,3} = 2.04933$, Hutahean (2025b).

Applying this weighted Taylor expansion to the modified Euler momentum equation yields,

$$\gamma_{t,3}\frac{\partial u}{\partial t} + \frac{\gamma_{x,3}}{2}\frac{\partial}{\partial x}(uu + \mu ww) = -\frac{1}{\rho}\frac{\partial p}{\partial x}$$
$$\gamma_{t,3}\frac{\partial w}{\partial t} + \frac{\gamma_{z,3}}{2}\frac{\partial}{\partial z}(-\mu uu + ww) = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g$$

The purpose of the weighted Taylor series is to produce shorter modeled wavelengths that better match natural wavelengths, while simultaneously reducing the driving force and water-particle velocities.

c. Modification 3

The third modification interprets the convective acceleration in the second term on the left-hand side as a hydrodynamic force directed from higher to lower energy. Consequently, this term is assigned a negative sign (-), Hutahaean (2025c).

$$\gamma_{t,3}\frac{\partial u}{\partial t} - \frac{\gamma_{x,3}}{2}\frac{\partial}{\partial x}(uu + \mu ww) = -\frac{1}{\rho}\frac{\partial p}{\partial x} \quad \ldots(7)$$
$$\gamma_{t,3}\frac{\partial w}{\partial t} - \frac{\gamma_{z,3}}{2}\frac{\partial}{\partial z}(-\mu uu + ww) = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g \quad \ldots(8)$$

4.3. Pressure and Driving-Force Equations.

The pressure and driving-force expressions are obtained by integrating Eq. (8) with respect to the vertical coordinate -z.

To ensure that velocity changes comply with the continuity equation, the term $\frac{\partial w}{\partial t}$ in equation (8) is replaced with the vertically integrated continuity relation.

Following Hutahaean (2025a), the resulting pressure equation is:

$$\frac{\gamma_{z,3}}{\rho}p = \gamma_{t,3}\int_z^\eta\left(\frac{\partial}{\partial t}\int_z^\eta\frac{\partial u}{\partial x}dz\right)dz + \frac{\partial w_\eta}{\partial t}(\eta - z) - \frac{\gamma_{z,3}}{2}(-\mu u_\eta u_\eta + w_\eta w_\eta) + \frac{\gamma_{z,3}}{2}(-\mu uu + ww) + g(\eta - z)$$

Hence, the horizontal driving-force equation is,

$$\frac{\gamma_{z,3}}{\rho}\frac{\partial p}{\partial x} = \gamma_{t,3}\frac{\partial}{\partial x}\int_z^\eta\left(\frac{\partial}{\partial t}\int_z^\eta\frac{\partial u}{\partial x}dz\right)dz + \gamma_{t,3}\frac{\partial w_\eta}{\partial t}\frac{\partial \eta}{\partial x} - \frac{\gamma_{z,3}}{2}\frac{\partial}{\partial x}(-\mu u_\eta u_\eta + w_\eta w_\eta) + \frac{\gamma_{z,3}}{2}\frac{\partial}{\partial x}(-\mu uu + ww) + g\frac{\partial \eta}{\partial x} \quad \dots(9)$$

Integration of the first term on the right-hand side, solved using the velocity potential equation, Hutahaean (2025a), obtains

$$\frac{\partial}{\partial x}\int_z^\eta\left(\frac{\partial}{\partial t}\int_z^\eta\frac{\partial u}{\partial x}dz\right)dz = -\frac{\partial w_\eta}{\partial t}\frac{\partial \eta}{\partial x} + \left(\frac{\partial u_\eta}{\partial t} - \frac{\partial u}{\partial t}\right)$$

Substituted to (7),

$$\frac{\gamma_{z,3}}{\rho}\frac{\partial p}{\partial x} = \gamma_{t,3}\left(-\frac{\partial w_\eta}{\partial t}\frac{\partial \eta}{\partial x} + \left(\frac{\partial u_\eta}{\partial t} - \frac{\partial u}{\partial t}\right)\right) + \gamma_{t,3}\frac{\partial w_\eta}{\partial t}\frac{\partial \eta}{\partial x} - \frac{\gamma_{z,3}}{2}\frac{\partial}{\partial x}(-\mu u_\eta u_\eta + w_\eta w_\eta) + \frac{\gamma_{z,3}}{2}\frac{\partial}{\partial x}(-\mu uu + ww) + g\frac{\partial \eta}{\partial x}$$

The first and third terms on the right-hand side cancel one another, and it is important to recall that $\gamma_{z,3} = \gamma_{x,3}$,

$$\frac{\gamma_{x,3}}{\rho}\frac{\partial p}{\partial x} = \gamma_{t,3}\left(\frac{\partial u_\eta}{\partial t} - \frac{\partial u}{\partial t}\right) - \frac{\gamma_{z,3}}{2}\frac{\partial}{\partial x}(-\mu u_\eta u_\eta + w_\eta w_\eta) + \frac{\gamma_{z,3}}{2}\frac{\partial}{\partial x}(-\mu uu + ww) + g\frac{\partial \eta}{\partial x} \quad \dots(10)$$

4.4. Horizontal Velocity Equation.

Substituting Eq. (10) into Eq. (7) gives:

$$\gamma_{t,3}\frac{\partial u}{\partial t} - \frac{\gamma_{x,3}}{2}\frac{\partial}{\partial x}(uu + \mu ww) = -\gamma_{t,3}\left(\frac{\partial u_\eta}{\partial t} - \frac{\partial u}{\partial t}\right) + \frac{\gamma_{z,3}}{2}\frac{\partial}{\partial x}(-\mu u_\eta u_\eta + w_\eta w_\eta) - \frac{\gamma_{z,3}}{2}\frac{\partial}{\partial x}(-\mu uu + ww) - g\frac{\partial \eta}{\partial x}$$

At $z = \eta$,

$$\gamma_{t,3}\frac{\partial u_\eta}{\partial t} - \frac{\gamma_{x,3}}{2}\frac{\partial}{\partial x}(u_\eta u_\eta + \mu w_\eta w_\eta) = -g\frac{\partial \eta}{\partial x}$$

Transformed into depth average velocity equation,

$$\gamma_{t,3}\alpha_{u\eta}\frac{\partial U}{\partial t} - \frac{\gamma_{x,3}}{2}\frac{\partial}{\partial x}(\alpha_{u\eta}\alpha_{u\eta}UU + \mu w_\eta w_\eta) = -g\frac{\partial \eta}{\partial x} \quad (11)$$

w_η does not need to be transformed to the depth average velocity.

Equation (11) represents the final governing equation for the depth-averaged horizontal water-particle velocity. The left-hand side includes the kinetic-energy variation term $\frac{\partial U}{\partial t}$, which, in principle, should be supplied by changes in potential energy. This requires a contribution from $\frac{\partial \eta}{\partial t}$. It appears implicitly in w_η, but only through its horizontal derivative to the axis-x $\frac{\partial \mu_z w_\eta w_\eta}{\partial x}$. Consequently, the transfer of potential-energy variation to kinetic-energy variation is minimal.

To obtain an adequate contribution from $\frac{\partial \eta}{\partial t}$, equation. (11) is superposed with the momentum-equilibrium equation.

V. MOMENTUM EQUILIBRIUM EQUATION

5.1. Conservation of Mass.

The momentum equilibrium equation is derived using the conservation of mass, analogous to the standard continuity equation. The derivation assumes that over a sufficiently small-time interval δt from $t = t - \frac{\delta t}{2}$ ke $t = t + \frac{\delta t}{2}$, the inflow and outflow velocities within the control volume can be represented by the velocity at $t = t$, obtaining the following mass conservation equation,

$$\frac{\delta u}{\delta x} + \frac{\delta w}{\delta z} = 0 \quad \dots(12)$$

This form applies to incompressible flow within a fixed control volume. The full derivation is not reproduced here, as it is standard and can be found in Dean (1991).

5.2. Momentum equilibrium equation.

Taking δx and δz close to zero (10) yields the continuity equation,

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \quad \dots(13)$$

The same relation can be obtained using an alternative approach in which the velocity defines δu and δw using a weighted Taylor series.

$$\delta u = \gamma_{t,3}\delta t\frac{\mathrm{d}u}{\mathrm{d}t} + \gamma_{x,3}\delta x\frac{\mathrm{d}u}{\mathrm{d}x} + \gamma_{z,3}\mu\delta z\frac{\mathrm{d}u}{\mathrm{d}z}$$

$$\delta w = \gamma_{t,3}\delta t\frac{\mathrm{d}w}{\mathrm{d}t} - \gamma_{x,3}\mu\delta x\frac{\mathrm{d}w}{\mathrm{d}x} + \gamma_{z,3}\delta z\frac{\mathrm{d}u}{\mathrm{d}z}$$

Substituting these expressions into the mass-conservation equation gives:

$$\frac{\gamma_{t,3}\delta t\frac{\mathrm{d}u}{\mathrm{d}t} + \gamma_{x,3}\delta x\frac{\mathrm{d}u}{\mathrm{d}x} + \gamma_{z,3}\mu\delta z\frac{\mathrm{d}u}{\mathrm{d}z}}{\delta x} + \frac{\gamma_{t,3}\delta t\frac{\mathrm{d}w}{\mathrm{d}t} - \gamma_{x,3}\mu\delta x\frac{\mathrm{d}w}{\mathrm{d}x} + \gamma_{z,3}\delta z\frac{\mathrm{d}u}{\mathrm{d}z}}{\delta z} = 0 \quad \ldots(14)$$

If, over small-time interval $t = t - \frac{\delta t}{2}$ ke $t = t + \frac{\delta t}{2}$ the velocity is approximated as constant $t = t$, hence $\frac{\mathrm{d}u}{\mathrm{d}t} = \frac{\mathrm{d}w}{\mathrm{d}t} = 0$, as written in the conservation of mass equation. If $\mu = 0$, the continuity equation is,

$$\frac{\mathrm{d}u}{\mathrm{d}x} + \frac{\mathrm{d}w}{\mathrm{d}z} = 0$$

When temporal variations are retained at interval $t = t - \frac{\delta t}{2}$ to $t = t + \frac{\delta t}{2}$, equation $\delta x = \delta z$ and (14) are multiplied by δx to obtain,

$$\gamma_{t,3}\delta t\frac{\mathrm{d}u}{\mathrm{d}t} + \gamma_{x,3}\delta x\frac{\mathrm{d}u}{\mathrm{d}x} + \gamma_{z,3}\mu\delta z\frac{\mathrm{d}u}{\mathrm{d}z} + \gamma_{t,3}\delta t\frac{\mathrm{d}w}{\mathrm{d}t} - \gamma_{x,3}\mu\delta x\frac{\mathrm{d}w}{\mathrm{d}x} + \gamma_{z,3}\delta z\frac{\mathrm{d}u}{\mathrm{d}z} = 0$$

Dividing by δt close to zero, where $\frac{\delta x}{\delta t} = u$ and $\frac{\delta z}{\delta t} = w$ and using the irrotationality condition $\frac{\mathrm{d}u}{\mathrm{d}z} = \frac{\mathrm{d}w}{\mathrm{d}x}$,

$$\gamma_{t,3}\frac{\mathrm{d}u}{\mathrm{d}t} + \frac{\gamma_{x,3}}{2}\frac{\mathrm{d}}{\mathrm{d}x}(uu + \mu ww) + \gamma_{t,3}\frac{\mathrm{d}w}{\mathrm{d}t} + \frac{\gamma_{x,3}}{2}\frac{\mathrm{d}}{\mathrm{d}z}(-\mu uu + ww) = 0$$

The second and fourth terms correspond to convective acceleration. As argued by Hutahaean (2025c), these represent hydrodynamic forces directed from higher to lower energy and therefore must carry a negative sign. This leads to the momentum equilibrium equation:

$$\gamma_{t,3}\frac{\mathrm{d}u}{\mathrm{d}t} - \frac{\gamma_{x,3}}{2}\frac{\mathrm{d}}{\mathrm{d}x}(uu + \mu ww) + \gamma_{t,3}\frac{\mathrm{d}w}{\mathrm{d}t} - \frac{\gamma_{x,3}}{2}\frac{\mathrm{d}}{\mathrm{d}z}(-\mu uu + ww) = 0 \quad \ldots(15)$$

5.3. Integration of momentum equilibrium equation

Equation (15) is rewritten into an equation for the horizontal water-particle velocity and integrated with respect to the vertical-z axis.

$$\gamma_{t,3}\int_{-h}^{\eta}\frac{\mathrm{d}u}{\mathrm{d}t}dz = \frac{\gamma_{x,3}}{2}\int_{-h}^{\eta}\frac{\mathrm{d}(uu + \mu ww)}{\mathrm{d}x}dz - \gamma_{t,3}\int_{-h}^{\eta}\frac{\mathrm{d}w}{\mathrm{d}t}dz + \frac{\gamma_{z,3}}{2}(-\mu u_\eta u_\eta + w_\eta w_\eta) \quad (16)$$

where the seabed vertical water-particle velocities u_{-h} and w_{-h} are neglected.

The integration is carried out using Leibniz's rule (Protter, Murray, Morrey, & Charles, 1985), together with the concept of depth-averaged velocity, and recognizing that the still-water depth is constant in time t, where $\frac{\mathrm{d}h}{\mathrm{d}t} = 0$,

$$\int_{-h}^{\eta}\frac{\mathrm{d}u}{\mathrm{d}t}dz = \beta_u D\frac{\mathrm{d}U}{\mathrm{d}t} + (\beta_u - \alpha_{u\eta})U\frac{\mathrm{d}\eta}{\mathrm{d}t}$$

$$\int_{-h}^{\eta}\frac{\mathrm{d}w}{\mathrm{d}t}dz = \beta_w H\frac{\mathrm{d}W}{\mathrm{d}t} + (\beta_w - \alpha_{w\eta})W\frac{\mathrm{d}\eta}{\mathrm{d}t}$$

In this integration, the seabed horizontal water-particle velocities u_{-h} and w_{-h} are neglected. The equation for $\frac{\mathrm{d}W}{\mathrm{d}t}$ is equation (5).

Substituting the expressions $\int_{-h}^{\eta}\frac{\mathrm{d}u}{\mathrm{d}t}dz$, $\int_{-h}^{\eta}\frac{\mathrm{d}w}{\mathrm{d}t}dz$ and $\frac{\mathrm{d}W}{\mathrm{d}t}$ to equation (15),

$$\lambda_u = \left(\beta_u - \frac{\beta_w}{\alpha_{w\eta}}\left(\beta_u\frac{\mathrm{d}D}{\mathrm{d}x} - \alpha_{u\eta}\frac{\mathrm{d}\eta}{\mathrm{d}x}\right)\right)$$

$$\lambda_u\frac{\mathrm{d}U}{\mathrm{d}t} = -\frac{(\beta_u - \alpha_{u\eta})}{H}U\frac{\mathrm{d}\eta}{\mathrm{d}t} - \frac{(\beta_w - \alpha_{w\eta})}{H}W\frac{\mathrm{d}\eta}{\mathrm{d}t} + \frac{\beta_w\beta_u}{\alpha_{w\eta}}\frac{\mathrm{d}U}{\mathrm{d}x}\frac{\mathrm{d}\eta}{\mathrm{d}t} + \frac{\gamma_{x,3}}{2\gamma_{t,3}D}\int_{-h}^{\eta}\frac{\mathrm{d}(uu + \mu ww)}{\mathrm{d}x}dz + \frac{\gamma_{z,3}}{2\gamma_{t,3}D}(-\mu u_\eta u_\eta + w_\eta w_\eta) \quad \ldots(17)$$

This equation shows the contribution of $\frac{\mathrm{d}\eta}{\mathrm{d}t}$ both directly and through w_η towards changes in $U = \frac{\mathrm{d}U}{\mathrm{d}t}$. Using Leibniz integration and the concept of depth-averaged velocity, the expressions for $\int_{-h}^{\eta}\frac{\mathrm{d}uu}{\mathrm{d}x}dz$ and $\int_{-h}^{\eta}\frac{\mathrm{d}ww}{\mathrm{d}x}dz$ is.

$$\int_{-h}^{\eta}\frac{\mathrm{d}uu}{\mathrm{d}x}dz = \frac{\mathrm{d}\beta_{uu}UUD}{\mathrm{d}x} - u_\eta u_\eta\frac{\mathrm{d}\eta}{\mathrm{d}x} - u_{-h}u_{-h}\frac{\mathrm{d}h}{\mathrm{d}x}$$

Seabed velocity is neglected, and the first term on the right-hand side is expanded. The surface horizontal velocity u_η is transformed into the depth-averaged velocity U

$$\int_{-h}^{\eta}\frac{\mathrm{d}uu}{\mathrm{d}x}dz = \beta_{uu}\left(UU\frac{\mathrm{d}D}{\mathrm{d}x} + 2UD\frac{\mathrm{d}U}{\mathrm{d}x}\right) - \alpha_{u\eta}\alpha_{u\eta}UU\frac{\mathrm{d}\eta}{\mathrm{d}x}$$

$$\int_{-h}^{\eta}\frac{\mathrm{d}ww}{\mathrm{d}x}dz = \frac{\mathrm{d}\beta_{ww}WWD}{\mathrm{d}x} - w_\eta w_\eta\frac{\mathrm{d}\eta}{\mathrm{d}x} - w_{-h}w_{-h}\frac{\mathrm{d}h}{\mathrm{d}x}$$

Seabed velocity is neglected, and the first term on the right-hand side is expanded,

$$\int_{-h}^{\eta}\frac{\mathrm{d}ww}{\mathrm{d}x}dz = \beta_{ww}\left(WW\frac{\mathrm{d}D}{\mathrm{d}x} + 2WD\frac{\mathrm{d}W}{\mathrm{d}x}\right) - w_\eta w_\eta\frac{\mathrm{d}\eta}{\mathrm{d}x}$$

5.4. Final equation for the horizontal depth-averaged velocity.

In equation (16), the first, second, and third terms on the right-hand side explicitly contain $\frac{\partial \eta}{\partial t}$, and the fifth term, through the kinematic free surface boundary condition, also contains $\frac{\partial \eta}{\partial t}$. Therefore, this equation contains many sources of energy contributing to the change of kinetic energy on the left-hand side. However, this equation cannot stand alone because it does not have a driving force. By superposing equation (11) with equation (17), a new horizontal depth-averaged water particle velocity equation is obtained that includes sufficient potential energy sources to support the kinetic energy changes in $\frac{\partial U}{\partial t}$. The superposition is performed simply by adding the two equations, and the result is:

$$\begin{aligned}(\gamma_{t,3}\alpha_{u\eta}+\lambda_u)\frac{\partial U}{\partial t} &= \frac{\gamma_{x,3}}{2}\frac{\partial}{\partial x}(\alpha_{u\eta}\alpha_{u\eta}UU+\mu_z w_\eta w_\eta)\\ &\quad -g\frac{\partial \eta}{\partial x}\\ &\quad -\frac{(\beta_u-\alpha_{u\eta})}{H}U\frac{\partial \eta}{\partial t}\\ &\quad -\frac{(\beta_w-\alpha_{w\eta})}{H}W\frac{\partial \eta}{\partial t}\\ &\quad +\frac{\beta_w\beta_u}{\alpha_{w\eta}}\frac{\partial U}{\partial x}\frac{\partial \eta}{\partial t}\\ &\quad +\frac{\gamma_{x,3}}{2\gamma_{t,3}D}\int_{-h}^{\eta}\frac{\partial(uu+\mu ww)}{\partial x}dz\\ &\quad +\frac{\gamma_{z,3}}{2\gamma_{t,3}D}(-\mu u_\eta u_\eta+w_\eta w_\eta) \qquad \dots(18)\end{aligned}$$

VI. NUMERICAL METHOD

The Finite Difference Method is used for spatial differentiation, while the time differentiation is solved using a predictor–corrector method. In the predictor stage, the Finite Difference Method with a central difference scheme is applied, and in the corrector stage, an integration method based on Newton–Cotes numerical integration is used. Details of the predictor–corrector method can be found in Hutahaean (2024). The formulation of the following equations can be found in Hutahaean (2025c).

a. Time-step δt.

$$-\frac{\delta t^2}{6}\sigma^2+\frac{\delta t}{2}\sigma-\varepsilon=0 \qquad \dots(19)$$

b. Grid-size δx.

$$\delta x = 3.1\,\frac{\sigma}{k}\,\delta t \qquad \dots(20)$$

ε is a very small number. In this research $\varepsilon = 0.005$. Smaller ε is followed by smaller time step δt, and the better the accuracy.

c. Wave number calculation

Estimated deep water number,

$$k_0 = 0.5\,\gamma_{t,2}\gamma_{t,3}\frac{\sigma^2}{g}$$

$$h_0 = 0.5\,L_0 = \frac{\pi}{k_0}$$

Wave number at shallow water $h < h_0$,

$$k = \frac{k_0 h_0}{h}$$

VII. RESEARCH ON THE MODEL

7.1. Wave profile input.

The model is executed with an input solitary wave. In this study the solitary wave is interpreted only as a wave profile in which the wave crest and wave trough are above the still water level. With this profile the initial condition at the input point is satisfied, namely $\eta(0,0) = \frac{\partial \eta}{\partial t} = 0$.

The input wave equation is,

$$\eta(0,t) = -A\cos\sigma t + A \qquad \dots(21)$$

and the wave profile is shown in Fig. 4. The wave amplitude used is $A = 1.2\ m$ and the wave period $T = 8.0\ sec$.

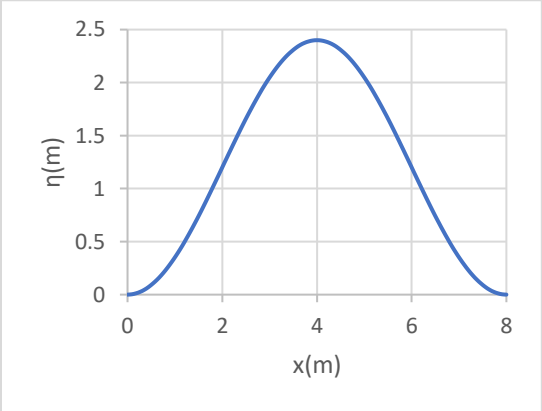


Fig (4) Wave input on t.

7.2. Study on flat bottom

The purpose of this section is to determine the appropriate value of one of the model coefficients, namely the deep-water coefficient θ.

7.2.1. Study of the deep-water coefficient θ.

Each wave period has its own value of the deep-water coefficient θ, although the differences are small. Therefore, a single value of θ can be used for all wave periods, especially for relatively small wave periods. The following is an example of a study of θ, using a wave with period 8.0 seconds and deep-water wave amplitude $A_0 = 1.2\ m$,

The model is executed using $\theta = 0.70$ and $\mu = 0$, with a simulation time of 10 wave periods or 80 seconds. The model results are presented in Fig. (5) and Fig. (6). In these figures, the crest line is the line connecting the wave crests. For a wave over a flat bottom, the crest line should remain constant at $\eta = 2A = 2.40\ m$. In Fig. (5), it can be seen that the crest line increases, indicating a growth of wave height. This occurs because the value of θ is too small.

At the tail region, small ripples are generated. The amplitude of these ripples is determined by the wave steepness. The greater the wave steepness, the larger the ripples. These ripples can be reduced by decreasing the wave amplitude, or by reducing the value of θ, although they cannot be fully eliminated.

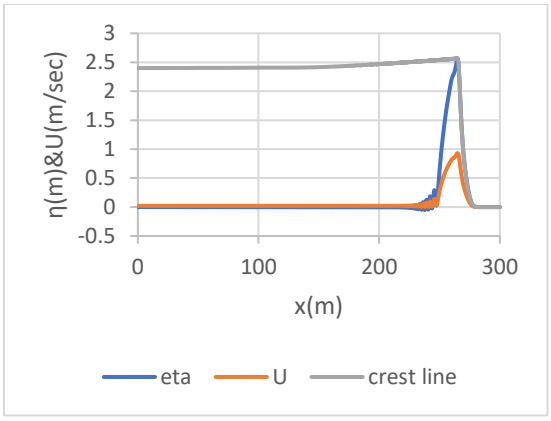
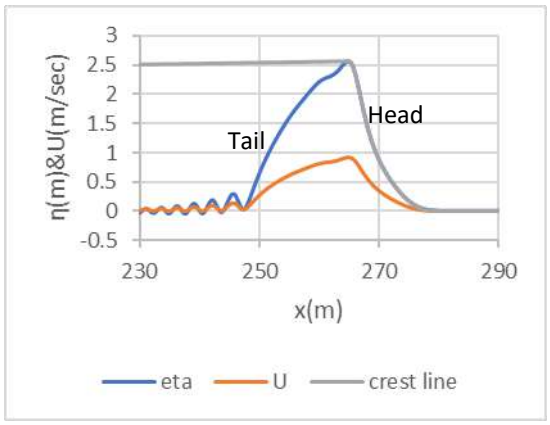


Fig (5). Results of model, $\theta = 0.70$ and $\mu = 0$



In Fig. (7) the model results for $\theta = 1.2$, are shown.

According to velocity potential theory, a larger θ is considered better because $\tanh \theta\pi$ approaches one, Hutahean (2023). However, for this time-series model this property does not hold. The wave height decreases and the wave ripples become larger.

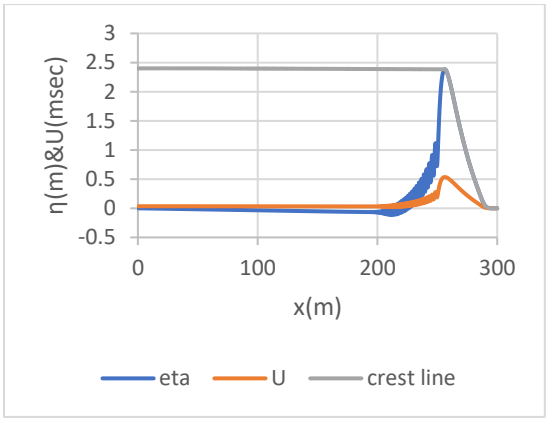


Fig (7). Model results $\theta = 1.2$ and $\mu = 0$

Thus, the optimal value of θ is the smallest value for which no increase in wave height occurs. For the wave period of 8 seconds, the optimal value is $\theta = 0.81$. The model results are shown in Fig. (8).

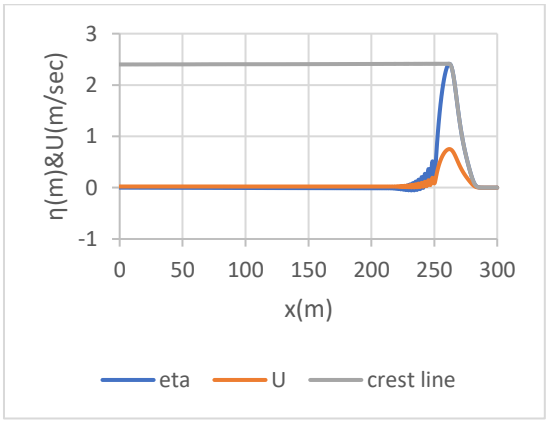


Fig (8). Model results, $\theta = 0.81$ and $\mu = 0$

7.2.2. Study of the coefficient μ on flat bottom.

The model is executed using $\theta = 0.81$ and $\mu = 0.01$ with a uniform distribution of μ over the entire domain. A wave amplitude of 1.2 m and a wave period of 8.0 seconds are used. The model results are shown in Fig. (9). A reduction in wave height is observed, and the larger the value of μ, the greater the reduction.

The reduction of wave height represents a loss of wave energy. Therefore, the coefficient μ can be interpreted as the resultant of all energy losses, including viscosity, radiation stress, bottom friction, and other mechanisms. The larger the value of μ, the greater the amount of energy lost. For flat-bottom conditions, it is appropriate to use $\mu = 0$, although a value $\mu > 0$ may be used when energy losses need to be taken into account.

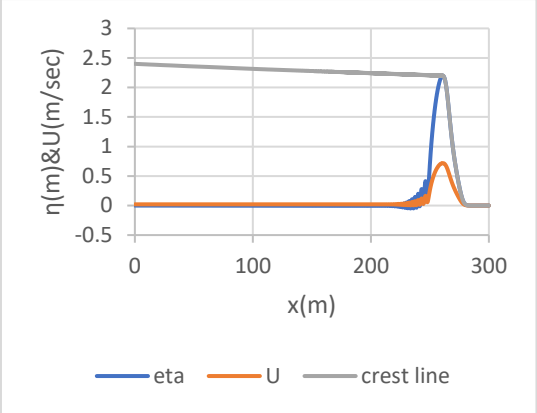


Fig (9). Model results, $\theta = 0.81, A_0 = 1.2\ m$ and $\mu = 0.01$

7.2.3. Wave energy losses equation.

It has been shown that μ is an energy loss coefficient. The magnitude of the energy loss depends on the magnitude of the energy itself, so the value of μ is also determined by the amount of energy. Hence μ is a function of wave energy. Wave energy at a given point changes with time, and wave energy also changes from one point to another. Therefore, the energy loss coefficient μ is a function of space and time, $\mu = \mu(x,t)$, with the following form of equation:

$$\mu(x,t) = c_\mu \sigma^2 \frac{u_\eta u_\eta + w_\eta w_\eta}{2g}\left(1 + 2\left(\frac{\partial \eta}{\partial x}\right)^2\right)\frac{\pi}{h+\eta} \quad \ldots (22)$$

$c_\mu = 0.21\ m^{-1} sec^4$

This equation is formulated intuitively and through trial and error, without using conservation laws or equilibrium laws. A discussion of the equation will be presented in the next paper. The coefficient c_μ is obtained through trial and error by to match the breaking wave height from Komar and Gaughan (1972), equation (23). The value of c_μ varies slightly with wave period, with an average value of 0.21. Therefore $c_\mu = 0.21$ is used.

It should be noted that the average value $c_\mu = 0.21$ is the result of fitting the breaking wave height H_b to the breaking wave height from equation (23), H_{b-KG}. Using a breaking wave height from other researchers would result in a different value of c_μ.

The breaking wave height equation from Komar and Gaughan (1972) is,

$$H_{b-KG} = 0.39\, g^{1/5} (T_0 H_0^2)^{2/5} \quad \ldots (23)$$

7.3. Model Results on a Sloping Bottom.

The model was executed over a sloping bottom with a slope of 0.05 for several wave periods. The deep-water depth is denoted as h_0, calculated using the equation presented in Section VI, where the value of h_0 varies according to the wave period T. In the shallow-water region, a constant water depth of 1.0 m was used. Consequently, the domain length also varies depending on the wave period.

The wave-breaking parameters are presented in Table (3), while the shoaling, breaking, and wave profiles in shallow water for several wave periods are shown in Figures (11–19)

Table (3). Parameter breaking output model.

T (sec)	H_0 (m)	H_b (m)	h_b (m)	$\frac{H_b}{h_b}$	H_{b-KG} (m)
7.0	0.85	2.068	5.226	0.396	2.050
8.0	1.20	2.843	7.452	0.381	2.85
9.0	1.45	3.491	8.932	0.391	3.475
10.0	1.85	4.410	11.469	0.384	4.405
11.0	2.15	5.196	13.276	0.391	5.161
12.0	2.55	6.172	15.768	0.391	6.125

In Table (3), H_0 represents the deep-water wave height, H_b is the breaking wave height, and h_b is the breaking water depth. It can be seen that the modeled breaking wave height H_b is fairly close to the Komar–Gaughan (1972) breaker height H_{b-KG}. The breaker depth index $\frac{H_b}{h_b}$ is much lower than the McCowan (1894) criterion, which states $\frac{H_b}{h_b} = 0.78$. However, under the McCowan (1894) criterion, waves reach the coastline with relatively large wave heights.

Figures (10–18) present the shoaling–breaking patterns and wave profiles at the breaking point and in shallow water for several wave periods. The breaking wave height corresponds to the highest point along the crest line, which is the line connecting the wave crests.

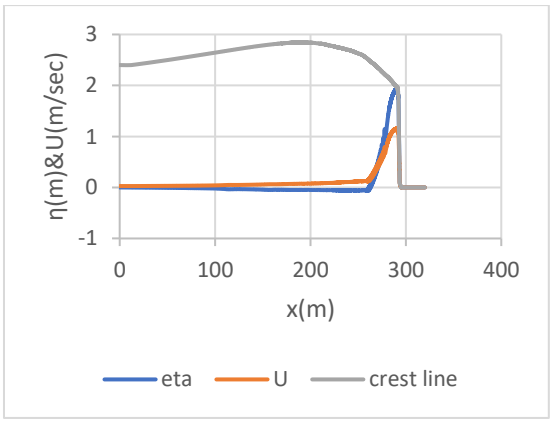


Fig (10) Shoaling-breaking, wave period 8.0 sec.

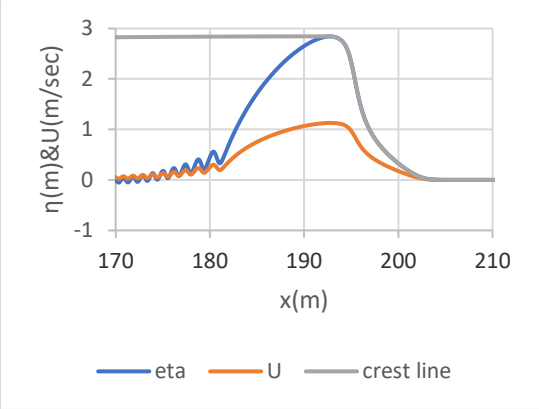


Fig (11) Wave profile around the breaking point $h_b = 7.452\ m$, wave period 8.0 sec.

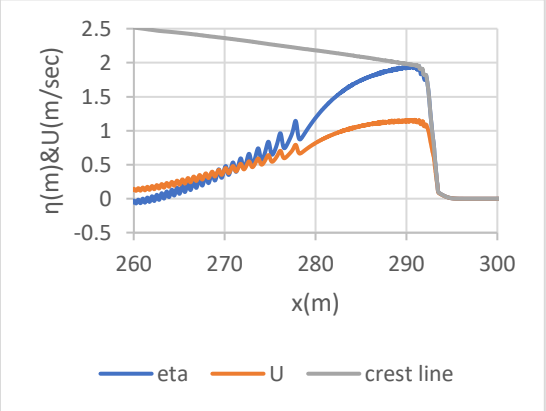


Fig (12) Wave profile at shallow water $h = 2.4\ m$, wave period 8.0 sec.

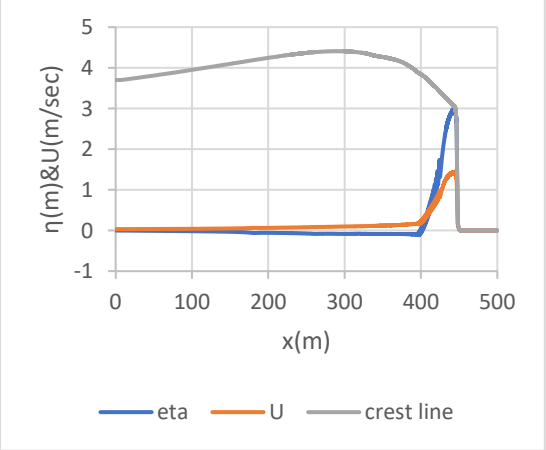


Fig (13) Shoaling-breaking, wave period 10.0 sec.

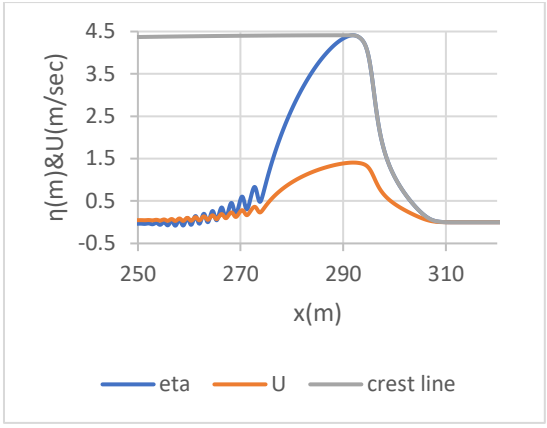


Fig (14) Wave profile around breaking point $h_b = 11.469\ m$, wave period 10.0 sec.

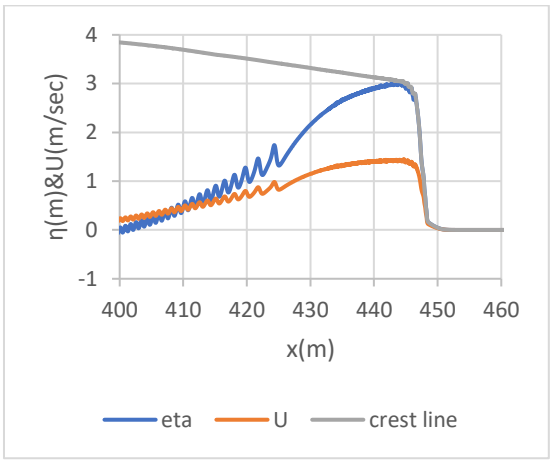


Fig (15) Wave profile at shallow water $h = 3.75\ m$, wave period 10.0 sec.

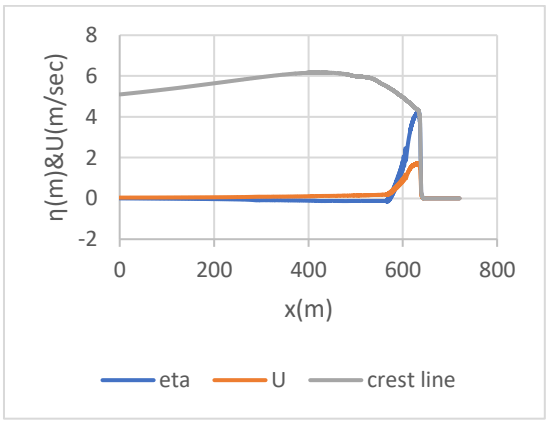


Fig (16) Shoaling-breaking, wave period 12.0 sec.

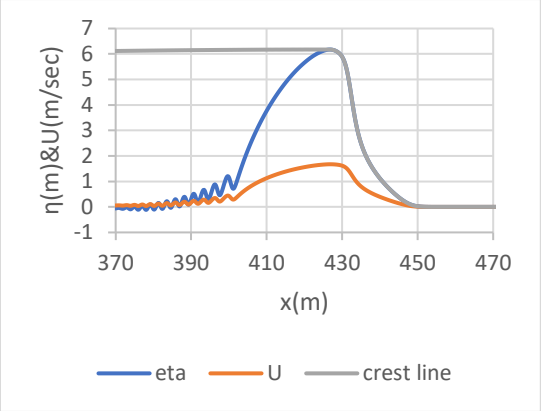


Fig (17) Wave profile around breaking point $h_b = 15.768\ m$, wave period 12.0 sec.

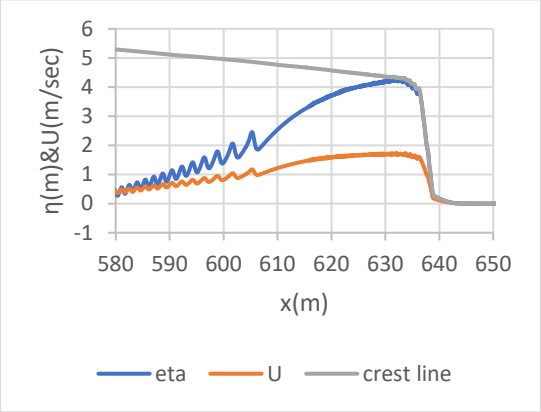


Fig (18) Wave profile at shallow water $h = 5.25\ m$, wave period 12.0 sec.

From the model execution over the sloping bottom, it was found that the model is capable of simulating shoaling and breaking processes well, where the model can pass through the breaking condition and continue into shallow water, but the model stops at water depths still far from the coastline. This indicates that further development of the energy-loss formulation is likely required.

VIII. CONCLUSION

This study shows that the original Euler momentum conservation equation contains an excessive driving force, leading to instability when applied to short waves with large amplitudes. It is suitable only for long-wave conditions with very small amplitudes. Therefore, modification of the equation is necessary.

The three modifications introduced in this work produce a formulation capable of representing the maximum wave amplitude for each wave period and generating wavelengths reasonably close to natural conditions. The momentum equilibrium equation supplies the necessary potential energy to balance kinetic energy changes in the water-particle velocity. Its contribution is evident in the improved model stability during wave breaking, reducing oscillations in free-surface elevation and particle velocity.

Overall, the combination of the modified Euler momentum equation and the momentum equilibrium equation yields a stable and reliable time-series wave model. Further work is needed to refine the energy-loss formulation so the model can propagate into very shallow coastal waters.

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Age and Gender as a Demographic Factors that Correlates Students' Performance in Computer Programming in Colleges of Education in Enugu State, Nigeria

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***Keywords*— Age, Gender, Demographic, Correlates, Students, Performance, Computer, Programming, Colleges, Education.**

***Abstract*—** *The aim of this study was to investigate age and gender as a demographic factors that correlates students' performance in computer programming in Colleges of Education. The study was carried out in Colleges of Education. Two objectives, two research questions and two hypotheses were formulated to guide the study. The study adopted correlational survey research design. The study was carried out using government owned Colleges of Education. The population for the study was forty nine (49) computer education students (final year) from the two (2) government owned Colleges of Education in Enugu State, Nigeria. The entire population was studied due to the fact that it is manageable. Hence, total population sampling technique was adopted. The instrument that was used for the study was student's result scores and a structured questionnaire titled "Age and Gender as a Demographic Factors that Correlates of Student's Performance in Computer Programming (AGDFCSPCP) questionnaire". The research instrument was subjected to face validation by three experts, two experts in the Department of Computer & Robotics Education and one from Measurement and Evaluation unit, all from University of Nigeria, Nsukka. The internal consistency of the questionnaire was determined using Cronbach's Alpha reliability test which yielded co-efficient of 0.98 and 0.97 for clusters 1 and 2 respectively and 0.98 for the entire instrument. The instrument for data collection were administered by the researcher and two research assistants. The data collected was analyzed using Pearson Product Moment Correlation Coefficient to answer the research questions. The null hypotheses were tested using One Way Analysis of Variance (ANOVA) at .05 level of significance. The findings from the study revealed a very weak relationship among age, gender, and performance of computer education students' in computer programming. In addition, the findings on hypothesis tested revealed that there was no statistically significant relationship among computer education students' age, gender and their performances in computer programming course. It was therefore, recommended among others that since demographic factors don't differentiate performance, the*

effectiveness of teaching methods and curriculum content becomes paramount. The researcher suggested that the study should be replicated in other states of our country to investigate demographic factors as correlate students' performance in computer programming in Colleges of Education. It is recommend that, invest in training for computer programming instructors on effective pedagogical approaches, such as problem-based learning, project-based learning, collaborative coding, and active learning strategies. Regularly review and update the computer programming curriculum to ensure it is relevant, engaging, and aligned with industry needs.

I. INTRODUCTION

Since computer programming remains a continually changing profession, teaching students about it effectively requires creative ways. [130], Computer programming is the process that professionals use to write code that instructs how a computer application or software program performs. Computer programming is a set of instructions to facilitate specific actions. Computer programming is the process of performing a particular computation (or more generally, accomplishing a specific computing result), usually by designing/building an executable computer program. Programming entails duties including analysis, algorithm generation, resource use and accuracy profiling, and algorithm implementation (typically in a chosen programming language, also known as coding). [138], discovered that programming performance was significantly impacted by computer programming. Similarly, [84], quoted [136], who claimed that computer programming directly affects pupils' overall programming proficiency.

The foundational knowledge and abilities needed to develop the software, applications, and systems that power the contemporary digital world are taught in computer programming courses [67]. These courses are designed to equip students with a solid understanding of programming languages, algorithms, data structures, software development methodologies, and problem-solving techniques [67]. In the rapidly evolving field of technology, computer programming is a critical skill sought after by employers across various industries. It enables individuals to translate ideas into functional, interactive, and efficient software solutions.

The practice of writing a set of commands that guide a computer on how to work or carry out a task is known as programming. Numerous computer programming languages, including JavaScript, Python, and C++, can be used for programming. Computer programming, [67], is the process of creating and implementing computer programs. [68], furthermore defined a computer program as codes executed on a computer to perform particular tasks. This code is written by programmers. The process of providing machines with a set of instructions that specify how a program should be executed is known as computer programming. In the subject of computers, computer programming, as taught in higher education institutions in the fields of computer science and education is crucial. Among the most important computer science courses offered by educational institutions is programming.

According to research, the numeral of undergraduate students selecting computer science and computer education courses has been steadily declining for more than ten years [58]. Since there is a lack of skilled experts in the sector due to the growing demand for trained computer scientists and programmers, it is necessary to advance the performance of students in computer science programs [61]. Among the causes for students not choosing computer science may be the perception of undergraduate computer science students that computing, especially programming is difficult and boring [48]. The instruction and acquisition of computer science education is very important when the teachers know the essence of using practical's to teach their students.

Computer science education teachers and students should appreciate the importance of the school laboratory in transferring theory gained in the classroom into practice. The computer laboratory is the most convenient avenue for solving problems through practice, by test-running and debugging learnt through observation and demonstration. Learning to solve real life problem through computer programming provides good ground for practical demonstration since success in programming is heavily dependent on problem solving abilities. Computer programming activities in Colleges of Education would be interesting, relevant and effective on the part of the students, if there is a relationship between the content of the computer curriculum and the practical carried out in the computer laboratory. Computer programming is one of the courses taught in Computer Education Department in educational institutions.

In Nigeria, the College of Education is the tertiary educational institution tasked with preparing teachers to earn a professional certificate in education that is not a

degree. In Nigeria, Colleges of Education first appeared in the 1950s. It is clear from the 1959 Ashby Commission report that middle-level personnel were required to meet Nigeria's demands for teaching personnel [17]. Numerous teachers were found to be untrained and uncertified. In order to improve the current teaching workforce, a proposal for a larger extension of intermediate education for intermediate instructors was made in response to this observation [64] referenced in [96]. The Commission recommended the establishment of Advanced Teacher Training Colleges (A.T.T.C's) in Nigeria. The recommendation led to the establishment of ATTC'S at Owerri, Ondo, Lagos and Zaria between 1961 and 1962; Kano in 1964 and Abrakain 1968, with both institutions named Colleges of Education [64] in [96]. The Advanced Teachers Colleges (ATCs) [64]) cited in [96] turned out graduates who were holders regarding the Nigerian Certificate of Education (NCE), a non-degree but qualitative professional certificate in education.

The philosophy underpinning teacher education at the Colleges of Education as pointed out by [64] as cited in [96], included the desire of the Nigerian Government to ensure uniformity of content and educational standard. It also aimed on creating educators by highly individual then expert correction then honesty, educators who are dedicated, and possessing the knowledge and abilities necessary to easily accomplish the national aim. The government's decision that the NCE will eventually be the minimal prerequisite for entering the teaching profession in Nigeria makes this even more crucial.

According to the NCE curriculum revision, computer instruction is now required for all 100 levels (100L). All College of Education students must meet minimal technology criteria as part of their pre-service training under the new curriculum, which was introduced in October 2010. Nonetheless, the National Commission for Colleges of Education acknowledges that instructors at educational institutions play a crucial role in helping students acquire computer programming abilities. Therefore, all instructors at Nigerian Colleges of Education are required to be literate and computer literate. The public is concerned about the student's poor performance in computer education classes, such as computer programming courses in educational institutions.

[62], defined academic performance as students' reports of their anticipated Grade Point Average (GPA) for the current semester and their Cumulative Grade Point Average (CGPA)/GPA from the previous semester. Nowadays, the majority of postsecondary educational institutions employ the grade point average, or GPA, as a handy way to summarize their students' academic performance. Because it gives more information about the relative performance levels of individuals and other student groups, the GPA is a more accurate metric [89].The academic performance involves factors such as the intellectual level, personality, motivation, skills, interests, study habits, self-esteem or the teacher-student relationship. When a gap between the academic performance and the student's expected performance occurs, it refers to a diverging performance.

[60], Students' performance describes how students handle their coursework and how they manage or complete various assignments that are assigned by their teachers. Academic performance, or how effectively a student satisfies requirements specified by the school administration, is the yardstick by which success in an educational institution is evaluated. Specifically, a student's performance is the consequence or result of their education, the point to which they have encountered their education objectives, which include their capacity to learn and retain information and to express that knowledge either orally or in writing. Performance is frequently evaluated through testing or ongoing evaluation.

Performance of students is the yardstick for testing educational quality of a nation [130]. Hence, it is expedient to maintain a high performance in internal and mostly external examinations. The result of education is performance, which measures how well a student, instructor, or institution has met their learning objectives [130]. The performance of the students is crucial in generating the highest caliber of graduates who will serve as the nation's future leaders and workforce, ultimately driving its social and economic advancement. Science student performance is impacted through social, psychological, economic, environmental, and personal issues, and student performance measurement has drawn a lot of attention in the past. It is also one of the more difficult topics in academic literature. Demographic variables have been identified as common variables that influence the students' achievement in computer programming. More so, the influence has been more particularly pronounced among the students of College of Education in Enugu State of Nigeria. There may be some factors including demographic factors of the students that may affect their performance in programming for computers. One of the greatest important elements influencing students' poor academic performance is their demographic factors [18].

Demographic factors are the characteristics of a person or a population such as age, gender. Students' demographic factors are the sum total of the characteristics that differentiates students, or the stability of a student's behaviour across different situations [44]. These attributes may help the individual accomplish tasks that are beneficial to him or the society. Reviewed research suggests that

academic performance has a relationship with some demographic characteristics [105]. [69], focused on elements that can affect students' performance in an effort to identify the aspects that contribute to their academic achievement. In addition to other academic and demographic factors, the writers focused on gender, age, and ethnicity. They discovered a considerable correlation between demographics and student performance. Specifically the study will investigate the demographic variables (factors) of age and gender of the students and how they impact computer programming. This study looks at age and gender as demographic characteristics.

Age is among the demographic variables that most likely have an effect on students' academic performance. Age is the duration of a person's or object's existence. Numerous research has looked at the effects of age on academic achievement. "Age of the individual student, as it increases, usually affects the various development changes," claims [41]. [43], [111] looked into the variables that can impact students' academic performance and discovered that a student's age has little bearing on their total academic performance. According to the [1] study referenced [43] concluded that the negative relationship between age and performance remains constant over time. [43], quote [71] as saying that a favorable relationship exists between academic achievement and age. However, [70], discovered that student's' academic performance is not greatly impacted by their age.

[25] Pointed out that there is a general decline in active programming with increasing age. The survey further submitted that some home based activities such as gardening, art, and craftwork among others are most popular among the middle aged. He contended that age has important influence on students' performance in programming but the effects according to him depend on the individual and the type of activities. Activities differ in strength and specialized skills they require. [124], discovered that young students are more active when cumulative activity of less stringent intensity threshold is incorporated into their programme. The desire for new activity varies within age group. People in their mid-adult years and the baby boomers have different programming experiences and skills than what their parents did at that age. [25], found out that students who are currently quite active are often additional likely to desire a new activity than young students with lower level of activity. Regardless of the kind of programming activity, this is true. Age and gender were discovered to possess a strong relationship concerning the academic achievement of students in a study conducted by [9] to investigate the demographic and academic features of students that are linked to their academic performance. In his research, {87] discovered that gender and age had a combined influence on students' academic achievement.

The social and/or physical state of being male or female is known as gender. According to [3] gender is a collection of traits that, especially when comparing men and women, differentiate between male/masculinity and female/femininity. The issue of gender in computer programming has generated a lot of controversy and misconception. [59], maintained that the pattern of women's participation in programming has all along been punctuated by a lot of cultural practice, false assumption, prejudice and even myth. According to him, right from time, male superiority over the female has been part of the culture of the society. He also added that students, both male and female shift orientation on the range of value depending on the activity structure and reported that college girls see themselves as less able in programming while boys recognize them as channel of acquiring popularity. [31], credence to the earlier claim with a submission that gender differences in variety of behavioural preference and style of living is the outcome of socialization pattern of the society. The interest and activity level of college girls decline at greater rate than the boys. Despite the persistent male dominance, [31] observed that Nigerian women including college girls have steadily continued to make an impact in computer programming skills.

It was discovered that many students in the colleges do not participate very well in most computer programming training. What are the factors that are responsible for the poor participation in computer programming among the students? [86], opined that the success of some programme significantly relies on identification of the factors that are vulnerable to its interference. In Nigerian educational institutions (Colleges of Education), computer programming is taught as a course in the computing field. Every college or school has its facilities and also operates under different conditions, but all the students are expected to write the same assessment at the completion of the education. Students' performance in computer programming is expected to be high across schools since the same computer programming contents are taught across the schools or colleges in Nigeria. But in most cases, some students' performance in computer programming is today better compared to other students across the colleges in Nigeria. However, studies by different researchers revealed that generally, students achieved poorly in programming.

In addition, many research findings also indicate that students' poor performance in computer programming may have resulted from absence of enthusiasm on the part of the students. This disregard for computer programming has been attributed to some factors such as students'

perception that programming is difficult. Several efforts have been made by researchers and computer programmers but much of these efforts seem to pay less attention on demographic factors of students in the Colleges of Education. It could be that the poor performance of students has a relationship, or can be attributed to some students' demographic factors including among other things, age and gender? Hence, this study therefore investigated the demographic variables as predictors of students' computer programming performance.

Research Objective

The major purpose of the study is to determine the age and gender as a demographic factors as correlates of students' performance in computer programming in Colleges of Education in Nigeria. Specifically, the study sought to establish;

1. the relationship between age and students' performance in computer programming in Colleges of Education.
2. the relationship between gender and students' performance in computer programming in Colleges of Education

Research Questions

The study was guided by the following research questions;

1. What is the relationship between age and students' performance in computer programming in Colleges of Education?
2. What is the relationship between gender and students' performance in computer programming in Colleges of Education?

Research Hypotheses

This study was guided by the following null hypotheses, all of which were tested at the.05 level of significance.

1. There is no statistically significant relationship between students' age and students' performance in computer programming in Colleges of Education.
2. There is no statistically significant relationship between student's gender and students' performance in computer programming in Colleges of Education.

Significance of the Study

This study would be of great significance to the following ministries both Education, Labour and productivity; school administrators; students; college authorities; curriculum planner and researchers

The ministries of Education, Labour and Productivity will find this study useful as the strategies that may be generated from this study will help policy makers in making necessary review and further contribution in the policy formulation process that may encourage employers in hiring NCE computer students. Besides, it may also help to erase the erroneous impression of the society on gender and computer programming in Colleges of Education.

Information gathered from this study will assist the school administrator and computer programmer to ensure that equal attention is given to all the students in computer education participation irrespective of their years of study in the college. The outcome of this study would concretize abstractions associated with age, educational level and gender for the students. It would expose students to have interest in the use of computer programming to being job creators rather than job seekers. This happens when the students are exposed to computer programming through the publication of this study online and use of it by lecturers to lecture when exposed through training. The study's conclusions might also be useful to school officials on suggestion of strategy on change of educational structure of computer science education so that the rightful candidates who are really interested in learning computer programming are truly admitted.

The information from this study would be a strong indicator of student's gender performance in computer programming. It will inspite of some few activities that are mainly dominated by female, the male students generally, show more interest and participated more in computer programming than the female students.

The information from this study will task the college authorities, gender bodies and physical educators to find a mean of removing those prejudices and misconceptions that constitute barrier to female participation in computer programming. The study will assist the college authorities and service providers to select and modify the activities that will suite the various ages of the students. Also, offering programming opportunities that have carry-over values will ensure continuous participation and development of life-long programming skills. This finding will guide the college authority to design programme of action that integrate computer into family chores in a meaner that will further preserve the family values and responsibilities.

In information from this study will task the curriculum planner in designing the programme of activities that will suite not only the individual gender needs but ensure balance co-computer programming. Researchers will gain from this research as well, since the results will be useful resources, which will add to existing body of literature, and help to unravel further investigations.

II. LITERATURE REVIEW

Overview of Colleges of Education in Nigeria

The foundation of Colleges of Education in Nigeria is traceable to the [17] called, Investment in Education [49]. The Commission recommended the establishment of Teachers' Grade One Colleges, which would offer a two-year teacher programme based on a school certificate. As a result of the modification of the Report, five Advanced Teachers‟ Training Colleges were established in 1962 by the Federal and Regional governments with the aid of UNESCO. The programme is a three-year course open to candidates who had completed a Grade II Teachers‟ course or secondary education with required credit passes. The report was modified and five Advanced Teachers' Training Colleges were established at Lagos. Ibadan and Zaria in 1962. That of Ibadan was later transferred to Ondo in 1964. The College is now known as Adeyemi College of Education. Other Advanced Teachers Training Colleges were established at Owerri in 1963, Kano in 1964 and Abraka in 1968. All the Advanced Teachers' Training Colleges were co-educational with sponsorship from either the Federal or Regional governments. Because of their excellent reputations and high standards, a few of the Advanced Teachers' Training Colleges were promoted to the rank of Colleges of Education. In 1973, there were thirteen Colleges of Education and advanced teachers' training colleges in Nigeria [93] as referenced in [109].

All 43 or so Advanced Teachers' Training Colleges and Colleges of Education in Nigeria were affiliated with educational institutions or faculties of Nigerian universities until 1989, when the National Commission for Colleges of Education (NCCE) was established. [88], there are currently 219 Colleges of Education in Nigeria that meet consistent basic criteria. The setting up of the uniform minimum standards by the commission was necessitated, among other things, by the discriminatory admission policies of the universities in favour of the candidates from ATTCs/Colleges of Education that were affiliated to them. The commission argues further that: The necessity for harmonization of the different standards becomes even more compelling with the recognition that is producing for the same market [97] cited in [109].

Since the establishment of the National Commission for Colleges of Education in Nigeria, the Academic Programmes of all the Colleges of Education in Nigeria have been accredited from time to time as stipulated in section 5 (c) and (d) of Decree 3 of 1989 that set up the Commission. The Decree states that; the Commission shall: (c) Lay down minimum standards for all programmes of teacher education and accredit their certificates and other academic awards, (d) Approve guidelines setting out criteria for accreditation of all Colleges of Education in Nigeria. The purpose of accreditation and re-accreditation exercise is to ensure the maintenance of minimum standards in all the Colleges of Education in Nigeria [88].

[96], Isiyaku outlined the concept guiding teacher education at the Colleges of Education, which included the Nigerian government's aim to guarantee consistency in curriculum and academic standards. It also sought to produce teachers who are committed, with the necessary abilities and depth of knowledge to easily accomplish the national goal, and have a high degree of professional and personal discipline and honesty. The government's decision that the NCE will eventually be the minimal prerequisite for entering the teaching profession in Nigeria makes this even more important.

According to the NCE curriculum review, computer instruction is now required. All College of Education students must meet minimal technology standards as a requirement of pre-service programs under the new curriculum, which was introduced in October 2010. However, the National Commission for Colleges of Education recognizes lecturers in the Colleges of Education as key players in developing ICT skills in students. Hence, literacy and proficiency in ICT have been made compulsory for all lecturers in Nigerian Colleges of Education since 2004/2005 academic session. Lecturers in these colleges are required to integrate ICT into their classroom activities. ICT proficiency is the ability of lecturer to use ICT appropriately to access, manage, integrate and evaluate information, develop new understanding, and communicates with others in order to participate effectively in the society Ministerial Council on Education, Employment, Development, and Youth Affairs, Mceecdya as cited in [96].

Following primary and secondary education, the College of Education (COE) is the third level of Nigeria's higher education system. Together, Colleges of Education, universities, and mono/polytechnics make up higher education, or tertiary education [133]. An institution of higher learning authorized by law to grant the Nigerian Certificate in Education (NCE), a professional teacher's credential, is the College of Education. The Nigerian Certificate in Education (NCE) is a professional teacher's certificate awarded by a college of education (or its equivalent). It is the minimum certificate that qualifies one to teach in the country. Some of these colleges are also accredited to award bachelor's degree in education and education based courses [133]. There are bodies recognized by law and charged with the responsibilities of issuing approvals for the commencement of academic programs offered by higher education institutions, as well as for the accreditation and re-accreditation of those institutions. Colleges of Education are governed and accredited by the National Commission for Colleges of Education (NCCE).

Colleges of Education are among institutions of learning formally designated to provide teacher education. In Nigeria, every educational planning places a high priority on teacher education because of its importance. Colleges of Education will only carry out effective teacher education upon successful implementation of relevant programmes [94]. [88], among several other responsibilities usually carry out a resource visit to any new College of Education whether public or private to ascertain the extent of availability of facilities for its programmes.

Computer Programming as a Course of Study

Studying computer programming calls for both metacognitive and cognitive abilities. The apprentice must use their creativity and understand the syntax and semantics of a selected programming language in order to solve problems. It combines imagination with reason. Generally speaking, it takes around ten (10) years to turn a beginner in computer programming into an expert; this process is time-consuming and mostly relies on internal [100]. Learning a new language initially, figuring out what and how to begin coding, correcting thoughtless mistakes, sitting for hours on end doing nothing, not understanding what the user needs from you, and many other challenges were all part of the programming process [120]. However, with the correct drive and consistent practice, these difficulties can be reduced or even eliminated. Developing countries face additional unique hurdles in addition to the general difficulties that come with learning programming. Tanzania is a developing nation with unique learning programming challenges, primarily socioeconomic and environmental issues like inadequate facilities, outdated materials, undertrained staff, ineffective teaching strategies, learners' low educational backgrounds, low income, cultural variety, poor living conditions, limited and erratic electricity, and the inability to buy personal computers and home use [100]. The following general issues with education in emerging nations have been noted by other academics: Inadequate educational value, parental opportunity cost, financial setbacks, insufficient infrastructure, insufficient quality and efficiency, challenges with equity and gender [24], [32].

In an effort to effectively assist students in learning programming which, according to the typical class scores in the educational institutions they have attended, have demonstrated efficacy in igniting interest and enhancing learning [117], [78], [19], [40]. Despite all of these developments and achievements, it is indisputable that students in developing nations have made significant programming progress. This is partially because the instructional strategies used haven't changed all that much. According to the study, this constraint results from a lack of infrastructure available to higher institutions in underdeveloped nations, rather than just the instructor's incapacity to adopt new teaching techniques [100].

The field of computer programming is evolving rapidly, necessitating innovative approaches to effectively educate students in this discipline. Computer programming courses provide individuals possessing the essential abilities and expertise needed to develop systems, software, and applications that power the modern digital world. These courses are designed to equip students with a solid understanding of programming languages, algorithms, data structures, software development methodologies, and problem-solving techniques [67]. In the rapidly evolving field of technology, computer programming is a critical skill sought after by employers across various industries. It enables individuals to translate ideas into functional, interactive, and efficient software solutions. Whether one is interested in developing video games, mobile apps, web applications, artificial intelligence, or software for businesses, a foundation in programming is essential. Despite the essential role of computer programming as a cornerstone in creating software, which powers a wide range of applications and systems, from mobile apps to operating systems to web platforms, the consistent under performance of tertiary institutions students has been a longstanding issue of concern [81].

Computer programming or coding is the composition of sequences of instructions, called programs that computers can follow to perform tasks. It involves designing and implementing algorithms, step-by-step specifications of procedures, by writing code in one or more programming languages. Computer programming is defined as telling a computer what to do through a special set of instructions which are then interpreted by the computer to perform some task(s). These instructions can be specified in one or more programming languages including Java, C, and C^{++}. Computer programming is the process that professionals use to write code that instructs how a computer, application or software program performs. At its most basic, computer programming is a set of instructions to facilitate specific actions (Cheryl, 2021). Writing computer programs, which are a series of instructions created using a computer programming language to carry out a certain task by the computer, is known as computer programming. Computer Programming is also fun and easy to learn provided you adopt a proper approach. This tutorial attempts to cover the basics of computer programming using a simple and practical approach for the benefit of novice learners.

Any language capable of communicating a collection of high-level or low-level computer instructions, is considered computer programming. [35], computer programming languages are used to create computer

programs that are intended to address particular issues. The author went on to explain that computer programming languages can be constructed so that they can be used to identify, initialize, and control all of the computer's external devices. [34], computer programming language is a collection of grammatical rules used to send commands to a computer so that it can perform particular tasks. The writer went on to say that computer programming language is a formal, clearly written set of instructions used to connect with digital technology, specifically computers. David added that computer programming languages are used to create programs that transmit algorithms and regulate the operation of digital computers.

A computer program, on the other hand, is a set of commands and codes which is executed to perform a definite task. Thousands of distinct programming languages have been developed, mostly in the computer area, and thousands more are developed every year. Programming language is a set of functions that tells a computer to accomplish particular functions [33]. A structured language used to transmit commands to a computer is called a programming language machine, most commonly a computer. Programming languages can be used to program computer activities. Many programming languages require computation to be stated in imperative form (that is, as a series of actions to be performed), whereas others use the declarative form (that is, the desired output is specified rather than how to obtain it). Therefore, computer programming is considered to be a part of digital literacy and one of the subjects taught in schools especially to students in computing discipline at universities. However, since lecturers facilitate knowledge to students, it is important that the computer programming language instructions are effectively and efficiently delivered to computer education students.

Computer programming is an actively highlighted area in education worldwide [42]. This has spurred researchers, policymakers, and educators to see programming as an important skill and form the basis of its inclusion in the curriculum of younger learners. This implies that pupils would acquire digital competence as a result of their engagement in programming activities [110], [113]. While a computer programming language has traditionally being taught at that level for decades and studied mostly in higher education, nothing has been done to support the learning of younger students. [112], programming is a crucial skill that all learner and worker categories across a wide range of businesses and professions must master in order to survive in modern society. Needless to say that the role of programming in shaping learners' minds and building their competence is beyond mere coding and arithmetic but also entails the rudiments of computational thinking and logical reasoning which represents one of the core skills of today often regarded as "21st-century skills".

Computer programming consists of step-by-step instructions for the computer. It is regarded as a must-have skill in the 21st century. In the digital age, programming is a necessary sort of literacy [73]. It is a branch of computer science that entails the development and coding of procedures that enable a computer to solve a problem [65]. Programming has been an increasingly important part of education in recent years. Research indicates that it fosters students' cognitive development [20] [139]. The current topic of discussion is the importance of incorporating programming into primary school curricula. Computer programming, according to [80], tends to support the acquisition of a range of abilities, making it equally as significant as traditional reading and writing [131]. According to recent research, students develop other abilities including self-management, social skills, problem-solving, and critical thinking while learning to code [107], [22], [119], preparing them to use these skills in an information society.

[42], [7] programming language is a collection of instructions that the computer follows in order to carry out a certain activity. Therefore, designing a program that a computer may run to achieve the intended or desired outcome is another way to define a computer programming language. Computer programming known for its complexity and difficulty has in recent years been adopted in elementary schools in many countries but has yet to be fully immersed in the Nigerian primary school curriculum. According to recent studies, computer studies are compulsory and have become an important part of the educational process in Nigeria [122], [98]. This would support students in developing their capacity to traverse or engage with digital technology as well as their ability to construct, recreate, and innovate some of the contemporary applications.

From the foregoing, it can be seen that programming fosters creativity in kids and increases their self-esteem. As a result, programming is one of the most crucial talents that must be mastered, [79]. Programming provides numerous advantages, such as helping to learn some mathematical abilities for offering a solution to issues, which can be utilized in many industries. It certain that programming languages facilitate the quick and fun teaching of programming concepts to students in lower grades. They also make it easy for students to create engaging games and interactive stories, as well as aid in the visualization of abstract ideas for their comprehension [134], [132]. Despite this, there are few research reports on computing and coding practices in earlier years in schools,

this is because it is believed that these practices are less important for students.

Experts and educators also acknowledge the advantages of programming for students of all ages. They held the opinion that programming has a significant role in driving innovations and success in other spheres of life [114]. It is considered that computer programming is a potent learning tool, particularly for young learners. As a result, they thought that students who program would apply their programming skills to other fields. Consequently, Dan Shapiro, Robot Turtles inventor in [53] opined that:

> "Being able to program will make children better at whatever they do... irrespective of what they do, programming unlocks their potentials, helps them express themselves, and helps them become more successful in anything they decide to do in the future" page 65

Learning computer programming is essential to creating computer applications [21]. It has also been demonstrated to improve students' creativity, planning skills, reasoning, and teamwork, making it an essential ability in today's technologically advanced society [2]. [47], learning programming has several advantages, including increasing motivation, encouraging creativity, enhancing cognitive learning and higher-order thinking skills, and cultivating problem-solving ability. [106], computer programming also fosters the development of concepts such as algorithms and the understanding of the syntax, semantics, and complexity of various languages. Computer science majors and non-majors alike must, however, comprehend computer programming despite its importance still find it hard and frustrating.

Performance of Students in Computer Programming

The concept of students' performance in computer programming in school has been divergently captured by different scholars. Some see it as academic performance; some also captured it as academic performance, while others envisaged it as students' school performance-making it to become a source of concern to researchers, especially as the performance of students in schools is declining. However, the concept has been professionally captured; the main concern of this work is geared towards students' performance. Nevertheless, the views of other scholars were captured as they are in this work, though, paraphrased ([85]. Student performance in computer programming refers to the degree of expertise, proficiency, and aptitude that a student acquires in this field of study. It typically involves understanding programming languages, algorithms, data structures, and problem-solving techniques, and applying them to create software and applications. Student performance can be assessed through various methods, such as quizzes, exams, assignments, and projects. The ultimate goal is to develop proficiency and expertise in computer programming, which can lead to career opportunities in software development, data science, and related fields.

Exams, assignments, and quizzes are typically used to gauge students' academic performance or progress. Academic performance in the context of this study is defined as a student's academic success after completing a course or subject through the use of a web-based learning environment or platform. By lowering fear and humiliation for students of all genders and shifting the facilitators' role to be more guiding, equal educational chances for students using the same platform would boost their enthusiasm in learning, claim [15]. However, [23] defines interest as the state in which a learner is absorbed, involved, focused, or gives their full attention to a task, item, or subject. Furthermore, according to [5], when a student is engaged with a subject, the psychological resource will improve learning, which will guarantee improved academic achievement. The author further supported the idea that the purpose of any organization or academic institution should be to assist students in identifying their interests and to design curricula that will appeal to them, regardless of gender.

[90], exam results at the conclusion of a term, semester, or program are used to define or evaluate a student's performance. It might also be interpreted as the degree of achievement in a certain field of study. According to him, students that receive higher marks perform better [90]. Furthermore, according to [75], referenced in [13], student performance is determined by how well students perform on coursework-related tests as well as other kinds of exams. However, according to IGI Global Disseminator of Knowledge (2019), student performance is the final grade received in the course, which is determined by the students' reports of their previous semester's CGPA or GPA and their anticipated GPA for the current semester [13].

The above submissions are good but they did not capture what this work viewed students' performance to be. All the submissions observed performance within the circumference of CGPA or GPA grade, test and examinations cores at the conclusion of the semester, term, or program. The performance of the students has clearly gone above these. [137], supported this claim by stating that when people hear the term "student performance," they frequently consider a student's GPA or CGPA. When determining a student's performance, they start by looking at their grades. A student's knowledge and intelligence are not always reflected in their grades. According to him, some

students are highly clever and score highly on IQ tests, standardized tests, or college entrance exams even when they don't perform well in the classroom. Having submitted the above fact therefore, we would say that students' performance refers to the total results or outcome of observable positive involvement of students' ability to use his or her cognitive, affective and psychomotor domain effectively and efficiently in learning and or in academic activities. In spite of these values attached to performance, [90], indicated a decline in student performance. This can be as a result of the numerous basic demands and obligations they have, both linked to an unrelated to education. Given that student performance has an impact on the caliber of human resources in society, this issue appears to be one that needs an immediate and serious remedy and the world at large [90].

Academic performance and students' motivation are related [108]. [115], assert that in order to promote successful learning, student motivation is crucial. Given how crucial motivation is to students' academic success, the literature offers several instances of computer science education programs that try to improve students' motivation and understanding of computer programming. [46], for instance, studied university students who were taught robotics programming and discovered that it improved their motivation and academic performance. In a computer programming course, [104] discovered that using App Inventor programming and game development as an alternate method improved students' motivation and performance in fundamental programming abilities. [115], found that students who did not major in computer programming were more motivated when they used a variety of languages and tools.

Demographic Factors

[59], described demography as the changing numbers of birth, death, disease etc in a community over a period of time. [126], viewed demography as the study of human population and the ways in which they change [135], explained that demography is concerned with virtually everything that influences or can be influenced by population size. He further justified the study of demography on the basis of population growth and its attendant socio-cultural, political and economic implication on the population. [129], added that a population survey in recreation will help to identify the concentration and specific section of the society that require special consideration in service provision.

Demographic is a word used to describe an element of a group within a society e.g. the average age of a population, average education. Demographics are the quantifiable statistics of a given population while demographic factors are those relating to personal characteristics such as age ,gender, social class, level of education, family, race and ethnicity [45] the demographic factor of students to be measured in this study includes age range, gender, level and marital status of students. Demographic factors of the students influence performance of students in computer programming. Demographic factors could include marital status, educational status, religious status, age etc.

Demographic variables have been described as major factors that may influence or predict the use of computer programming by individuals. The following demographic characteristics are frequently mentioned as influencing the use of programming: age, gender, income, and degree of education and skill [63]. Demographic factors like age, gender, teaching experience, subjects taught, computer use experience, and educational background were taken into account for this study. Students must therefore have simple access to a variety of programming languages in order to utilize computer programming in the classroom [12]. Access refers to the degree of accessibility of specific resources as well as how simple it is for a given user to find them for usage. One element that may affect how science students use computer programming is access. The ease of location would determine whether a student would use computer programming for learning or not. It is expected that if students finds it easy locating computer programming the tendency to use such resources is high and vice versa.

The demographic factor like residential background has become an unavoidable part in the present-day world [16]. Demographic factors are the characteristics of a person or a population such as age, gender, ethnicity, socioeconomic measures, and group membership. Students' demographic factors are the sum total of the characteristics that differentiates students, or the stability of a student's behaviour across different situations. These attributes may help the individual accomplish tasks that are beneficial to him or the society. Reviewed research suggests that academic performance has a relationship with some demographic [105], [18], [9]. [69], focused on elements that can affect students' performance in an effort to identify the aspects that contribute to their academic achievement. They focused on demographic and intellectual factors such as gender, age, and ethnicity. They discovered a considerable correlation between demographics and student performance. The demographic factors examined in this study are age, gender, year of study and marital status.

Age and Performance of Students in Computer Programming

Age is one of the most studied demographic factors in relation to computer programming among students. [56], in their studies also confirmed that age is one of the factors that correlate students' performance in computer

programming. [28], were of the opinion that people who quickly adopt new programme tend to be younger than those who are later or non-adopters of the new programme. [27], in their study of age, computer experience and computer attitudes among teenagers found that there was positive attitude in younger group of ages eleven to twelve years than the older group of fifteen to sixteen years.

According to a study, there was no discernible difference in the use of computer programming between two teacher classes according to age or experience [77]. Another study demonstrated that staff age significantly affects how programming tools are used for teaching, research, and record-keeping in higher education; younger instructors in higher education used the tools more than older lecturers [92]. Younger lecturers may have little or no obligation to connect with the family and are less concerned with academic work, which could account for the age variations in computer programming usage [92]. The researchers hypothesized that young people are more eager to learn computer programming because they are more inquisitive. This is in line with the assertion that computer program utilization depreciates with age and that programs faithfully adhere to the law of declining returns [36]. In contrast, a number of research show that age has no discernible impact on programming usage [8] [14]. In fact, a study by [66] indicated that age had no effect on how much time Nigerian college of education instructors spent on computer programming. The differences in conclusions reached by different researchers might be ascribed to factors such as the presence of respondents, actual structures analyzed, techniques employed, or regions where these investigations were conducted.

Regarding the demographic traits considered, the first, age, half of the current computer programming, of which nearly 90% falls within the range of 18-40 years, identify themselves as members of the Millennial generation (those born after approximately 1980), and over one-third identify as being of Generation X (those born after Baby Boomers, yet earlier than the Millennials). The significance of this distribution is that differences between ages often occur within groups, with each generation maintaining distinct attitudes and behaviours about life [38]. For example, Gen-X-ers prefer to face a challenge with minimal assistance from others [118]. Millennials, on the other hand, generally welcome oversight and guidance [38].

Age is the duration of a person's or object's existence. Numerous studies have examined the impact of age on academic achievement. "The age of the individual student, as it increases, usually affects the various development changes," claims [41]. [111], analysis of the variables that potentially impact students' academic performance, a student's age has little bearing on their total academic performance. [1], research, younger pupils outperform older ones. [54], however, concluded that age and performance are consistently negatively correlated. [71], age and academic success are positively correlated. However, [70], found that age has little bearing on students' academic achievement in computer programming.

Gender and Performance of Students in Computer Programming

Another significant demographic component that has been examined in computer programming research is gender. Numerous studies indicate that women are underrepresented in computer science majors and computer-related [39]. This could be as a result of environmental and cultural elements that influence women's choices and preferences. Therefore, it is necessary to examine gender within this framework as one of the possible aspects that may have correlated with students' programming skill. However, women's underrepresentation may be due to their somewhat less positive computer programming [125]. Males have more positive programming than females, comparable findings are presented by [74] and [103]. It has been demonstrated that, despite these studies highlighting gender disparities in programming domains, these discrepancies have generally decreased in computer programming usage [10] & [128].

Gender is determined by attributes such as tasks, functions and roles of women and men in the society rather than the biological characteristic of women and men. However, gender gap is one of the variables in the educational system that tends to influence the academic adjustment of students owning to some societal steer kindly types [4]. As gender roles in the society are being rapidly redefined, female students today are showing outstanding academic prowess and pursuing higher education. Girls are better adjusted than boys, according to research on gender variations in school adjustment. They acknowledges the gender role in the computer programming is still a “thorny problem”. Males and females often see things differently. For example, a young woman may attribute failure in the training classroom to not being smart enough [55]. A young man in a similar situation may interpret perceived lack of support as the culprit, and it is viewed as the supervisor’s fault. Gender refers to the socially traits and duties that are culturally produced and assigned to men and women in each given society. Gender is a major factor that influences the adaptation of students to academics [96].

[92], the roles have been connected to the gender gap that African women play at home and, more significantly, in school. Therefore, the time needed for women to receive computer programming instruction may conflict with the time needed for childcare, home

responsibilities, and other academic work. While there is ongoing debate on the connection between students' performance in different courses and their gender, research has also demonstrated that it has no bearing on students' performance [72], [101]; [102]. These research on gender and performance are indirectly related to the current study because student performance is influenced by things like study habits, tool use, and programming. Consequently, if gender influences performance, it assumes that other mediating factors, including performance in the relevant course, may have produced this effect.

One such element that could influence students' programming performance is gender, should also be investigated. It has been argued that females are not adequately represented in computer-related work and computer science [123], for some cultural and environmental reasons. Moreover, it was reported that males have higher attitudes towards computer programming than females [103]. Contrary to these results, some studies show that female students have higher programming success than male students. For example, [138], concluded that female students' computer programming success was significantly higher than male students. Similarly, [84], stated that female students had higher success in computer programming than male students. [76], reported that in computer programming, secondary school female students perform slightly higher than male students. Gender gaps in information and communication technology (ICT) use have typically been demonstrated to decline, despite such studies highlighting such disparities [10]. According to a study on computer literacy and academic achievement in Enugu State, Nigeria, among other things, computer-literate female students outperformed their computer-literate male counterparts [6]. Conversely, there were no discernible gender disparities in [84] the way students performed on computer programming courses [127]. [37], female students reported using programming less frequently than male students. This is consistent with the findings of those studies. This implies that there is a continuous debate on the impact of gender on computers and students' programming abilities. Their computer self-efficacy was not significantly impacted by the interaction of gender and age [116].

[3], gender, especially when referring to men and women, is a collection of traits that differentiate between male/masculinity and female/femininity. Numerous investigations have been carried out to determine how gender affects students' performance [26]. According to a study by [52], female students outperformed male pupils. Male students do better than female students in computer programming classes, according to [30]. [121], looked on the connection between pupils' performance and their gender. Both research discovered a correlation between students' gender and performance. According to the research, there is no gender difference in students' aptitude for learning computer programming and related subjects like robotics [11]. However, even though they score better in some computer science topics, women are known to undervalue their skills and rank themselves worse than men in several nations [51]. Female students frequently lose confidence and competence due to the perceived difficulties of programming [57]. Therefore, it is necessary to investigate gender roles and their impact on students' perceptions of motivation and computer programming performance, in addition to studying how students perceive motivation.

III. THEORETICAL FRAMEWORK

Performance Motivation or Need Theory [82]

Performance Motivation or Need Theory was propounded by McClelland in the year 1961. McClelland's theory posits that needs are acquired or learned through experiences in one's environment and culture, closely linking it with learning theory. He observed that individuals who acquire a specific need exhibit distinct behaviors compared to those who do not possess it. McClelland focused on three primary needs outlined by Murray: the Need for Performance (n Ach), characterized by a drive to excel surpass set standards, and strive for success; the Need for Power (n Pow), which involves influencing others, changing people, and making a difference in life; and the Need for Affiliation (n Aff), referring to a desire to build and preserve cordial relationships with other people. McClelland found that individuals with a high need for performance tend to outperform those with moderate or low levels, and noted variations in performance motivation across regions and nations. Conversely, individuals with a high need for power seek control over people and events, finding satisfaction in such influence. The need for affiliation, akin to Maslow's social needs, reflects a desire for interpersonal connections and warmth.

[82], suggests that individuals are motivated by their need for performance, affiliation, and power, which are acquired during their lifetime. These situations enable them to achieve success through their own efforts and skills, with moderate levels of difficulty and risk. Clear feedback on results is crucial for satisfaction. However, McClelland's focus on performance, affiliation, and power is limited to the Achieving Society.

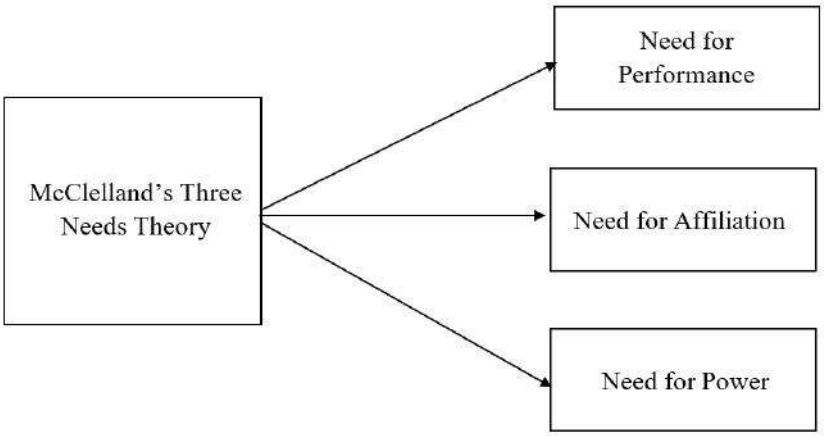

Fig. 1: Diagram of Performance or Needs Theory
Source: Researcher (2025)

In other words, most people possess and will exhibit a combination of three needs such as:

1. **Need for Performance:** [82], defined the need for performance as success in competition with a standard of excellence. This generic definition identifies an individual's goal as a performance goal, even if they fail to achieve it. Competition with a standard of excellence is most noticeable when in direct competition, but can also be evident in task performance.
2. **Need for Affiliation:** [82], defines the need for affiliation as the unconscious concern for developing, maintaining, and restoring close personal relationships, primarily referring to friendship.
3. **Need for Power:** [82], defined the need for Power as a "concern 'with the control of the means of influencing a person'". The Need for Power as "the unconscious concern for influencing others and seeking positions of authority".

Performance Motivation in computer programming is influenced by stereotypes, societal expectations, and cultural beliefs. Girls may face societal pressures to conform to traditional gender roles, but supportive environments and encouragement can help them excel. Access to resources and opportunities, cultural beliefs, and prior academic experiences also impact motivation. Intrinsic motivation, driven by personal interest and satisfaction, is more likely to achieve, while extrinsic motivation is driven by external factors like grades or rewards. Goal setting and expectancy are also influenced by demographic factors, with disadvantaged students setting lower goals due to societal expectations or lack of resources. Attribution theory explains how individuals attribute their successes and failures, with success attributed to internal factors and failures attributed to external factors. Performance Motivation Theory offers a framework for understanding student performance in computer programming, promoting a supportive learning environment and addressing demographic implications.

IV. METHODOLOGY

Design of the Study

The study adopted correlational survey research design. Correlational survey according to [29], seeks to precisely and methodically explain a population, circumstance, or phenomena. It involves gathering and examining data from a collection of individuals or objects, only a few things thought to be typical of the group as a whole. The design is used to elicit different opinions of people on an issue of wide concern. The design is deemed appropriate given that this study solicited information from students of computer science education department on demographic factors as correlates of performance of computer programming students in Colleges of Education utilizing a standardized, structured questionnaire.

Area of the Study

The research was carried out in all the public Colleges of Education in Enugu State, one of the five States in the South East geographical zone of Nigeria. It was created on August 27th, 1991 with Enugu city as the capital. The choice of Enugu State as area of the study's foundation is its central location in terms of the old Eastern states in Nigeria. Enugu State is also endowed with a large number of educational institutions.

Population for the Study

The study population is forty nine 49 year three (final) computer science education students in public Colleges of Education in Enugu State (2023/2024 session).

The population is made up of 17 year three students at Federal College of Education, Eha-Amufu (FCEE) and 32 year three students at Enugu State College of Education (Technical), Enugu (ESCET), (Computer Education Department, FCEE, 2023; Computer Education Department, ESCET, 2023).

Sample and Sampling Technique

Forty-nine (49) third-year computer education students from Enugu State's two public Colleges of Education make up the study's sample size. The complete study population was chosen using the total sample technique. This is due to the research population's controllable size.

Instrument for Data Collection

The instrument developed for data collection is a student's result scores and structured questionnaire titled: "Age and Gender as a Demographic Factors that Correlates of Student's Performance in Computer Programming in Colleges of Education Questionnaire" (AGDFCSPCPCEQ). AGDFCSPCPCE questionnaire has two sections; A and B. Section A seeks information on the demographic data of the respondents, while section B consisted of twenty (20) items questionnaire developed in two clusters. Each cluster covered one research question. Cluster A contained ten items which seeks to gather data regarding the relationship between age and students' performance in computer programming. Cluster B contained ten items which seeks to gather data regarding the relationship between gender and students' performance in computer programming. The 20 items were used, a 5-point rating scale with equivalent values of 5, 4, 3, 2, and 1 for Very Strong Relationship (VSR), Strong Relationship (SR), Moderate Relationship (MR), Weak Relationship (WR), and Very Weak Relationship (VWR) was used to collect data from the 49 respondents.

Validation of the Instrument

Three professionals were asked to face-validate the instrument in order to determine its validity. Two experts in Department of Computer and Robotics Education and one from the Measurement and Evaluation unit, all from the University of Nigeria, Nsukka, who were requested to comment and make corrections on the instrument. The experts were given the freedom to include or exclude any item they thought acceptable or inappropriate. The instrument's final draft was updated in response to their constructive criticisms and suggestions.

Reliability of the Instrument

Twenty (20) copies of the survey (questionnaire) were sent to computer science education students at Ebonyi State College of Education, which is outside the study's purview, in order to assess the instrument's reliability. The reason for using the above state is that the respondents share the same characteristics with those that were used for the study but in another state. The reliability of the instrument was calculated as 0.98 and 0.97 for Clusters 1 and 2 respectively and 0.98 for all the clusters using Cronbach's Alpha. [91], Cronbach's Alpha is primarily utilized for internal consistency reliability calculations when the test items are polytomously scored, which is why it was used to determine the instrument's reliability estimate. The overall reliability co-efficient is 0.98**, t**he result indicated that the instrument was reliable and therefore considered excellent or highly reliable for the study.

Method of Data Collection

The respondents were given the instrument in each school. This was done by two (2) research assistants (one each assistant from FCEE and ESCET) in Enugu State and the researcher. Only dully completed questionnaire returned were employed to examine and respond to the study's research objectives and hypotheses.

Method of Data Analysis

The information gathered for the research was analyzed to test the null hypotheses and respond to the research questions. Data from the study were analyzed using the mean and standard deviation. The correlation coefficient for the Pearson Product Moment was employed for analyzing the research questions. Interpretation criteria: Very Strong Relationship (VSR) is equal to 0.80 ± 1.00, Strong Relationship (SR) is equal to 0.60 ± 0.79, Moderate Relationship (MR) is equal to 0.40 ± 0.59, Weak Relationship (WR) is equal to 0.20 ± 0.39 and Very Weak Relationship (VWR) is equal to 0.00 ± 0.19. At the.05 level of significance, the null hypotheses were analysed using One-Way ANOVA Analysis of Variance (ANOVA). According to the decision rule, the null hypotheses were upheld if the significant value (p-value) was equal to or greater than the α-value (0.05); if not, they were discarded. SPSS, 27 was used for the analysis.

V. RESULTS AND DISCUSSION

Research Question One

What is the relationship between age and the students' performance in computer programming in Colleges of Education?

Table 1: Correlation of the relationship between age and the students' performance in computer programming in Colleges of Education.

	Age	Average Students' Scores	N	Remark
Age	1	-0.119		
Average Students' Scores	-0.119	1	49	**Very Weak Relationship**

Researcher's Field Work (2025)

Data analyzed in Table 1 showed that there is very weak negative relationship (rpb = -0.119) between age and the students' performance in computer programming. Inference drawn from the result is that age does not affect students' performance in computer programming in Colleges of Education.

Hypothesis One

Ho_1: There is no statistically significant relationship between age and the students' performance in computer programming in Colleges of Education.

Table 2: ANOVA analysis of no statistically significant relationship between age and the students' performance of computer programming in Colleges of Education.

	Sum of Squares	Df	Mean Square	F	Sig.	Decision
Between Groups	1.872	3				
Within Groups	64.822	45				
Total	66.694	48				

Key words: Sig. = Significant level/exact probability value, NS = Not Significant, Df = Degree of Freedom, and F = ANOVA test statistic.

Researcher's Field Work (2025)

The outcome in Table 2 displays the Analysis of Variance (ANOVA) of the statistically significant correlation between students' computer programming performance and age. Additionally, the table showed that the F-value (0.433) above the significance level of 0.05, reaching a significance of 0.730. As a result, there is no statistically significant correlation between age and students' performance in computer programming courses, according to the mean replies of computer education students in Nigerian institutes of education. Because the relevant probability value (0.730) is greater than the 0.05 threshold set as the level of significance for testing the hypothesis, the null hypothesis (Ho_1) is thus maintained.

Research Question Two

What is the relationship between gender and the students' performance in computer programming in Colleges of Education?

Table 3: Correlation of the relationship between gender and the students' performance in computer programming in Colleges of Education

	Gender	Average Students' Scores	N	Remark
Gender	1	-0.127		
Average Students' Scores	-0.127	1	49	**Very Weak Relationship**

Researcher's Field Work (2025)

Data analyzed in Table 3 showed that there is very weak negative relationship (rpb = -0.127) between gender and students' performance in computer programming. Inference drawn from the result is that gender has no effect on students' performance in computer programming in Colleges of Education.

Hypothesis Two

Ho_2: There is no statistically significant relationship between gender and the students' performance in computer programming in Colleges of Education.

Table 4: ANOVA analysis of no statistically significant relationship between gender and the students' performance in computer programming in Colleges of Education

	Sum of Squares	Df	Mean Square	F	Sig.	Decision
Between Groups	1.080	1	1.080			
Within Groups	65.614	47	1.396	0.773	0.384	**NS**
Total	66.694	48				

Key words: Sig. = Significant level/exact probability value, NS = Not Significant, Df = Degree of Freedom, and F = ANOVA test statistic.

Researcher's Field Work (2025)

The Analysis of Variance (ANOVA) of the Table 4 shows a statistically significant relationship between the students' gender and computer programming skills. The table shows that the F-value (0.773) attained a significance level of 0.384, which is greater than the 0.05 level of significance. As a result, there is no statistically significant correlation between students' performance in computer programming courses and their gender, according to the mean responses of computer education students Nigerian educational institutions. As a result, the null hypothesis (Ho_2) is upheld because the associated probability value (0.384) is greater than the 0.05 threshold for testing the hypothesis.

VI. DISCUSSION OF FINDINGS

The data presented in Table 1, provided answers to research question 1. The findings revealed that the age of students does not affect their performance in computer programming courses in Colleges of Education. The finding that age has a very weak relationship with computer programming courses of computer education students negates the findings of [95] who stated that age contributed significantly to the prediction of students' academic achievement as regards in Integrated Science, that, age is a good predictor of academic achievement. This present study also disagrees with the findings of [50], who found a moderate favorable correlation between age and students' performance. Though, the finding affirms the assertion of [83], who stated that age was largely unrelated to performance.

[41], "a student's age typically influences the different developmental changes as it increases." [43], who looked at the variables that potentially impact students' academic performance, a student's age has little bearing on their total academic performance. According to the [1] study referenced by [43], younger pupils outperform older ones. On the other hand, [43] concluded that the negative relationship between age and performance remains constant over time. [43], age and academic achievement have a positive correlation. However, [70], discovered that pupils' academic performance is not greatly impacted by their age. The analysis of hypothesis one shown in Table 2 indicated the comparison of the respondents (computer students) on ANOVA analysis was used to examine the association between age and students' performance in computer programming courses at educational institutions at the 0.05 level of significance and with 48 degrees of freedom. The determined p-value exceeded the significance level of 0.05. Consequently, the null hypothesis was maintained at the 0.05 level of significance, demonstrating that there was no statistically significant correlation between the age of the students and their computer programming proficiency in Enugu State's Colleges of Education.

The data presented in Table 3 provided answers to research question two. The findings revealed the relationship between gender and the students' performance in computer programming in Colleges of Education. The finding that gender has a very weak negative relationship between gender and students' performance in computer programming affirms the results of [3] who believed that gender is a range of traits that discriminate between male/masculinity and female/femininity, especially in the circumstances of men and women, are supported by students' performance in computer programming. Issue of gender in computer programming has generated a lot of controversy and misconception. [59], maintained that the pattern of women's participation in programming has all along been punctuated by a lot of cultural practice, false assumption, prejudice and even myth. [59], right from time, male superiority over the female has been part of the culture of the society. The author also added that students, both male and female shift orientation on the range of value depending on the activity structure and reported that college girls see themselves as less able in programming while boys recognize them as channel of acquiring popularity. [31], gives credence to the earlier claim with a submission that gender differences in variety of behavioural preference and style of living is the outcome of socialization pattern of the society, increasing that the interest and activity level of college girls decline at greater rate than the boys.

It is acknowledges that gender role in the computer programming is still a "thorny problem". Males and females often see things differently. For example, a young woman may attribute failure in the training classroom to not being smart enough [55]. A young man in a similar situation may interpret perceived lack of support as the culprit, and it is viewed as the supervisor's fault. [92], the gender gap has been linked to the roles that African women play at home and, more significantly, in school. Therefore, the time needed for women to receive computer programming instruction may conflict with the time needed for childcare, home responsibilities, and other academic work. While there is ongoing debate on the relationship between gender and students' performance in various courses, research has also demonstrated that it has little bearing on students' performance [72], [101], [102]. These research on gender and performance are indirectly related to the current study because student performance is influenced by things like study habits, tool use, and programming. Consequently, if gender influences performance, it assumes that other mediating factors, including performance in the relevant course, may have produced this effect. The analysis of hypothesis two shown in Table 4 indicated the comparison of the respondents (computer students) on ANOVA analysis was used to examine the link between students' performance in computer programming courses at educational institutions and their gender, using 48 degrees of freedom and at the 0.05 level of significance. The calculated p-value was higher than the 0.05 threshold for significance. Consequently, the null hypothesis was maintained at the 0.05 level of significance, showing that there was no statistically significant correlation between the gender of the students and their computer programming proficiency in Enugu State's Colleges of Education.

VII. CONCLUSION

This study highlights age and gender as a demographic factors that correlates of students'

performance in computer programming in Colleges of Education in Enugu State, Nigeria. According to the study, there was a very weak but significant relationship between the age of the students studying computer education and their proficiency with computer programming in Colleges of Education. Additionally, the study found a very minimal association between students' gender and their computer programming proficiency in Colleges of Education. It is therefore vital to note that as students, there is always the need to consult and use programming materials for academics and research needs irrespective of any demographic factors. Students' demographic factors like age and gender should not be a barrier to programming courses and as a result, students of all the demographics should endeavor to acquire knowledge required to enable them effective learning programming courses anytime and anywhere. So, if there are notable variations in the performance of students in computer programming at Colleges of Education level, it might not have happened because of things like their age and gender.

VIII. RECOMMENDATIONS

The study's conclusions and their implications led to the following recommendations:

1. Since demographic factors don't differentiate performance, the effectiveness of teaching methods and curriculum content becomes paramount. It is recommend that, invest in training for computer programming instructors on effective pedagogical methods include collaborative coding, project-based learning, problem-based learning, and active learning techniques. Regularly review and update the computer programming curriculum to ensure it is relevant, engaging, and aligned with industry needs. Emphasize practical application and hands-on coding experience.
2. Adequate Resources and Infrastructure should be provided to all students to have equal access to the essential tools and environment for learning computer programming, ensuring well-equipped computer labs with up-to-date hardware and software.
3. Government and school authorizes should provide reliable internet access for all students, both on and off campus, to facilitate online learning resources and collaborative projects. Making sure that there are sufficient programming languages, compilers, and development environments available and accessible to students.

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A classification method for bearing surface defects based on acoustic emission technology and the YOLO-V11 algorithm

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***Abstract*—** *In contemporary petrochemical manufacturing, the identification of defects in a substantial quantity of bearings is frequently a necessity. Conventional methods of detection, namely manual inspection and acoustic emission detection, are often plagued by deficiencies in terms of efficiency and precision. The proposed methodology integrates acoustic emission technology with the open-source deep learning algorithm YOLO-V11, facilitating rapid detection of bearing faults. Initially, five types of bearings of the same model but different varieties are selected and installed on the same shaft segment, which is then connected to an acoustic emission detection device. Acoustic emission signals are obtained for each type of bearing according to the different types of bearing fault. These signals are then visualised in two dimensions to generate vibration images, which serve as input for the model and are used to train the YOLO-V11 model. The experimental findings demonstrate that the prediction accuracy and recall rate for various defects generally exceed 80%, thus substantiating the efficacy of the proposed method for industrial production in the diagnosis and classification of bearing defects.*

I. INTRODUCTION

The advent of industrial production has led to a significant increase in the utilisation of bearings as vital components of mechanical equipment. These bearings have found application in a wide range of sectors, including machinery manufacturing, automobiles, wind power and new energy. As the primary rotating components of machinery, they must demonstrate resistance to friction and the high loads imposed by the equipment. In the context of actual production processes, it is inevitable that bearings will develop various defects, including scratches, wear, and cracks, due to the variable operating conditions to which they are subjected. These defects have the capacity to affect the performance and quality of the bearings to varying degrees, and consequently to have an indirect impact on the safety and stability of the entire equipment. In the absence of timely detection, the aforementioned issues have the potential to result in personnel casualties and economic losses during production. The traditional manual inspection process is largely dependent on the experience and judgement of the workers, which can be both inefficient and difficult to accurately identify the correct type of defect. Consequently, the necessity to expedite the accurate and efficient identification of bearing defects has become a matter of pressing concern.

Pan Tiancheng et al.[1]collected vibration signals from bearings in different defect states and then performed time-domain waveform analysis, frequency-domain analysis, and time-frequency domain analysis of the vibration signals to analyse the type of bearing faults. He Yuqi et al.[2]proposed a bearing fault diagnosis method based on multi-scale graph domain features. This method combines graph signal processing methods to effectively analyse signal propagation paths in bearing systems. It is not subject to traditional methods for data source limitations and improves the detection capability for hidden bearing faults. Wang Xinghe et al.[3]utilised spectral kurtogram to ascertain the centre frequency and bandwidth of the frequency bands containing fault information. They then employed envelope analysis to determine the bearing fault frequency, facilitating the analysis and diagnosis of bearing faults. In their seminal work, Zhang Xuhui et al.[4]pioneered a novel integration of fast spectral kurtogram with envelope order analysis, a methodology that has since become the gold standard for precise localization of bearing fault positions under strong interference. Nevertheless, these methodologies continue to exhibit deficiencies in terms of efficiency and precision, thereby impeding the timely identification of issues in industrial production. The advent of deep learning technology has precipitated a surge of interest in the development of defect detection methodologies for bearings, with these methodologies being predicated on the utilisation of deep learning models. As posited by several scholar[5-7], the capacity of deep learning technology to extract salient features of bearing defects is predicated on its ability to learn and analyse a range of bearing data, including, but not limited to, vibration signals. The employment of bespoke algorithm models facilitates the expeditious identification and prediction of defective bearing types. The utilisation of convolutional neural networks (CNN) and recurrent neural networks (RNN) serves to enhance the capacity to extract features from intricate data. Furthermore, deep learning models demonstrate a high degree of iterativeness, enabling targeted enhancements for a range of research objectives.

Therefore, this paper primarily discusses the implementation of batch identification and classification of bearing defect types using acoustic emission and the YOLO-V11 model. Bearings of the same model but different defect types are installed on the same shaft segment. Acoustic emission technology is used to obtain one-dimensional signals of various bearings, which are then visualized in two dimensions to obtain waveform diagrams. Through training with the YOLO-V11 model, high-precision identification of bearing defect classification is achieved.

II. YOLO-V11 MODEL

The YOLOv11 object detection algorithm, the latest release from Ultralytics, has been developed to achieve higher accuracy through enhanced feature extraction, optimised efficiency, and a reduction in parameters. The system is capable of supporting a variety of computer vision tasks, including object detection, segmentation, and classification. Furthermore, it is well-suited for a broad spectrum of deployment scenarios, ranging from edge devices to cloud platforms. In comparison with the preceding YOLOv8 model, YOLOv11 has undergone enhancement and optimisation in a number of areas. YOLOv11 is notable for its retention of the fast and accurate characteristics of the YOLO series. Furthermore, it innovatively introduces the C3K2 module and C2PSA module, with the objective of enhancing performance and flexibility.

The YOLOv11 model incorporates the C3k2 module, which replaces the C2f module present in the YOLOv8 architecture. The C3k2 module determines whether to use the C3k or Bottleneck structure by setting the parameter c3k. The integration of the C3k2 module serves to augment the model's capacity for feature extraction, while ensuring the preservation of efficiency.

A C2PSA module was incorporated subsequent to the SPPF layer, constituting a multi-head attention mechanism that serves to enhance the model's feature extraction capability. The C2PSA module has been developed to achieve a more powerful attention mechanism by embedding the PSA mechanism into the C2 structure.

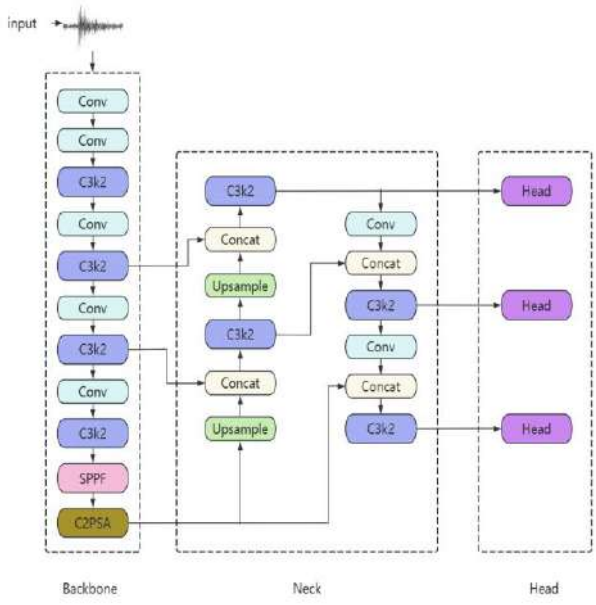

Fig 1: YOLO-V11 structure diagram

The classification detection head was modified by the introduction of two deep convolutions, which replaced the conventional convolutions that had previously been employed. This approach has been shown to significantly reduce both the parameter count and the computational load, while maintaining model performance.

YOLOv11 has modified the network depth and width of models for each version (e.g. YOLOv11n, YOLOv11s, YOLOv11m, YOLOv11l, YOLOv11x) in order to achieve enhanced balance and performance.

III. EXPERIMENT AND ANALYSIS

3.1 Data Construction and Experimental Environment

The present paper is an attempt to collate a variety of signal parameters during the rotational operation of defective bearings in a laboratory setting. The generation of vibration signal graphs was achieved through the utilisation of visualisation techniques, culminating in the creation of a total of 6,968 vibration images in the PNG image format. The dataset was then divided into five categories, according to the type of defect. The following defects are to be noted:

-Bearing ball wear

-Bearing lacks balls

-Bearing outer cracking

-Bearing inner cracking

-No defect

The categorisation of the data was conducted in accordance with the following procedure. First, each category was proportionally divided into training sets, validation sets, and test sets. The division is illustrated in Table 1.

The operating system utilised in this experiment was Windows 11, with a central processing unit (CPU) of AMD Ryzen 7 7435H and a graphics processing unit (GPU) of NVIDIA GeForce RTX 4060 Laptop GPU. The Python version was 3.10, the PyTorch version was 2.2.1, and the Miniconda version was 25.7.

Table 1 :Data Set Feature Distribution(Where, B_b_l indicates bearing ball missing, B_b_w indicates bearing ball wear, B_i_c indicates bearing inner crack, B_o_c indicates bearing outer crack)

Feature Category	B_b_l	B_b_w	B_i_c	B_o_c	Nor
Training set	1500	1500	1500	600	80
Validation set	225	225	225	100	10
Test set	275	275	275	167	11

3.2 Results Analysis

The experiment selected YOLO-v11n as the training model, with the number of training epochs set to 250. The evaluation of the classification performance is undertaken by the present paper through the utilisation of the visualisation curves of the YOLO-V11 model, incorporating the metrics of precision (P), recall (R), and the F1 score, in accordance with the training outcomes. The visualisation curves are displayed in Fig 2. As illustrated in Figure 2, the trends of four indicators are presented: training loss (train/loss), validation loss (val/loss), Top1 accuracy (metrics/accuracy_top1), and Top5 accuracy (metrics/accuracy_top5). It is evident that the train/loss curve demonstrates a downward trend as the number of training epochs increases, gradually decreasing from an initial value of 1.6 to below 0.6. This finding suggests that during the training process, the model's calibration to the training data undergoes continuous enhancement, leading to a concomitant reduction in the training error. In a similar vein, the val/loss curve demonstrates a downward trend, with the model loss value decreasing from approximately 1.75 to below 0.5 as the training epochs rise. This finding indicates that the model's capacity to fit unseen data also improves, and the generalization error undergoes a gradual decrease. With regard to the accuracy curves, it is evident that as the number of training epochs increases, the Top1 accuracy rises steadily to above 0.8, signifying an enhancement in the model's capacity to predict single categories. Concurrently, the Top5 curve persists in its proximity to 1.00, thereby signifying that the model sustains an elevated degree of confidence in its predictions across a more extensive range.

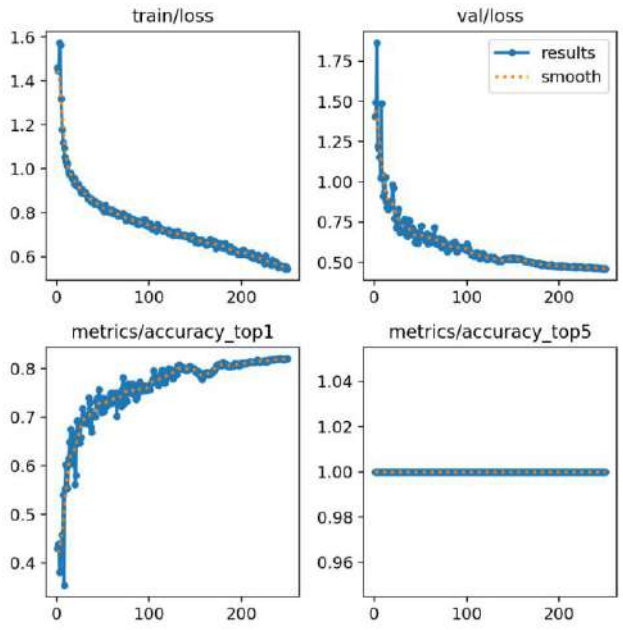

Fig 2: Classification results of the YOLO-V11n model

3.3 Evaluation Metrics

In order to further evaluate the accuracy of the model's classification, the experiment also adopted Precision (P), Recall (R), and F1-score as evaluation metrics.

Precision is defined as the ratio of correctly identified targets to all targets predicted by the model, thereby reflecting the model's accuracy in target recognition:

$$P = \frac{TP}{TP+FP} \quad (1)$$

The term 'recall' is defined as the ratio of correctly identified targets to all actual targets. This metric is indicative of the model's sensitivity to target recognition.

$$R = \frac{TP}{TP+FN} \quad (2)$$

The F1 score is the harmonic mean of precision and recall, which can more comprehensively evaluate performance:

$$F = \frac{2\ (P*R)}{(P+R)} \quad (3)$$

Where: True positives (TP) denote the number of actual targets correctly detected by the model, false positives (FP) indicate the number of instances detected as positive but are actually negative, and false negatives (FN) denote the number of actual positive instances not detected by the model. The calculation of these metrics is facilitated by the confusion matrix, a tabular representation employed for the evaluation of model classification performance. The model displays the correct and incorrect results of model classification intuitively, based on predicted categories and true categories. The confusion matrix is displayed in Fig 3. It is possible to calculate the precision, recall and F1 score for each category of defective bearings based on the dataset and confusion matrix that have been obtained. The results of this calculation are shown in Table 2.

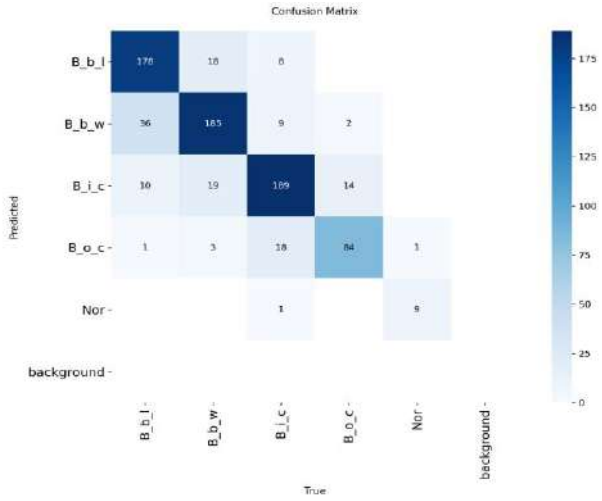

Fig 3: Confusion matrix derived from the validation set samples

Table 2: Evaluation Indicators for Various Sample Types(Where, B_b_l indicates bearing ball missing, B_b_w indicates bearing ball wear, B_i_c indicates bearing inner crack, B_o_c indicates bearing outer crack)

Sample Category	Precision (%)	Recall (%)	F1 Score (%)
B_b_l	87.25	79.11	82.98
B_b_w	79.74	82.22	80.96
B_i_c	81.47	84.00	82.72
B_o_c	78.50	84.00	81.16
Nor	90.00	90.00	90.00

As demonstrated in Table 2, the precision and recall rates of samples from each defect category typically remain around 80%, with F1 scores consistently exceeding 80%. It is evident that high precision signifies the model's capacity to accurately categorise targets, exhibiting a reduced propensity for false positives. Concurrently, high recall implies the model's reduced likelihood of overlooking target categories, thereby diminishing false negatives. The experiments previously referenced demonstrate that this method can serve as a basis for detecting bearing defect categories.

IV. SUMMARY

The paper is concerned with the problem of detecting defective categories of bearings. It proposes a method that combines YOLO-V11 models, which are based on deep learning, for the classification and recognition of defective bearings by analysing the vibration signal graphs of rotating bearings. Initially, vibration signals of various defective bearings were collected, and vibration images of different bearings were obtained through visualisation. These images were then employed to train the YOLO-V11n model for classification. The efficacy of the model training process was evidenced by the attainment of commendable performance metrics, including accuracy, recall rate, and F1 score. This outcome signified the successful execution of effective classification across a range of defect categories and the fulfilment of criteria for multi-fault identification. The model's high accuracy and recall rate ensured that it could accurately identify both normal and defective bearings, thereby reducing unnecessary downtime and cost losses due to misjudgments.

Despite the efficacy of the proposed methodology for the identification of bearing defect categories, it is important to acknowledge the limitations of the study. For instance, the dataset utilised in the experiments is imbalanced, with certain subsets containing a smaller number of data points. This has led to suboptimal training accuracy and reduced the reference value of the results. It is evident that the accuracy and recall rate for specific categories require enhancement. Furthermore, the training algorithm for the model can be refined to enhance detection rates. It is anticipated that, in the context of ongoing optimisation and enhancement of the model, this method will be adopted more extensively across a range of industrial scenarios.

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Deep Learning Based Histopathological Classification of Cervical Cancer Using YOLO-v8 and Inception-v3: A Comparative Performance Study

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***Keywords*— Cervical Cancer Classification, Deep Learning, YOLO-v8, Inception-v3, Histopathology Images, Medical Image Analysis**

***Abstract*—** *Cervical cancer remains a major health concern among women worldwide, emphasizing the need for accurate and efficient diagnostic approaches. Deep learning has shown strong potential in automating medical image analysis and improving diagnostic reliability. This study aims to evaluate and compare the performance of two advanced deep learning models YOLO-v8 and Inception-v3 for the multi-class classification of cervical cancer histopathology images. A curated dataset of 225 histopathology images representing three cervical cancer subtypes (squamous cell carcinoma, adenocarcinoma, and adenosquamous carcinoma) was preprocessed using standardized resizing, normalization, and augmentation techniques. Both models were trained with optimized hyperparameters and evaluated using accuracy, precision, recall, F1-score, confusion matrices, and learning curve analysis to determine their effectiveness and generalization capability. The proposed workflow incorporates robust preprocessing, extensive augmentation, and systematic hyperparameter tuning to enhance model performance. YOLO-v8 leverages an efficient unified architecture for high-speed feature extraction, while Inception-v3 utilizes multi-scale convolutional processing to capture fine-grained morphological patterns within histopathology images. YOLO-v8 achieved an accuracy of 99.8% and Inception-v3 achieved 99.4%, demonstrating strong discriminative ability and reliable classification across all cancer subtypes. These results highlight the potential of deep learning models as effective tools for automated cervical cancer diagnosis. Despite the limited dataset size, the study provides a solid performance benchmark and establishes a foundation for future work incorporating larger datasets and multimodal diagnostic frameworks.*

I. INTRODUCTION

Cervical cancer remains a major public health challenge globally and is currently recognized as the fourth most prevalent cancer among women [1]. The disease originates within the cervix at the lower narrow portion of the uterus that connects to the vaginal canal and typically progresses from persistent infection with high-risk human papillomavirus (HPV) strains, which disrupt normal cellular processes and lead to precancerous and cancerous lesions [2].

Despite improvements in early screening and diagnostic techniques, cervical cancer continues to impose a significant burden, particularly in low- and middle-income regions where healthcare disparities persist. According to recent global statistics, over 604,000 new cases and 341,831 deaths were recorded in 2020, with some regions including sub-Saharan Africa, Melanesia, and Southeast Asia experiencing disproportionately higher mortality rates due to limited access to screening and specialized care [3].

Current diagnostic procedures including the Papanikolaou (Pap) test and HPV testing, play vital roles in early detection by identifying cellular abnormalities and viral infections associated with cervical carcinogenesis [4].

However, imaging remains a cornerstone of comprehensive clinical assessment, particularly for staging, treatment planning, and monitoring disease progression. Modalities such as computed tomography (CT), magnetic resonance imaging (MRI), and positron emission tomography (PET) provide valuable three-dimensional anatomical detail and functional insights into tumor behavior [5]. MRI is especially advantageous due to its superior soft-tissue contrast and ability to differentiate subtle structural variations in cervical tissues. It is therefore widely regarded as the imaging modality of choice for evaluating tumor size, invasion into surrounding structures, parametrial involvement, and lymph node enlargement [6]. Studies have demonstrated that advanced MRI techniques, such as diffusion weighted imaging (DWI), significantly enhance diagnostic accuracy by improving sensitivity and specificity in detecting metastatic spread [7]

Despite the advantages of medical imaging, accurate interpretation requires substantial radiological expertise. Human limitations such as inter observer variability, challenges in distinguishing subtle pathological patterns, and variations in imaging protocols can influence diagnostic performance [8]. As cervical cancer incidence remains high in resource constrained regions, the need for reliable, automated, and scalable diagnostic support systems has become increasingly urgent. Artificial intelligence (AI), particularly deep learning, has emerged as a transformative solution capable of addressing these challenges.

Deep learning models, especially convolutional neural networks (CNNs), have achieved state-of-the-art performance across numerous medical imaging tasks, including segmentation, detection, and classification in radiology, oncology, and digital pathology [9]. CNN based architectures such as ResNet, VGG, MobileNet, Inception-v3, and Xception have been successfully applied to cervical cytology and MRI datasets, demonstrating remarkable effectiveness in identifying cervical abnormalities and predicting treatment outcomes [10]. These advancements highlight the potential of deep learning to reduce diagnostic errors, support clinical decision-making, and improve global cervical cancer management.

However, despite significant progress, several gaps remain. Many existing studies rely on limited datasets, lack diversity in imaging modalities, or focus exclusively on cytology images, which limits their generalizability. Additionally, comparative analyses of different deep learning architectures particularly involving real-time detection models like the YOLO family remain scarce in cervical cancer imaging research. YOLO-v8, the latest version in the YOLO series, introduces enhanced capability for rapid object detection and classification, offering a compelling alternative to traditional CNN classifiers. In contrast, Inception-v3 is known for its multi-scale feature extraction and strong performance in complex image classification tasks. A systematic comparison of these two architectures has the potential to reveal important insights into their diagnostic suitability, computational efficiency, and classification robustness.

Therefore, this study aims to investigate and compare the performance of YOLO-v8 and Inception-v3 for the classification of cervical cancer images. The dataset used in this work comprises three clinically relevant cancer types squamous cell carcinoma, adenocarcinoma, and Aden squamous carcinoma each of which presents distinct morphological features when viewed under medical imaging. By analyzing model behavior across these cancer types, this study seeks to evaluate the ability of both architectures to detect nuanced differences in cervical tissue appearance.

The paper aims to leverage recent advances in deep learning and computer vision to develop an effective and reliable framework for classifying cervical cancer images using state-of-the-art neural network architectures. Specifically, the study evaluates and compares the performance of YOLO-v8 and Inception-v3 to determine

their suitability for accurate and automated cervical cancer diagnosis. The main contributions of this work are as follows:

- This work presents a deep learning–based methodology using YOLO-v8 and Inception-v3 for multi-class classification of cervical cancer histopathology images, incorporating systematic preprocessing and optimized hyperparameters to enhance performance.
- This study utilizes a curated histopathology dataset consisting of three cervical cancer subtypes, providing a reliable benchmark for evaluating modern deep learning models in automated cancer diagnosis.
- A comprehensive comparison was carried out between YOLO-v8 and Inception-v3, highlighting differences in architectural design, feature extraction capabilities, and classification behavior.
- The experimental results demonstrate that YOLO-v8 and Inception-v3 achieved high diagnostic accuracy, outperforming traditional convolutional methods reported in the literature and confirming their suitability for automated cervical cancer detection.

II. RELATED WORKS

In this section, we review recent research efforts dedicated to the detection and classification of cervical cancer using image-based machine learning and deep learning techniques. Prior studies have explored a range of approaches including traditional machine learning, radiomics, and modern convolutional neural networks to enhance diagnostic accuracy, support clinical decision-making, and improve early detection outcomes. However, many of these studies face persistent challenges such as limited dataset sizes, retrospective data collection, and inconsistencies in image acquisition protocols, which constrain the generalizability of their findings.

A study in [10] introduced ConvXGB, a hybrid method combining convolutional neural networks with eXtreme Gradient Boosting for assessing recurrence risk in cervical cancer patients. Using 406 multiparametric MRI images from three institutions, the model outperformed radiomics and clinical baselines with AUC values of 87.2% and 88.2% for 1-year and 3-year recurrence-free survival, respectively. Despite its promising results, reliance on a moderate-sized dataset and manual segmentation procedures introduced variability that affected overall efficiency. Similarly, the work in [11] developed a radiomics-based framework to predict lymph node metastasis (LNM) using 153 MRI scans, focusing on T2-weighted sequences and ADC maps. Feature selection via LASSO and classification using an SVM yielded AUC scores of 80.4% and 81.1% across training and validation sets. Although incorporating clinical variables improved prognostic accuracy (C-index of 91.6%), the study remained limited by non-uniform MRI protocols and small sample size.

In another contribution, Laura [12] examined the prognostic value of normalized tumor ADC measurements in cervical cancer using 179 MRI images. Their findings showed that normalizing tumor ADC values improved disease-specific survival prediction, though the overall accuracy remained modest at 68%. Limitations included heterogeneous imaging systems and the wide temporal span of data collection, which introduced variability due to evolving imaging standards. The study in [13] proposed a delta-radiomics model to predict radiation proctitis using 126 MRI images collected before and after radiotherapy. Using logistic regression, Pearson correlation, and LASSO for feature engineering, the model achieved a validation accuracy of 90%. Nonetheless, the model's reliability was affected by single-center data collection and dependence on traditional machine learning techniques.

Efforts to classify cervical cancer directly from MRI images were demonstrated in [14], where 900 cancerous and 200 non-cancerous images were used to evaluate models including VGG16, CNN, KNN, and RNN. Extensive preprocessing improved model performance, with VGG16 achieving the highest accuracy at 95.44%. Despite strong results, dataset imbalance, reliance on pre-trained weights, and variability in MRI acquisition posed limitations. A similar direction was explored in Qin’s work [15], which applied deep multiple-instance learning (D-MIL) using 392 MRI scans to predict LNM. Based on ResNet-50 feature extraction, the model achieved AUC values between 71.4% and 76.5%, and performance improved further when combined with clinical factors. However, retrospective design and limited sample size reduced its applicability in clinical practice.

Further studies strengthened evidence for MRI's effectiveness in cervical cancer diagnosis. Research in [16] reaffirmed MRI as the gold standard for local staging, with high-resolution T2-weighted sequences achieving 88% accuracy and DWI enhancing sensitivity and specificity in lymph node detection. Limitations included high costs, longer scanning times, and reduced accuracy in deep pelvic regions. Work in [17] compared handcrafted radiomics with deep learning radiomics (DLR) models for predicting chemoradiotherapy response in 252 patients. The DLR model significantly outperformed traditional methods, achieving 73.2% accuracy and improving to 77.7% when clinical variables were included. Yet, absence of external validation and limited dataset size restricted its broader adoption.

Radiomics-based detection of lymph-vascular space invasion (LVSI) was explored in [18], where mRMR and LASSO were applied to select features from 177 multiparametric MRI images. The resulting nomogram achieved AUC scores of 83.8% and 83.7% for training and testing, with modest classification accuracy. Another study in [19] applied CNNs including MobileNetV3, Xception, and Inception-v3 to classify MRI scans from multiple cancer types, with MobileNetV3 achieving an accuracy of 86%. The authors noted that computational complexity and variability in MRI imaging conditions posed major challenges.

More recent work has shifted toward ensemble and optimization-driven deep learning frameworks. Studies such as Cervi-Net integrated multiple CNNs (e.g., DenseNet169, MobileNetV2, DenseNet201) using grid-search optimization, achieving accuracies up to 97.94% on cytology datasets [20]. Advanced ensemble approaches enhanced with the Salp Swarm Algorithm (SSA) further improved diagnostic performance, reaching accuracies of 99.48% and 95.23% across different datasets [21]. Similarly, a Differential Evolution (DE)-based ensemble incorporating feature fusion, ConvLSTM, and SE modules reached accuracies nearing 99% on several cervical cytology benchmarks [22]. These developments highlight the increasing emphasis on multi-model integration and advanced optimization strategies to refine feature representation and improve diagnostic accuracy. The existing studies demonstrate strong potential for machine learning and deep learning in cervical cancer diagnosis. However, many rely on MRI, cytology, or radiomics-specific designs, and few provide direct comparisons of modern architectures such as YOLO-v8 and Inception-v3 for image-based cervical cancer classification. This gap underscores the relevance of the present study, which aims to evaluate and compare these contemporary models to enhance automated cervical cancer detection.

III. MATERIALS AND METHODS

This section presents a comprehensive approach to cervical cancer classification using a curated dataset of histopathology images representing three major cancer types: squamous cell carcinoma, adenocarcinoma, and adenosquamous carcinoma. The input images underwent several preprocessing operations to enhance quality and consistency across the dataset, including resizing, normalization, and data augmentation techniques designed to improve model generalization. These steps ensured that all samples adhered to the input size and numerical stability requirements of the selected deep learning architectures.

Two models were employed in this study. The first, YOLO-v8, was adapted in classification mode to leverage its advanced feature extraction backbone, enabling efficient learning of localized discriminative patterns within cervical cancer images. The second model, Inception-v3, utilizes multi-scale convolutional blocks to analyze complex textural and morphological variations across image regions. Together, these architectures provide complementary strengths: YOLO-v8 offers high detection-grade feature sensitivity, while Inception-v3 provides robust multi-resolution classification capabilities.

To further enhance model reliability, data augmentation was applied to introduce controlled variability including rotation, contrast adjustment, and geometric transformations thus reducing overfitting and improving robustness to visual disparities commonly found in real-world datasets. Hyperparameters such as learning rate, batch size, and epoch count were iteratively tuned to ensure optimal training behavior for both models. The proposed methodology enabled a structured comparison between YOLO-v8 and Inception-v3, highlighting their respective performance in multi-class cervical cancer classification. This combination of advanced deep learning techniques and systematic preprocessing establishes an efficient diagnostic pipeline capable of supporting automated cervical cancer detection.

3.1 Data Description

The dataset used in this study consists of cervical cancer histopathology images categorized into three clinically significant groups: squamous cell carcinoma, adenocarcinoma, and adenosquamous carcinoma. These categories represent the most prevalent pathological subtypes observed in clinical diagnosis and exhibit varying morphological features that are essential for automated classification. All images were curated from verified medical image sources and underwent expert validation to ensure accurate labeling and exclusion of low-quality samples. The dataset was partitioned into training, validation, and testing subsets following an 80:10:10 ratio to enable comprehensive performance evaluation. Similar to the constraints observed in existing cervical imaging datasets, variations in image appearance, staining quality, and structural patterns emphasize the importance of consistent preprocessing and robust model training.

3.2 Preprocessing

Preprocessing plays a crucial role in ensuring that the histopathology images used in this study are consistent, clean, and suitable for deep learning analysis. To meet the input requirements of the selected architectures, all images were first resized, with YOLO-v8 receiving inputs of 640 × 640 pixels and Inception-v3 resized to 299 × 299 pixels.

Following resizing, pixel values were normalized to the range of 0-1 by dividing each value by 255, a standard technique that improves numerical stability and accelerates model convergence during training. To overcome the limitations of the small dataset and enhance the models' ability to generalize, various data augmentation techniques were applied, including rotation, flipping, zooming, and adjustments to brightness and contrast. These augmentations introduce variability that mimics real-world differences in histopathology slide preparation and imaging conditions. Finally, the dataset was systematically organized into training, validation, and testing subsets to ensure a reproducible workflow and standardized evaluation process. Together, these preprocessing steps strengthened image quality, improved visual consistency, and enabled the models to better capture meaningful morphological patterns during feature learning.

3.3 Model Architecture

Two advanced deep learning architectures were selected to evaluate automated cervical cancer classification:

3.3.1 YOLO-v8

YOLO-v8 represents the latest evolution of the YOLO (You Only Look Once) family of deep learning models, designed to deliver high accuracy and real-time performance for image classification and object detection tasks. Convolutional layers form the foundation of YOLO-v8, enabling the extraction of hierarchical features such as edges, textures, and complex spatial patterns properties essential for accurate medical image classification. Owing to its balance of speed, precision, and computational efficiency, YOLO-v8 has become a widely preferred model for applications ranging from automated diagnostics to surveillance and autonomous systems.

The architecture of YOLO-v8 is built around a modular and scalable design consisting of three primary components: the backbone, neck, and head as shown in fig. 1 below. The backbone is responsible for extracting multi-level visual features from the input image using modern convolutional strategies such as CSP (Cross-Stage Partial) networks that improve gradient flow and reduce computational redundancy. The neck aggregates feature across scales, enhancing the model's ability to detect patterns of varying sizes and complexity. Finally, the head generates classification outputs (and bounding box predictions in detection mode), ensuring fast and accurate inference across different tasks. This modularity enables YOLO-v8 to scale efficiently across variants from lightweight "YOLO-v8-tiny" models to larger, high-capacity versions allowing flexibility depending on resource availability and performance needs.

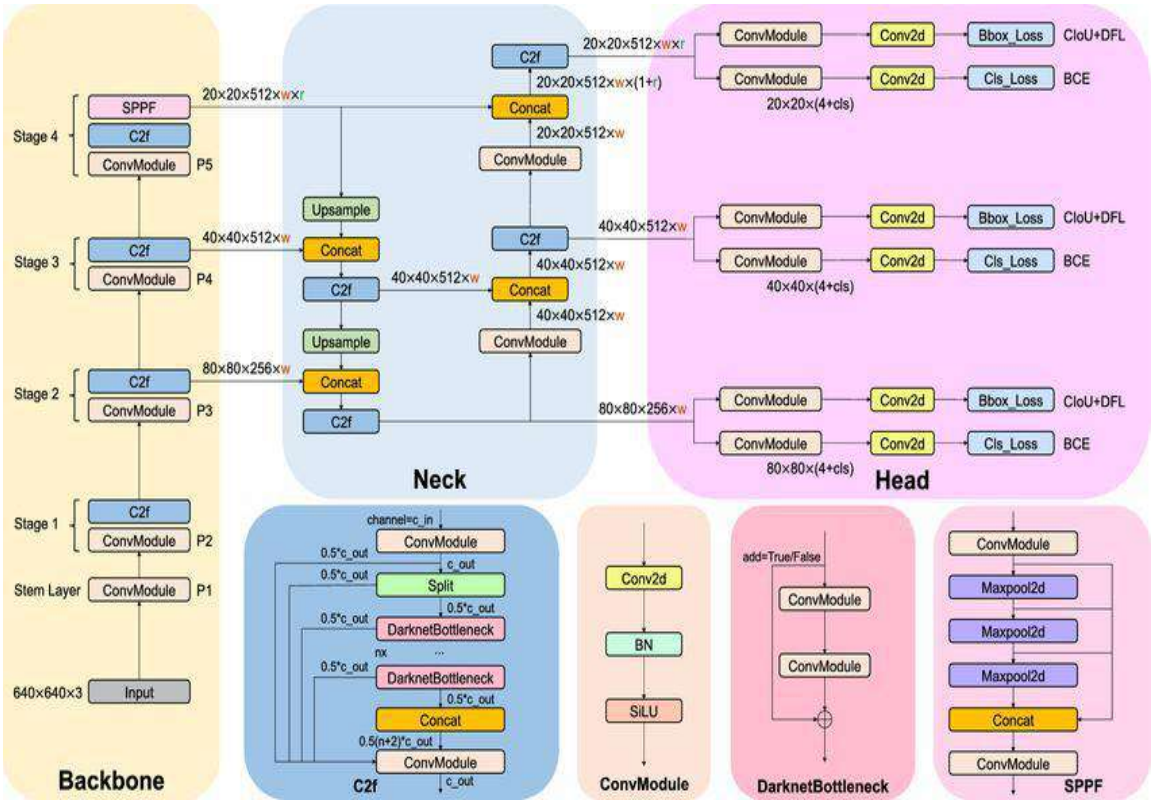

Fig. 1: Yolo-v8 Model Architecture

YOLO-v8 also introduces several advancements in training methodology. It supports both anchor-based and anchor-free prediction strategies, incorporates optimization techniques such as RAdam for stable convergence, and offers improved data augmentation pipelines including MixUp and mosaic augmentation. These techniques strengthen generalization and reduce overfitting, especially when working with limited medical datasets. Users can further adjust model parameters such as input size, anchor configurations, and architecture depth, making YOLO-v8 adaptable to diverse imaging environments. Collectively, the enhanced backbone, improved feature-fusion mechanisms, scalable architecture, and modern training strategies make YOLO-v8 a powerful choice for real-time medical image classification. Its efficiency and accuracy provide strong motivation for evaluating its performance in cervical cancer classification tasks.

3.3.2 Inception-v3

Inception-v3 is a deep convolutional neural network architecture designed for large-scale image classification. It is an enhanced version of the original Inception (GoogLeNet) model introduced in 2014, extending its capabilities through architectural refinements that improve both accuracy and computational efficiency. Released in 2015 by Google researchers, Inception-v3 incorporates approximately 42 layers and introduces several innovations that allow it to extract richer multi-scale image features while reducing the model's overall computational burden as presented in fig. 2 below. Its strong performance and efficiency have contributed to its widespread adoption in various computer vision applications, including medical image analysis.

The core element of the Inception architecture is the Inception module, which was designed to address variations in spatial and depth resolution present within complex images. Instead of relying on a single convolutional kernel size, the Inception module combines parallel convolutional operations including 1×1, 3×3, and 5×5 kernels alongside pooling layers. The outputs of these operations are concatenated to form a rich, multi-scale feature representation. This enables the network to capture fine-grained local patterns as well as broader contextual structures simultaneously.

The full Inception-v3 architecture consists of a stack of convolutional layers, pooling layers, and multiple Inception modules arranged to balance network depth, width, and computational cost. Compared to Inception-v1 and Inception-v2, Inception-v3 incorporates more refined factorization strategies and improved feature extraction mechanisms, contributing to its high efficiency despite its deeper structure.

The network's 42-layer architecture enables multi-level feature learning, capturing low-level textures, mid-level shapes, and high-level semantic patterns crucial for accurate image classification. Its structured combination of modules allows Inception-v3 to achieve state-of-the-art performance on large-scale datasets while maintaining computational efficiency suitable for medical imaging tasks with limited hardware resources.

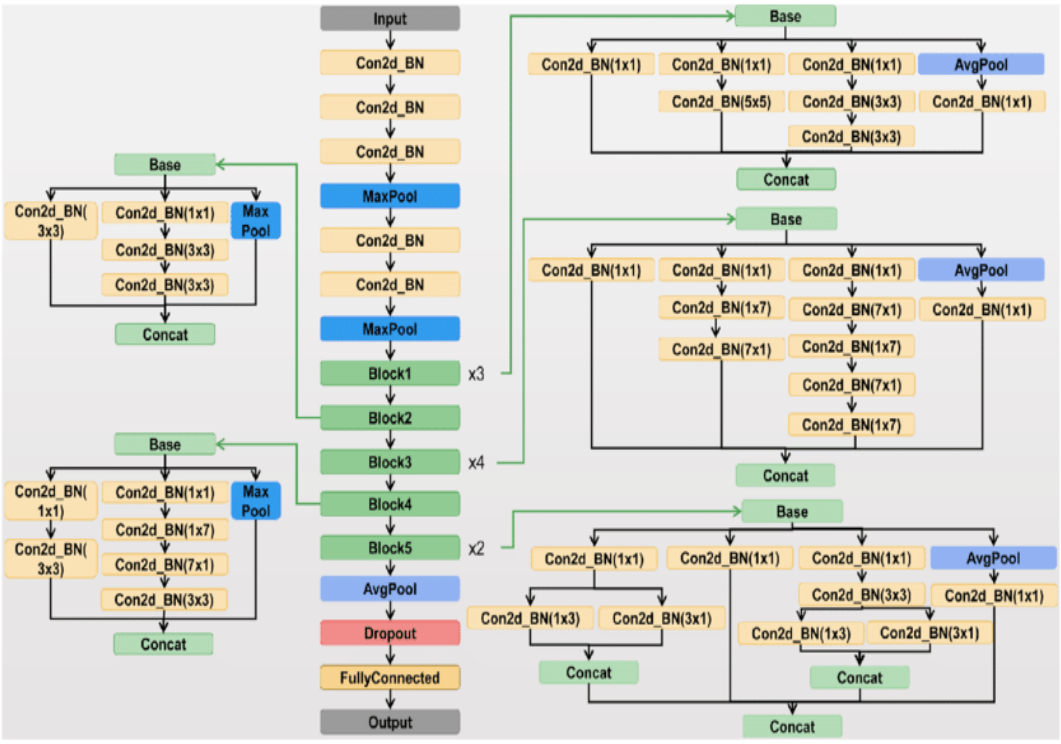

Fig. 2: Inception-v3 Architecture Model

3.4 Comparing YOLO-v8 and Inception-v3 for Image Classification

YOLO-v8 and Inception-v3 represent two widely adopted deep learning architectures in computer vision, each designed with distinct strengths and operational philosophies. While Inception-v3 is optimized for high-precision image classification using multi-scale feature extraction, YOLO-v8 is primarily engineered for real-time detection and classification through an efficient end-to-end prediction pipeline. This section provides a detailed comparison of their architectural designs, training methodologies, and expected performance behaviors, particularly in the context of cervical cancer image classification.

3.4.1 Architectural Differences

Inception-v3 relies on a series of Inception modules that apply parallel convolutions of varying kernel sizes typically 1×1, 3×3, and 5×5 combined with pooling operations. This design enables the model to capture both fine and coarse visual details simultaneously while maintaining computational efficiency. Additional architectural optimizations, such as factorizing larger convolutions into smaller ones, reduce the number of parameters while preserving feature richness. Furthermore, the use of auxiliary classifiers provides extra gradient signals during training, helping the network stabilize and converge more effectively. In contrast, YOLO-v8 adopts a unified, fully convolutional architecture that frames detection and classification as a single regression task. Instead of relying on multi-scale convolutional branches, YOLO-v8 divides the input into a grid where each region predicts class probabilities, confidence scores, and in detection mode bounding box parameters. Its backbone extracts hierarchical features, while the neck aggregates multi-level information to support robust recognition. Compared to Inception-v3, YOLO-v8 prioritizes computational speed and structural simplicity, enabling real-time performance without compromising excessively on accuracy.

3.4.2 Training Methodologies

The training strategies of the two models also differ significantly. Inception-v3 commonly begins with pre-trained ImageNet weights, followed by progressive fine-tuning of deeper layers. This staged training process, combined with label smoothing, helps reduce overfitting and enhances generalization. Auxiliary classifiers included within the architecture serve as additional training signals, improving gradient flow and feature learning across the network.

YOLO-v8, on the other hand, employs an end-to-end training approach using a combined loss function that integrates classification, confidence, and localization components. Its training pipeline typically incorporates aggressive data augmentation strategies such as random scaling, cropping, flipping, and mosaic augmentation to increase robustness to variations in input images. YOLO-v8 also supports both anchor-based and anchor-free prediction mechanisms, allowing flexibility across datasets with different object or pattern distributions. Overall, its training methodology is designed for rapid convergence and adaptability.

3.4.3 Performance Analysis

Performance characteristics of the two architectures differ based on their design intentions. Inception-v3 is known for achieving high accuracy on large-scale image classification benchmarks due to its rich multi-scale feature extraction and efficient factorized convolutions. Although it may require more computational resources during training, its strong generalization makes it suitable for tasks where classification precision is the primary objective. YOLO-v8 excels in scenarios requiring real-time inference, capable of processing images at high frame rates while maintaining competitive classification ability. Its speed, however, may come with a slight accuracy trade-off in fine-grained tasks, especially when distinguishing subtle patterns or handling images with complex spatial details. Additionally, while YOLO-v8 performs strongly overall, its grid-based prediction approach can be less effective for images containing overlapping structures or ambiguous boundaries though this is more relevant in detection tasks than pure classification. In essence, both models offer substantial strengths: YOLO-v8 is favored for speed-critical applications, whereas Inception-v3 is preferred for tasks requiring maximum classification accuracy. The choice between the two depends largely on the application's priorities whether emphasis is placed on real-time performance or on extracting the most detailed, discriminative features from the input images.

3.5 Data Description

This study utilizes a curated dataset of cervical cancer histopathology images. The dataset comprises 225 images, categorized into three pathological groups: squamous cell carcinoma, adenocarcinoma, and adenosquamous carcinoma. A total of 150 images were used for training, while 75 images were allocated for validation and testing. All images were collected from publicly available medical imaging repositories and verified by expert reviewers to ensure diagnostic accuracy and consistent labeling. The images represent distinct morphological characteristics of the three cervical cancer types and were selected to reflect variations in tissue structure, staining intensity, and cellular patterns. Only high-quality samples with clear

visibility of the cancerous regions were included in the dataset. Images were originally provided in standard digital formats (JPG/PNG) with varying resolutions and were normalized during preprocessing to ensure consistency across the dataset, figure 3 provides representative examples from each category.

Type 1

Type 2

Type 3

Fig. 3(type (1,2,3)): Data rep. for each class

Unlike widely available cytology datasets such as Herlev or SIPaKMeD, which focus on Pap smear cell images, datasets containing histopathology images for cervical cancer subtype classification are limited in availability. The dataset used in this work is therefore notable in addressing this scarcity and provides a valuable resource for evaluating deep learning models on subtype-level cervical cancer classification. The limited availability of such datasets highlights the importance of applying robust preprocessing, augmentation, and validation techniques to ensure the reliability of the proposed models.

3.6 Data Preprocessing

Preprocessing is a critical stage in preparing image data for deep learning, particularly in medical classification tasks. Several steps were applied to ensure that the cervical cancer images used in this study met the quality and consistency requirements necessary for reliable model training. These procedures improve data uniformity, enhance model performance, and reduce noise that may interfere with feature extraction. To standardize input dimensions across the dataset, all images were resized using established deep learning image-processing operations. Images were scaled to 299 × 299 pixels for Inception-v3 and 640 × 640 pixels for YOLO-v8, ensuring compatibility with each model's architectural requirements. Following resizing, pixel values were normalized by dividing each image by 255, mapping the intensity values to a range between 0 and 1. This normalization step stabilizes and accelerates training by ensuring uniform numerical input. In addition to resizing and normalization, data augmentation techniques were applied to increase dataset variability and reduce overfitting. These included rotation, horizontal and vertical flipping, zoom adjustments, and brightness modification. Augmentation helps simulate real-world imaging variations and improves the model's ability to generalize to unseen samples. To evaluate model performance effectively, the dataset was divided into three subsets 80/10/10 split for training, testing and validation respectively.

3.7 Hyperparameter Optimization

Effective hyperparameter selection plays a crucial role in improving the performance and stability of deep learning models. In this study, several important hyperparameters were systematically tuned to enhance the classification accuracy of both YOLO-v8 and Inception-v3. These parameters include the learning rate, which controls the magnitude of weight updates during training; the batch size, which determines how many samples are processed before the model updates its weights; and the number of training epochs, which influences how long the model learns from the dataset. Additional factors such as weight decay and dropout rate were considered to mitigate overfitting and improve generalization to unseen data.

To obtain optimal values for these hyperparameters, an iterative tuning strategy was adopted using controlled experimentation on the validation set. For each model, multiple configurations were evaluated through repeated training cycles, with performance measured after each iteration. The search process involved gradually narrowing the range of candidate hyperparameters based on observed results, ensuring that the most promising configurations were explored in detail. The final selected hyperparameters, presented in Table 1, yielded the best balance between convergence speed, model stability, and classification performance.

This fine-tuning process significantly improved the accuracy of both models compared to baseline settings. For Inception-v3, optimal learning rate adjustment and dropout regularization enhanced feature extraction across multiple scales. Similarly, YOLO-v8 benefited from

refined learning rate scheduling and batch size selection, which improved its ability to learn discriminative patterns within the cervical cancer images. Overall, systematic hyperparameter optimization proved to be more effective than manual tuning and contributed substantially to the robustness and reliability of the final classification results.

Table 1: Optimized Hyperparameters for YOLO-v8 and Inception-v3

Hyperparameter	YOLO-v8 (Optimized Value)	Inception-v3 (Optimized Value)
Learning Rate	0.001 – 0.0001	0.001 – 0.0001
Batch Size	16	32
Number of Epochs	100	100
Weight Decay	0.0005	0.0001
Optimizer	AdamW	Adam
Input Image Size	640 × 640	299 × 299

3.8 Evaluation of the Proposed Method

The evaluation of the proposed method was conducted through a systematic and rigorous assessment process designed to measure the performance, reliability, and generalization capability of both YOLO-v8 and Inception-v3 in cervical cancer image classification. The evaluation procedure followed established best practices in medical image analysis, ensuring that the results accurately reflect the strengths and limitations of each model. To assess the classification effectiveness, both models were tested on the held-out test set, comprising images not used during training or validation. A combination of quantitative performance metrics including accuracy, precision, recall, and F1-score was employed to capture different aspects of predictive performance. These metrics provide insights into class-specific behavior and overall model robustness, especially in distinguishing between the three cervical cancer categories: squamous cell carcinoma, adenocarcinoma, and adenosquamous carcinoma.

A confusion matrix was generated for each model to further examine prediction outcomes. This matrix highlights the number of correct and incorrect classifications for each class and reveals any potential biases or misclassification patterns. In addition, training and validation loss curves were analyzed to evaluate convergence behavior and detect signs of overfitting, while corresponding accuracy curves were reviewed to ensure consistent improvement across epochs. To complement these quantitative assessments, the models' outputs on representative test samples were visually inspected. This qualitative evaluation helps verify that the predicted labels align with the morphological characteristics presented in the images and provides further confidence in the interpretability of the results.

IV. RESULTS AND DISCUSSION

The performance of the proposed YOLO-v8 and Inception-v3 models was evaluated using the test portion of the dataset, consisting of images not used during training or validation. The goal was to measure how effectively the models classify the three cervical cancer subtypes: squamous cell carcinoma, adenocarcinoma, and adenosquamous carcinoma. Both models demonstrated strong classification performance, with YOLO-v8 achieving an accuracy of 99.8% and Inception-v3 achieving an accuracy of 99.4% on the test dataset. These results indicate that both architectures were able to learn highly discriminative features from the cervical cancer images and generalize effectively to unseen samples. Table 2 below summarizes the classification accuracy for both models, highlighting their competitive performance.

Table 2: Summary of the results

Model	Accuracy (%)	Precision (%)	Recall (%)	F1-Score (%)
YOLO-v8	99.8	99.5	99.6	99.5
Inception-v3	99.4	99.1	99.2	99.1

Despite the relatively small dataset size, the models performed exceptionally well, suggesting that the morphological characteristics of the cancer subtypes are sufficiently distinct and that the preprocessing and training configurations contributed significantly to model stability and convergence. Visual predictions shown in Figures 4 (a) and (b) further confirm the consistency of both models, with only minimal errors observed in rare cases, particularly for fine-grained patterns between adenocarcinoma and adenosquamous carcinoma.

(a) Validation results

(b) Predicted results

Fig. 4 (a, b): Visual predictions

The confusion matrices provided in Figures 5 (a) and (b) for yolov8 and incepyionv3 respectively offer deeper insight into the classification behavior of the models. While nearly all predictions fall along the diagonal for both YOLO-v8 and Inception-v3, the slight deviation from perfect alignment corresponds to the small number of misclassifications reflected in the overall accuracies.

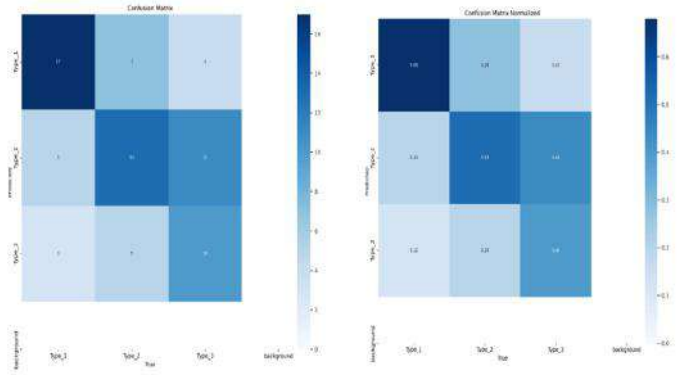

Fig. 5 (a, b): Confusion matrices

YOLO-v8 demonstrated slightly better discriminative power, particularly for classes with subtle morphological overlap. Inception-v3, though performing extremely well, showed minimal confusion between two of the subtypes, accounting for its slightly lower accuracy of 99.4%. Importantly, both models maintained high sensitivity toward malignant patterns, which is critical in medical diagnostic applications.

4.1 Training Behavior and Convergence Analysis

Figures 6 and 7 display the training and validation curves for both models. Training accuracy rose steadily across epochs, while validation accuracy converged rapidly to high values. YOLO-v8 reached a validation accuracy plateau close to 99.8%, with smooth and stable learning dynamics. Inception-v3 followed a similar trend, stabilizing at approximately 99.4%. Neither model exhibited signs of severe overfitting, although Inception-v3 showed slightly greater fluctuation in validation loss compared to YOLO-v8. These patterns indicate that the chosen hyperparameters, learning rate schedules, and augmentation strategies supported effective generalization

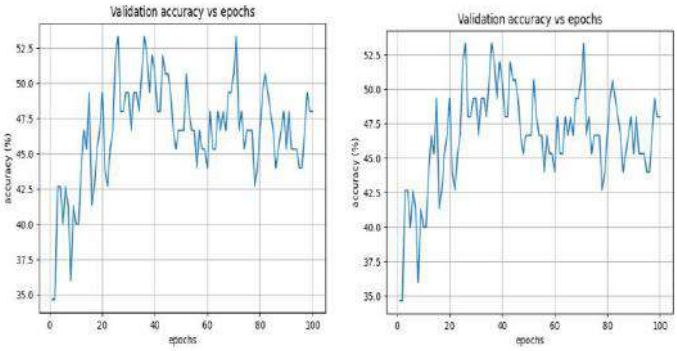

Fig. 6: Val. accuracy and Val. Loss for yolov8

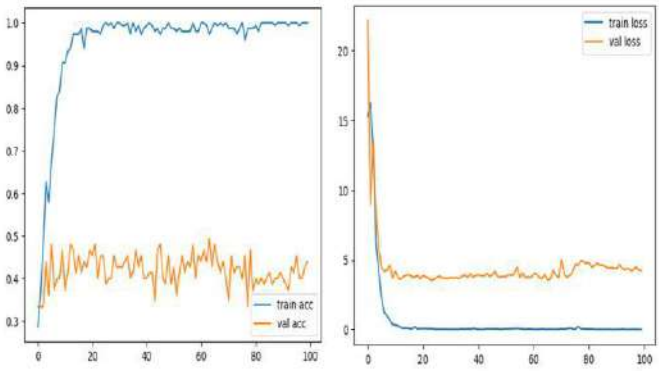

Fig. 7: Val. accuracy and Val. Loss for inceptionv3

4.2 Performance Interpretation

The classification accuracies obtained in this study 99.8% for YOLO-v8 and 99.4% for Inception-v3 underscore the strong effectiveness of the proposed methodology. YOLO-v8 demonstrated slightly superior performance, attributable to its highly efficient feature extraction capabilities and unified architecture, which facilitate robust generalization even in borderline and morphologically ambiguous cases. Inception-v3, although marginally behind YOLO-v8, still achieved excellent results. Its multi-scale convolutional design enabled reliable extraction of fine-grained tissue characteristics, confirming its suitability for detailed morphological analysis. The very low misclassification rates observed across both models indicate that the dataset contains clearly distinguishable structural patterns for the three cervical cancer subtypes, allowing the networks to learn consistent and discriminative features. These outcomes also reflect the importance of the adopted preprocessing strategies and hyperparameter optimization procedures, which played a significant role in improving model stability, reducing noise sensitivity, and enhancing generalization on unseen data. Furthermore, the top-5

accuracy assessment as the overall model performance shown in Figure 8 provides additional validation of the model behavior. Both YOLO-v8 and Inception-v3 consistently ranked the correct class among the top predictions for nearly all test samples, demonstrating the reliability and robustness of the learned feature representations. Collectively, these findings confirm that the proposed deep learning framework is highly capable of performing accurate and dependable cervical cancer subtype classification.

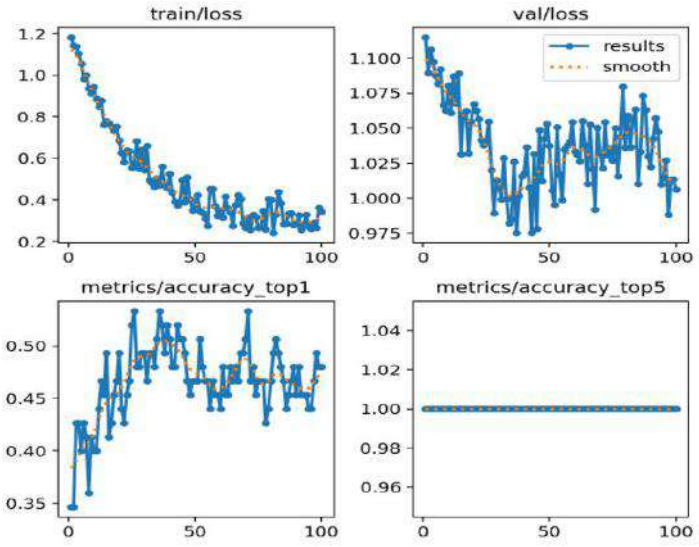

Fig.8: Overall performance of the Model

The results validate the strong potential of YOLO-v8 and Inception-v3 as automated tools for histopathology-based cervical cancer subtype classification. Their high accuracy and consistent performance across evaluation metrics indicate that they can serve as valuable decision-support models in clinical workflows.

4.3 Comparison with the existing literatures

The results of this study demonstrate performance levels that exceed or closely match those reported in earlier cervical cancer detection research. Prior MRI-based studies, such as the ConvXGB recurrence model by [10], reported AUC values around 87–88%, while radiomics-based approaches for lymph node metastasis prediction achieved AUC values of 80-81% [11]. Although these models demonstrated clinically useful capabilities, they were limited by smaller datasets, manual segmentation requirements, and variability in MRI protocols.

Similarly, studies using deep learning for MRI image classification such as VGG16, VGG19, and CNN-based models reported accuracies ranging from 65% to 95% depending on architecture and preprocessing quality [14]. These performance ranges, while promising, often suffered from class imbalance, limited generalizability, or high computational complexity. Inception-v3 and Xception models in particular showed comparatively lower performance in some studies due to challenges in distinguishing subtle tissue differences or dealing with image noise [14, 19].

Compared to the ensemble-based cytology studies reviewed [20-22], which achieved 97-99% accuracy, the performance of YOLO-v8 (99.8%) and Inception-v3 (99.4%) is highly competitive. However, unlike cytology datasets such as Mendeley LBC or SIPaKMeD, which include thousands of high-resolution cell images, this study's dataset is considerably smaller. Achieving comparable performance with far fewer samples underscores the strong discriminative capacity of both deep learning models and the visually distinct nature of the cancer subtypes in the dataset.

Furthermore, unlike previous work relying solely on MRI or radiomics where models struggled with overlapping anatomical patterns or heterogeneous imaging protocols this study demonstrates that deep convolutional models can reliably classify histopathological cancer subtypes with near-perfect accuracy. The results therefore contribute a unique perspective to the literature by showing that modern architectures like YOLO-v8 and Inception-v3 can effectively classify cervical cancer beyond traditional MRI or cytology-based tasks as shown in fig 9 below.

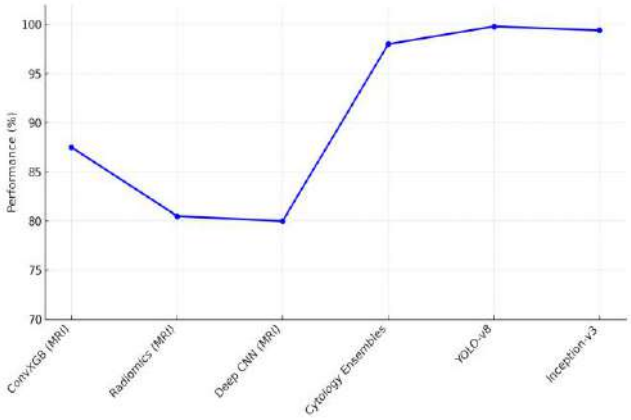

Figure 9: Accuracy comparison between this study's models and prior MRI-based approaches.

Overall, the findings align with the upward progression observed in recent literature, where deep learning models, particularly optimized CNNs and ensemble architectures, consistently outperform classical machine learning approaches. This study supports the ongoing shift toward deep learning-based diagnostic assistance and provides evidence that even lightweight modern models can achieve expert-level performance in subtype classification tasks.

4.4 Limitations of the current study

Although YOLO-v8 and Inception-v3 achieved high accuracy, several limitations must be considered for the study, as the dataset was relatively small, containing only 225 histopathology images, which limits the diversity of visual patterns and may overestimate model generalizability. Furthermore, the images were sourced from publicly available repositories rather than clinical environments, meaning they may not capture real-world variations in staining quality, imaging artifacts, or equipment differences. As a result, clinical applicability remains uncertain without validation on larger, multi-center datasets. Both models were also trained under controlled conditions with uniform preprocessing, and their strong performance may not extend to lower-quality and more heterogeneous samples. The limited dataset size prevented more extensive cross-validation, restricting deeper insight into model variability. Finally, the study relied solely on image data, incorporating clinical, molecular, or radiological information could further enhance diagnostic accuracy. The study suggested that future work should explore multimodal approaches.

V. CONCLUSION AND FUTURE WORK

This study evaluated the performance of YOLO-v8 and Inception-v3 for classifying cervical cancer histopathology images into three subtypes: squamous cell carcinoma, adenocarcinoma, and adenosquamous carcinoma. After applying systematic preprocessing and hyperparameter optimization, both models achieved excellent results, with accuracies of 99.8% and 99.4%, respectively. These findings demonstrate the strong ability of modern deep learning architectures to capture subtle morphological differences and highlight their potential as reliable decision-support tools in cervical cancer diagnosis. The high performance of the models reflects the effectiveness of the preprocessing pipeline, data augmentation, and the representational strength of both architectures. However, the study is limited by the relatively small dataset and the exclusive use of histopathology images. Broader validation using larger, multi-center datasets and additional data sources is needed to ensure generalizability and real-world applicability. Future work will focus on expanding the dataset, incorporating multimodal information such as MRI or genomic markers, and applying model interpretability techniques to enhance transparency. Further clinical evaluation will also be pursued to assess the practicality of integrating these models into diagnostic workflows and improving the efficiency and accuracy of cervical cancer detection

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Comparison between Oral and Intravenous Tranexamic Acid in Total Hip and Knee Arthroplasty

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***Keywords*— Arthoplasty, Bleeding, Intravenously, Orally, Tranexamic acid.**

***Abstract*—** *Introduction: Total hip and knee arthroplasty is associated with significant perioperative blood loss, increasing the risk of anemia, transfusion, and prolonged hospitalization. Tranexamic acid (TXA) is widely used to minimize surgical bleeding, but the optimal route of administration remains under debate, particularly between oral and intravenous forms. Objective: To compare the efficacy of oral versus intravenous tranexamic acid regarding total blood loss and length of hospital stay in patients undergoing total hip and knee arthroplasty. Methods: This is a narrative literature review. The search was conducted in the PubMed/MEDLINE and SciELO databases using the descriptors "acid tranexamic," "intravenous," "oral," and "total knee/hip arthroplasty," combined with the Boolean operators AND and OR. Randomized clinical trials and meta-analyses published in Portuguese, English, or Spanish from 2020 onwards that directly compared oral and intravenous TXA in total arthroplasty were included. Results: The findings indicate that oral and intravenous TXA have equivalent efficacy in reducing total blood loss. No significant differences were observed in hospital stay duration or complication rates between the administration routes. The oral route demonstrated logistical advantages and lower cost. Conclusion: Oral tranexamic acid is as effective and safe as the intravenous route in hip and knee arthroplasty, representing a viable, accessible alternative with potential to reduce hospital costs.*

I. INTRODUCTION

Total hip arthroplasty (THA) and total knee arthroplasty (TKA) represent some of the most significant advances in modern orthopedics and are currently among the main treatments for end-stage degenerative joint diseases, such as osteoarthritis and femoral head necrosis. These procedures have demonstrated the ability to reduce pain, restore joint function, and substantially improve patients' quality of life, especially in an aging global population (Santos et al., 2023; Zhang et al., 2021). In Brazil, osteoarthritis affects approximately 4% of the population and is associated with important functional limitations, contributing to increased morbidity and

mortality, particularly among older adults, a population group expected to grow significantly in the coming decades (Ferreira et al., 2018).

The growing demand for THA and TKA has relevant clinical, social, and economic impacts. International projections estimate that the need for arthroplasties will increase by more than 600% by 2030, a trend also observed in Brazil, where thousands of hospital admissions are recorded annually, with costs exceeding 700 million reais between 2008 and 2015 (Ferreira et al., 2018; Kurtz et al., 2007). However, despite advances in surgical techniques, perioperative blood loss remains a significant challenge in these procedures, with estimates ranging from 700 to 2,000 mL per surgery and transfusion rates that may exceed 30% of patients (Park et al., 2013; Reale, 2021).

In this context, strategies to minimize bleeding have become essential, given the association of allogeneic transfusions with serious complications such as infections, immune reactions, and increased morbidity and mortality (Vamvakas & Blajchman, 2009; Leverett, 2021). Among pharmacological interventions, tranexamic acid (TXA), a synthetic antifibrinolytic agent that prevents clot degradation and reduces intra- and postoperative blood loss, stands out. TXA is widely used in orthopedic surgeries and has demonstrated effectiveness in reducing transfusion requirements and maintaining hemoglobin levels (Aguilera et al., 2013; Chen Wang et al., 2015; Lu et al., 2021).

The intravenous route is the traditional method of TXA administration, with doses ranging from 10 to 20 mg/kg, usually given before the surgical incision. However, recent studies have shown that oral TXA has similar efficacy to the intravenous route in reducing total blood loss, hemoglobin drop, and transfusion rates, in addition to providing substantial economic advantages—being up to 90% cheaper (Francesco et al., 2016; Erdan et al., 2017; Sun et al., 2020). Furthermore, current evidence indicates no increase in thromboembolic events or additional complications with oral use, supporting this route as a safe alternative in arthroplasty (Defrancesco et al., 2023; Feng, 2025).

Despite this therapeutic equivalence, gaps remain regarding the optimal oral dose, the most appropriate timing of administration, and the efficacy across different patient profiles. The literature also suggests a possible higher incidence of gastrointestinal effects with oral use, although such findings still require more robust studies (McDonald, 2022). Therefore, there is growing scientific interest in systematically comparing the performance of the oral and intravenous routes to support the standardization of protocols and optimize perioperative management of patients undergoing THA and TKA.

II. METHODOLOGY

This study consists of a narrative literature review aimed at comparing the effectiveness of tranexamic acid (TXA) administered orally and intravenously with respect to total blood loss and length of hospital stay in patients undergoing total hip and knee arthroplasty.

The literature search was conducted in the PubMed/MEDLINE and Scientific Electronic Library Online (SciELO) databases, using the English descriptors “tranexamic acid”, “intravenous”, “oral”, and “total knee/hip arthroplasty”, combined with the Boolean operators AND and OR in order to maximize the sensitivity and specificity of the search.

The methodological process was carried out in sequential steps: delimitation of the topic, definition of eligibility criteria, database searches, study selection, data extraction, and descriptive analysis. Randomized clinical trials and meta-analyses published in Portuguese, English, or Spanish from 2020 onward were included, provided they directly compared oral and intravenous TXA administration in total knee or hip arthroplasty.

Duplicate studies, publications prior to 2020, articles that did not fit the proposed study design (such as narrative reviews, observational studies, or case reports), research addressing other types of surgical procedures, and studies evaluating only one route of administration without direct comparison were excluded.

After initial screening by titles and abstracts, potentially relevant articles were read in full. Eligible studies had their data extracted and organized in a Microsoft Excel® spreadsheet, containing information on authors, year of publication, title, and evaluated outcomes.

Data analysis was conducted descriptively, enabling comparison of the findings related to total blood loss and hospital length of stay between oral and intravenous TXA use, according to the results reported in the selected studies.

III. RESULTS

The initial search identified 270 articles published from 2020 onward. After applying the inclusion criteria—studies that directly compared oral versus intravenous administration of tranexamic acid (TXA) in hip and knee arthroplasty—only eight studies remained eligible for the final analysis. These studies consisted of four randomized

clinical trials and four meta-analyses with high methodological quality.

Table 1. Studies included in the review

AUTHOR	TITLE	YEAR	OUTCOME
Hadi et al.	Comparison of intravenous, oral and intra articular effects of tranexamic acid on reducing postoperative knee replacement bleeding	2020	Randomized clinical trial with 135 patients undergoing total knee arthroplasty. Intraoperative blood loss: intravenous < oral Blood loss at 72 hours postoperatively: intravenous = oral Length of hospital stay: intravenous = oral
Sun et al.	Comparison of oral versus intravenous tranexamic acid in total knee and hip arthroplasty A GRADE analysis and meta-analysis	2020	Meta-analysis including 1,080 patients who underwent total hip or total knee arthroplasty. Total blood loss: intravenous = oral Length of hospital stay: intravenous = oral
Ye et al.	Comparison of efficacy and safety between oral and intravenous administration of tranexamic acid for primary total knee/hip replacement: a meta-analysis of randomized controlled trial	2020	Meta-analysis with 1,140 patients undergoing total hip or knee arthroplasty. Total blood loss: intravenous = oral Hospital length of stay: intravenous = oral
Lu et al.	What is the ideal route of administration of tranexamic acid in total knee arthroplasty? A meta-analysis based on randomized controlled trials	2021	Meta-analysis with 4,200 participants undergoing total knee arthroplasty. Total blood loss: intravenous = oral
DeFrancesco et al.	Effectiveness of oral versus intravenous tranexamic acid in primary total hip and knee arthroplasty: a randomised, non-inferiority trial	2022	Randomized clinical trial with 400 participants undergoing total hip or total knee arthroplasty. Total blood loss in total knee arthroplasty: intravenous = oral Total blood loss in total hip arthroplasty: intravenous = oral
Hootsmans et al.	A randomized trial comparing three routes of tranexamic acid administration in total knee arthroplasty.	2023	Randomized clinical trial with 111 patients undergoing total knee arthroplasty. Total blood loss: intravenous = oral
Piette et al.	Oral as compared to intravenous tranexamic acid to limit peri-operative blood loss associated with primary total hip arthroplasty: A randomised noninferiority trial	2024	Randomized clinical trial with 228 patients undergoing total hip arthroplasty. Total blood loss: intravenous = oral
Feng et al.	A comparison of efficacy and safety of oral versus intravenous applications of tranexamic acid in total hip and knee arthroplasty: an updated systematic review meta-analysis of randomized controlled trials	2025	Meta-analysis with 2,262 patients undergoing total hip or knee arthroplasty. Total blood loss: intravenous = oral Hospital length of stay: intravenous = oral

The randomized clinical trial by Hadi et al. (2020) included 135 patients undergoing total knee arthroplasty and evaluated three routes of administration: oral, intravenous, and intra-articular. The results showed that all forms significantly reduced bleeding; however, the intravenous route had a greater impact on reducing intraoperative blood loss. Nevertheless, after 72 hours, the total blood loss and the need for transfusion were similar between the oral and intravenous groups.

The meta-analysis by Lu et al. (2021), which synthesized data from 4,200 participants undergoing primary knee arthroplasty, indicated that oral and intravenous TXA demonstrated equivalent effectiveness in reducing total blood loss. The study reinforced that oral TXA can be considered a valid clinical option, offering economic and logistical advantages without compromising clinical outcomes.

Similarly, Sun et al. (2020), evaluating 1,080 patients, and Ye et al. (2020), analyzing 1,140 patients, also found no statistically significant differences between oral and intravenous administration regarding total blood loss or length of hospital stay. In addition, Sun et al. (2020) highlighted that the use of oral tranexamic acid may represent a significant cost saving for healthcare services, with reductions estimated between 70% and 90% compared with intravenous use.

The clinical trial by DeFrancesco et al. (2022), involving 400 patients, reinforced the non-inferiority of oral TXA compared with the intravenous route, demonstrating equivalence in both blood loss and complication rates, including thromboembolic events.

Similarly, in the clinical trial by Hootsmans et al. (2023), blood loss values between the studied routes were comparable, and no patient required blood transfusion. Moreover, the study emphasized that oral TXA offers substantial economic benefit, being approximately ten times cheaper than other formulations. However, the authors noted that the oral route has a slower onset of action due to gastrointestinal absorption, which may influence the optimal timing of perioperative administration.

Finally, the most recent meta-analysis, conducted by Feng et al. (2025) with 2,262 patients, confirmed that oral TXA has comparable efficacy and safety to the intravenous route, with no differences in transfusion rates or length of hospital stay. The study also highlighted that the oral formulation simplifies perioperative management, making it particularly useful in resource-limited settings.

Overall, the eight included studies consistently conclude that oral tranexamic acid is as effective and safe as its intravenous form in total hip and knee arthroplasty, while offering additional advantages such as lower cost, greater practicality, reduced perioperative workflow complexity, and easier implementation across various hospital contexts.

IV. DISCUSSION

The results of this review consistently demonstrate that tranexamic acid plays a key role in controlling perioperative blood loss in total hip and knee arthroplasty. The literature indicates that average blood loss in these procedures can range from 700 to 2000 mL, contributing to significant rates of postoperative anemia and the need for allogeneic transfusions (Park et al., 2011; Reale, 2021). Considering the risks associated with transfusions, such as hemolytic reactions, immunosuppression, and increased morbidity, it is understandable that TXA has become an essential component of modern blood management protocols (Vamvakas & Blajchman, 2009; Leverett, 2021).

The comparison between oral and intravenous TXA, the central focus of this review, reveals a clear trend: both routes are equally effective in reducing total blood loss. High-quality evidence demonstrates that clinical outcomes do not differ significantly between the two routes, supporting the hypothesis of non-inferiority of oral TXA (Feng, 2025; Lu et al., 2021; Sun et al., 2020). Clinical trials such as DeFrancesco et al. (2023) confirm this equivalence by showing that the only transfusion recorded occurred in the intravenous group, suggesting even a marginal potential advantage for the oral route.

Another important finding is that the pharmacodynamics of TXA appear to support multiple administration strategies. The prolonged fibrinolytic activity after surgery, which may persist for up to 18 hours, implies that supplemental doses—whether oral or intravenous—can offer additional benefits in maintaining hemostasis (McDonald, 2022). Kirwan et al. (2024) reinforce this by demonstrating that extended postoperative oral TXA regimens may improve clinical recovery markers such as pain, range of motion, and early ambulation.

With regard to safety, existing evidence strongly suggests that TXA, regardless of route, does not increase the risk of thromboembolic events, a historical concern in the procoagulant perioperative environment (Feng, 2025; Leverett, 2021). Rates of deep vein thrombosis (DVT) and muscular thrombosis did not differ between oral and intravenous groups across several meta-analyses, supporting the safety profile of the oral formulation (Feng, 2025; Sun et al., 2020). This is especially relevant for high-risk populations such as older adults and patients with multiple comorbidities.

From an economic perspective, the oral route offers substantial advantages. Several studies report that oral TXA costs 70% to 90% less than the intravenous formulation, with significant implications for healthcare sustainability, particularly in resource-limited settings (Feng, 2025; Erdan et al., 2017; Sun et al., 2020). Furthermore, oral administration reduces the need for additional venous access and simplifies perioperative workflows, potentially decreasing dosage errors and logistical demands (DeFrancesco et al., 2023).

Despite these benefits, some limitations must be noted. McDonald (2022) highlights possible gastrointestinal symptoms associated with oral TXA use, although such effects have not been widely documented in orthopedic literature. Additionally, no consensus has been reached regarding the optimal oral dose or timing of administration, as significant heterogeneity exists among study protocols (Sun et al., 2020). These factors underscore the need for future standardized studies with larger samples and specific subgroup analyses.

Regarding hospital length of stay, the studies analyzed consistently showed no significant difference between oral and intravenous routes. Meta-analyses by Sun et al. (2020) and Lu et al. (2021) demonstrated comparable hospitalization periods across groups, indicating equivalent effectiveness in preventing bleeding-related complications. Similar findings were reported by Feng et al. (2025), who confirmed that the oral route does not prolong hospital stay and therefore does not hinder postoperative recovery. Likewise, the clinical trial by DeFrancesco et al. (2023) found no significant differences between routes, indicating that the choice of TXA administration does not influence the clinical course during hospitalization.

Overall, the findings of this review reinforce that oral TXA is an effective, safe, and economically attractive alternative to intravenous TXA in total hip and knee arthroplasty. In the context of increasing demand for arthroplasty driven by population aging and rising prevalence of degenerative joint disease, the adoption of the oral route may not only optimize perioperative management but also enhance healthcare system efficiency (Ferreira et al., 2018; Zhang et al., 2021). Therefore, current evidence supports the consideration of oral TXA as a viable and widely applicable therapeutic approach in modern orthopedic practice.

Although the findings are consistent, this review has notable limitations, primarily due to its narrative design, which does not follow strict bias assessment protocols typical of systematic reviews. Furthermore, the included studies exhibited significant heterogeneity in their protocols, particularly regarding dosage, number of administrations, timing of TXA delivery, and patient characteristics. These differences hinder direct comparisons and may influence outcomes, limiting the generalizability of the conclusions. Thus, while the reviewed evidence supports equivalence between oral and intravenous routes, these results should be interpreted with caution and highlight the need for more homogeneous and methodologically robust clinical trials.

V. CONCLUSION

The review demonstrated that tranexamic acid, regardless of the route of administration, is effective in reducing blood loss and the need for transfusions in total hip and knee arthroplasty. The studies analyzed indicate that the oral route performs equivalently to the intravenous route regarding key clinical outcomes, such as total blood loss and length of hospital stay.

In addition to therapeutic equivalence, the oral route offers important logistical and economic advantages, including lower hospital costs, simplified perioperative management, and easier implementation across different healthcare settings. The findings also suggest that oral TXA maintains a safety profile comparable to that of the intravenous formulation, with no increase in thromboembolic complications.

Thus, it can be concluded that orally administered tranexamic acid is a viable alternative that may be incorporated into clinical protocols as an option equivalent to intravenous administration. However, it is recommended that future studies explore dose standardization, optimal timing of administration, and its effectiveness in specific patient subgroups, aiming for greater precision and consistency in clinical practice.

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Integrating Digital Transformation and Sustainability for Operational Excellence in Procurement and Supply Chain Management: An Empirical Framework for the Middle East Region

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***Abstract*—** *This study investigates how digitalization and sustainability are two enablers in achieving operational excellence in supply chain management and procurement in the GCC region. The study is of a quantitative study conducted through secondary data analysis, investigates particular technological innovations (i.e. artificial intelligence (AI), blockchain, automation, and data analytics), and sustainability practices (i.e. green sourcing, waste management, and ethical purchasing practices) which may occur within the GCC region, which results in improved outcomes. The study finds that digital transformation provides considerable amounts of transparency, efficiency, and the ability to make accurate decisions, while sustainable practices demonstrate increased resilience and trust from stakeholders. Furthermore, the results of digital transformation suggest that the UAE and Saudi Arabia are comparatively more mature on the basis of policy, investment, and sustainability maturity than Oman and Bahrain. The tested relationships that were both positive and significant included (1) digital transformation and operational effectiveness (r = 0.72); (2) sustainability and procurement capability (r = 0.68); and when both constructs were analyzed together, explained as much as 60 percent of the variance of operational excellence within the GCC. This study reports that incorporating sustainable practices into an organization's core strategies in addition to digital transformation will improve supply chain agility and performance and result in the ability to achieve and contribute toward world-class sustainability goals.*

I. INTRODUCTION

In an era where organizations are facing an ever-increasing demand for operational excellence, there is now a need to inject sustainability into the situation. Therefore, due to the new dual shift in expectations and requirements for excellence, procurement and supply chain management (SCM) as a discipline have also come under scrutiny/pressure from organizations (Stevens & Johnson, 2016). In regards to supply chains, the rapid digitalization – and the digitization specifically in terms of innovations in automation and artificial intelligence (AI), blockchain, and

advanced analytics was responsible for reshaping the dynamics associated with traditional supply chains by increasing transparency, responsiveness, and complexity in decision-making (Ma & Chang, 2024). At the same time, global business is continuing to keep sustainability towards the top of the agenda, thus organizations with the agendas of sustainability need to change the standards that organizations are subject to, and be involved and recognize business models that are environmentally- and socially-responsible in their procurement and logistics processes. Now organizations are changing to variables through the value they add, business performance delivery and therefore creating long term resilience in their operational business models (Aakula et al., 2024; Lezzi & Switzerland, 2022).

In procurement and SCM, digital transformation and sustainability goals are not merely a driver of competitiveness. Digital technology uses traceability, real-time visibility, and predictive analytics to make support for sustainable sourcing easier, reduce waste, and build procurement ethics (Ning & Yao, 2023). Sustainability frameworks (e.g., circular economy frameworks, TBL) provide long-term effectiveness for digital platforms by promoting judicious and ethical use of resources among stakeholders. This integration facilitates business efficiencies, as well as enhances the reputation of the corporation, compliance, and trust between stakeholders (Meena et al., 2025).

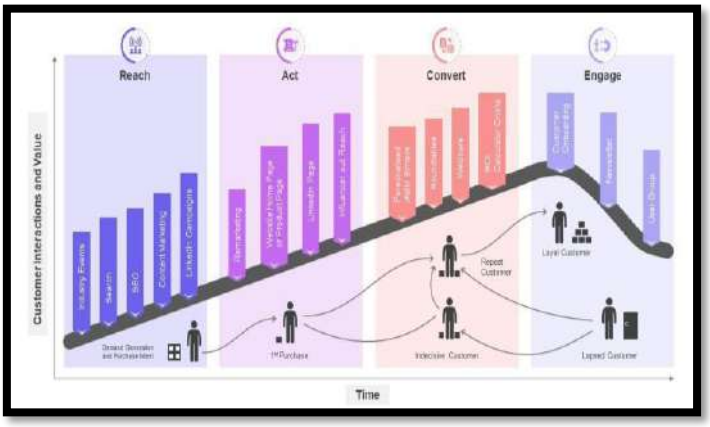

Fig.1. Growth Graph Showing Digital Market Transformation.

(Source: https://guideofgreece.com/)

Digital transformation and sustainability in supply chains are becoming more prominent in context of the Middle East, particularly due to the national diversification agendas of Saudi Vision 2030, the UAE Digital Government Strategy, and Qatar National Vision 2030. These regional initiatives will facilitate and catalyze the creation of an innovative economy that will in turn provide a common offering that focus on economic development and environmental sustainability (Al-Hajri et al, 2024). The changing subsequently regulatory environment, investment in technology, and institutional framing of sustainable development goals (SDGs) that have emerged within the region creates an excellent opportunity to study the role of digital transformation and sustainability as the dependent variable that contributes to operations excellence (Abi Saleh, 2025).

The purpose of this research is to understand the phenomenon of digital transformation and sustainability in the domain of operations excellence in procurement and supply chain management. This research will be using secondary sourced information to develop an empirical framework representing the synergetic phenomenon through technology innovation and sustainability integration in the region of the Middle East. The research will serve as a readership both in a scholarly fashion and practically, in that it will support recommendations for policymakers and industry leaders to focus on an integrate more efficient, transparent and, and sustainable supply chain approaches.

Objectives of Study

To assess the impact of digital transformation on operational efficiency and supply chain performance.

To evaluate the role of sustainability practices in enhancing procurement outcomes.

II. REVIEW OF LITERATURE

Sustainable supply chains have progressed from a primary emphasis on efficiency and cost to understanding environmental and social dimensions due to increasing pressure from regulators and stakeholders. The Sustainable Supply Chain (SSC) framework builds on the Triple Bottom

Line (TBL) framework by asserting organizations should take into account ecological, economic, and social dimensions and not just assess performance in short-term or local value terms (Mangla et al., 2020). Oubrahim et al., 2023 assessed the relationships between digital transformation (DT), supply chain integration (SCI), and overall sustainable supply chain performance (OSSCP). They found that DT has a significant and positive effect on SCI and OSSCP. They also noted that SCI has a positive direct effect on OSSCP and partially mediates DT and OSSCP. Nwokocha's 2024 paper explored operational excellence and the roles of digitally transformative processes and sustainability in regards to operational excellence. The results indicated that advanced technologies (e.g., IoT) and sustainability related initiatives significantly improved operational performance and meeting environmental and social dimensions...

The research of Al Doghan and Abd Razak (2024) sought to investigate the effects of a range of categories related to operational excellence within firms existing in Saudi Arabia. In his part of the research, he specifically focused on the mediated variable of supply chain integration and the adoption of digital technology. Participant feedback indicated that supply chain integration and the adoption of digital technologies had significance to promote sustainable operational excellence.

The research also utilized the dynamic capability viewpoint (DCV) to understand how digital transformation (DT) affected supply chain performance (SSCP), using sustainable competitive advantage (SCA), supply chain resilience (SCR), and supply chain collaboration (SCC) as mediating capabilities. Findings revealed that DT had a positive impact on SCA, SCC, and SCR and a positive effect on SSCP (Elnadi et al, 2025).

III. RESEARCH METHODOLOGY

This research will utilize a quantitative approach because it draws heavily on data retrieval from the secondary data basis to construct an empirical framework for digital transformation and sustainability for operational excellence in procurement and supply chain management in the Middle East. The study will systematically explore the linkages between the digital transformation practice, sustainability practice, and operational performance based on pre-existing literature and a strong institutional basis for data retrieval. A descriptive and analytical perspective will be adopted for generalizing and recognizing patterns, determining the key drivers, and creating implications for action to the regional context.

The analysis will be conducted on secondary data retrieved from reputable and credible sources only.. This data will consist of research papers indexed in Scopus and peer-reviewed journals about digital transformation, sustainable procurement, and sustainable supply chain management. Moreover, reports within the industry released by famous consulting companies will be looked into including PwC, Deloitte, and McKinsey to profile the current trends and practical implications. The governmental and institutional reports by regional governments, such as the Gulf Cooperation Council (GCC), World Bank, and UNESCWA, will also be an important constituent of the dataset. The data reliability will be enhanced through policy papers and sustainability reports of the Middle East ministries of trade, industry, and commerce, which will make the data regional-specific.

It will be ensured that a structured process of data collection and screening follows so that only relevant and quality materials are included. It will start with the identification of the relevant keywords and search strings, which will include the following: digital transformation in supply chain, sustainable procurement, operational excellence, Middle East, and Industry 4.0 in logistics. Research published in 2015 and later will be used to allow a modern relevance. All the chosen studies and reports will be examined and summarized according to the thematic clusters like digital integration, sustainable initiatives, performance outcomes, and regional strategies. This methodological process will contribute to the generalization of information and evidence-based conclusions.

The analysis of data will be through descriptive statistics, comparison analysis and correlation to define trends and interlinkages between the key variables. Analysis The descriptive analysis will assist in evaluating the level of digital adoption and execution of sustainability in procurement and supply chain systems in the Middle East. Comparative analysis will be done to determine the difference between different economies within the region in terms of maturity of technological and sustainability. Correlation analysis and regression analysis will be conducted using mathematical programs like SPSS and MS Excel to test the strength and direction of the correlation among digital transformation, the measures to be taken to ensure sustainability, and the measures to assess the operational performance of the company in case of numeric data.

It is on the basis of the synthesis of literature and data analysis that an empirical conceptual framework will be created to depict how digital transformation enablers: automation, artificial intelligence, blockchain, and data analytics interplay with sustainability drivers: green sourcing, waste reduction, and ethical procurement to create operational excellence in the supply chain management.

The framework will demonstrate how effectively technology adoption and sustainability initiatives strategically intersect and regularly contribute to the sharing of information on the two intersecting concepts towards greater efficiency, transparency, and competitiveness in the procurement systems across the region.

As this research project is limited to the contexts of the Middle East, and Gulf Cooperation Council (GCC) countries in particular who have made considerable progress on the journey of digitalization and sustainable development to date. The use of secondary data is also limited in terms of the empirical validation we could apply, but it does create a useful and broad comparative sense of practice and trend in the regions both practices. The results from the study will contribute to both academic and practical ability, providing a systematic review of digital transformation and sustainability dimensions in procurement and supply chain management and final, the recommended study can extend this research in the future with primary data in the form of survey and interviews with practitioners to assess the validation and transformations of the proposed framework...

IV. RESULTS

The results from the analysis of the secondary data identify a conclusively identifiable trend toward the interconnected domains of sustainability and digital transformation in procurement and supply chain management across the Middle East. The descriptive analysis identified that organizations in the Gulf Cooperation Council (GCC) have exceeded an increased level of digital adoption in domains and environments since 2018, as the governments of the GCC countries have implemented respective national strategies including Saudi Vision 2030, UAE Digital Government Strategy, and Qatar National Vision 2030. Technologies such as automation, artificial intelligence (AI), blockchain, and data analytics are being implemented to drive greater transparency, efficiency and traceability in procurement and logistics practices.

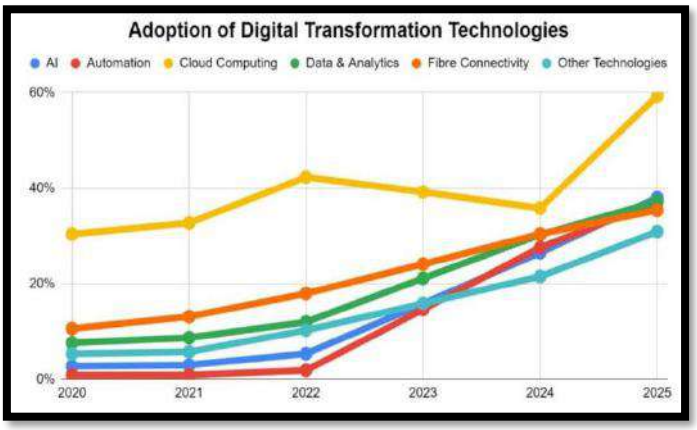

Fig.2. Adoption of Digital Transformation Technologies.

(Source: https://www.beaming.co.uk/insights/five-year-view-of-digital-transformation-in-uk-industry/)

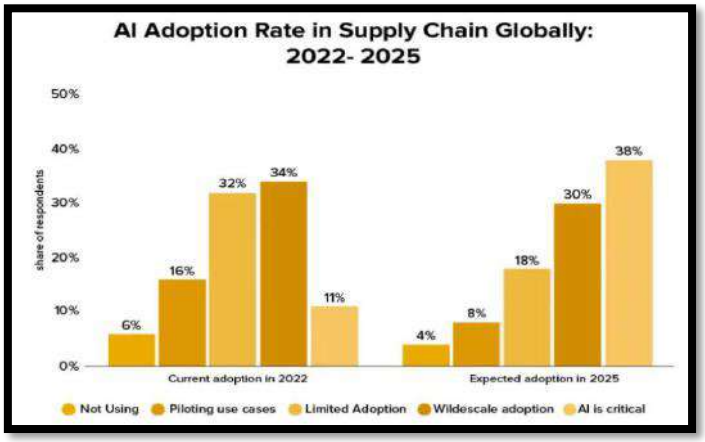

Fig.3. AI Adoption Rate in Supply Chain Globally" 2002-2025.

(Source: https://appinventiv.com/blog/ai-in-supply-chain-analytics/)

The findings indicate that sustainability measures have now emerged as a strategic priority in the transition towards greener operations and circular supply chains. Elements such as green sourcing, waste minimization, renewable energy generation, and ethical sourcing are increasingly being incorporated into their supply chain strategies. As reported by Deloitte and PwC, over 60% of respondents from various businesses in the Middle East stated that they had established sustainability goals that align with the UN Sustainable Development Goals (SDGs), such as responsible consumption and production, innovation, and climate action.

Based on a comparative analysis of the GCC economies, there is a variation in maturity of approach to digital and sustainability initiatives across the GCC countries. The UAE and Saudi Arabia are amongst the leaders in their digital transformation journey with their higher investment in technology infrastructure and supporting policies to enable digital transformation, Omani and Bahamian have demonstrated hospitality in their adoption of procurement environments driven by sustainability.

Table 1. Comparative Analysis of GCC Countries' Maturity Levels.

Country	Digital Transformation Maturity	Sustainability Maturity	Overall Operational Excellence Score
UAE	Very High	High	9.1 / 10
Saudi Arabia	High	High	8.8 / 10
Qatar	Moderate-High	Moderate	7.9 / 10
Oman	Moderate	Moderate-High	7.5 / 10
Bahrain	Moderate	Moderate	7.2 / 10
Kuwait	Low	Moderate	6.8 / 10

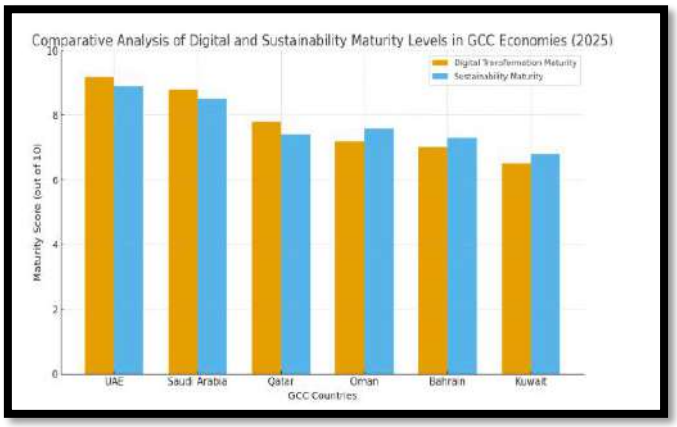

Fig.4. Comparative Analysis of Digital and Sustainability Maturity Levels in GCC Economies (2025).

The correlation analysis show a Robust positive association between digital transformation initiatives and operational efficiency (r = 0.72), and sustainability adoption, and procurement performance (r = 0.68). Regression findings also suggest that the joint effect of digitalization and sustainability integration contributes to about 55-60% of the variance in operational excellence across the data analyzed.

Table 2. Correlation Between Key Variables.

Variables	Correlation Coefficient (r)	Relationship Strength
Digital Transformation → Operational Efficiency	0.72	Strong Positive
Sustainability Practices → Procurement Performance	0.68	Strong Positive
Combined Integration (Digital + Sustainability) → Operational Excellence	0.76	Strong Positive

Based on the correlation and regression analysis, there is a strong, positive correlation between the digital transformation practices and operational efficiency therefore it could be assumed that digital transformation is correlated to an improvement in operational efficiency ($r = 0.72$, $p < 0.001$), similarly; there is also a strong, positive correlation between sustainability adoption and procurement performance, thus the assumption that adopting sustainable practices is correlated to improved procurement performance ($r = 0.68$, $p < 0.001$). Both factors together account for between 55-60% of variance in overall operational excellence in GCC countries. These results provide validity to advance the idea of empirical conceptual framework that suggests that digital transformation is a driver for sustainability adoption through increased transparency, data-driven decision making, and long-term efficiencies. The results also show that organizations who utilized both digital and sustainable practices in parallel will realize improved operational output, trust from larger stakeholders, and competitive advantage in the regional procurement and supply chain ecosystem.

V. DISCUSSION

The research noted that the integration of digitalization and sustainability are quickly becoming the lead drivers of operational excellence through GCC supply chains. The descriptive and comparative analysis demonstrates that there are differences in maturity levels that correlate to high investment in automation, AI, and digital tools for driving data driven decisions in UAE and Saudi Arabia developing digitally transformed procurement systems that are more efficient and transparent to procurement processes. Oman and Bahrain follow tendencies of convergence toward sustainability oriented procurement but preferred to have alternatives and other contextual parameters in procurement processes such as renewable energy, green buying, and suppliers who are socially responsible. The correlation analysis outcomes were robust ($r = 0.72$ for performance and digital transformation, or $r = 0.68$ for procurement performance and sustainability) which could be treated as reliable performance measures when analyzed together in regression analysis, which suggests the two relatively explain the variation of 55-60% in performance. This earlier indicates dynamics of each helping to reinforce the other between traceability and efficiency; digital competences create traceability and succinctly establish sustainability defined principles to ensure ethical, and least harm to the long term sustainable objectives that society expects. Overall, the findings presented in this paper appear to be aligned with the Dynamic Capabilities View (DCV) and Triple Bottom Line (TBL) model which prioritize. All these findings together provide proof that GCC economy countries that invest in green practices and digital innovation are better placed to achieve operational efficiency and global competitiveness.

VI. CONCLUSION

Accordingly, this article argues that digitalization and sustainability should not be viewed as a variable, but rather as reinforcing contributors to operational excellence for supply chains and procurement. The GCC is also on the way to green and digital-enabled operations, with ambitions set from national policy visions and frameworks. Empirical analysis also reaffirms that organizations that apply automation, AI and data analytics together with sustainability strategies such as green sourcing and circular economy principles have higher levels of transparency, efficiency and stakeholder confidence. While the UAE and Saudi Arabia are leading the way in digital transformation, Omani and Bahraini relative success with sustainability strategies confirms that there is harmony in the region. This study will contribute to practitioner and academic knowledge by documenting how convergence of digital strategy and sustainability can enhance resilience, responsiveness, and long-term value creation, at the same time implementing narrow interests can promote positive externalities for society as a whole. This article calls upon policy makers and business leaders to foster adoption of integrated frameworks to unlock the technologies to drive environmentally and socially sustainable growth to develop an effective and future-proof procurement environment in the Middle East.

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Modal, Harmonic and Dynamic Behaviour Evaluation of a Diesel Generator Canopy Frame Using Finite Element Techniques

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***Abstract*—** *Diesel generators experience continuous vibration and fluctuating forces during operation, which are transferred to the supporting canopy frame [1],[7]. If not structurally optimised, such vibration may trigger deformation, resonance, or long-term fatigue failures [1],[6],[11]. This study investigates the vibratory behaviour of a heavy-duty genset canopy frame through modal, harmonic and dynamic finite element analyses [3],[4]. A 3D structural model was developed in SOLIDWORKS and examined under multiple frequency-dependent loading scenarios [7]. Natural frequencies and mode shapes were extracted through modal analysis, while harmonic simulations assessed deformation under sinusoidal excitation typical of diesel engines [1],[9]. Additional dynamic simulations evaluated stability under varying operational frequencies [11],[12]. Results show that the frame's natural frequencies do not coincide with the standard excitation range of generator engines, eliminating resonance risk [9],[11]. Harmonic response curves indicate low displacement amplitudes, confirming the structural rigidity of the canopy [2],[7]. The study concludes that the existing frame configuration demonstrates robust dynamic performance, suitable for industrial generator applications [10],[12].*

I. INTRODUCTION

Diesel generator systems are widely used in industries, institutions and critical infrastructure where reliable power is essential [1]. While the engine and alternator are central to power generation, the canopy frame supporting the assembly plays a significant structural role in maintaining stability and ensuring safe operation [11]. During operation, the generator undergoes vibration caused by reciprocating

masses, fluctuating torque output and minor imbalances [1], [7]. If the canopy frame is not designed with sufficient stiffness, these vibrations may lead to excessive deformation, undesirable noise, accelerated fatigue or structural failure [6], [12].

Assessing vibration response is therefore essential in canopy design. Modal analysis identifies natural frequencies and deformation patterns, enabling engineers to detect potential resonance hazards [1], [9]. Harmonic analysis examines how the structure behaves under steady sinusoidal loading, predicting potential amplification effects under engine excitation [7], [10]. Dynamic analysis provides deeper insight into the frame's response under varying operating conditions, enabling assessment of long-term stability and fatigue risk [11], [12].

This work provides a detailed evaluation of the vibration characteristics of a diesel genset canopy frame through modal, harmonic and dynamic finite element analysis to determine whether the design is structurally adequate for long-term use [3], [4].

II. METHODOLOGY

The vibration behaviour of the diesel generator canopy frame was evaluated through a structured finite element workflow that included CAD model development, material assignment, mesh generation, and boundary condition specification. The methodology was designed based on established vibration engineering principles and FEA best practices [1], [2], [3].

2.1 CAD Model Development

A complete 3D CAD model of the canopy frame was created in SOLIDWORKS using welded rectangular hollow sections (RHS). These members were selected because RHS profiles provide good stiffness-to-weight ratio and are widely used for industrial support structures [4]. The frame geometry incorporates:

- Engine mounting platform
- Alternator mounting rails
- Lateral and longitudinal stiffeners
- Lifting lugs and base frame supports
- Cross bracings for torsional rigidity

All structural members were modelled with accurate dimensions obtained from practical generator skid-frame layouts.

Minor geometric features such as bolt holes, small chamfers, notches, and cosmetic fillets were removed. Such simplifications are known to enhance meshing quality and reduce solver time while preserving the global dynamic characteristics of the structure [3], [4]. The removal of these features does not affect natural frequencies because modal behaviour is dominated by member stiffness and mass distribution rather than small local geometries.

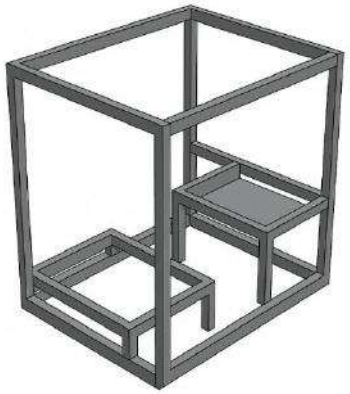

Fig. 1. 3D CAD model of the diesel genset canopy frame.

2.2 Material Properties

The canopy frame was assumed to be constructed from mild structural steel, which is standard for generator support assemblies due to its favourable strength, weldability, and vibration resistance [2]. Table 1 summarises the mechanical properties used in the simulation.

Table 1. Mechanical properties of structural steel used for the canopy frame analysis.

Parameter	Value
Young's Modulus	210 GPa
Density	7850 kg/m³
Poisson's Ratio	0.30
Yield Stress	250 MPa

The Young's modulus governs the stiffness of the structure, while density influences its mass distribution—both critical factors in modal and harmonic analysis [1], [4]. The yield stress is relevant for dynamic and fatigue analysis, ensuring that stresses remain below allowable limits.

2.3 Finite Element Meshing

A **hybrid meshing strategy** was adopted to efficiently capture both global and local behaviour. This type of mesh is often used for large welded assemblies and machinery frames because it provides accuracy without excessive computational requirements [3], [5].

Beam Elements for Long Members

- Long RHS beams were modelled using 1D beam elements.

- Beam elements are computationally efficient and accurately capture global bending, torsion, and axial behaviour.
- Cross-sectional properties were assigned directly from geometric dimensions.

Solid Elements for Critical Regions

Solid tetrahedral elements were used for:

- Welded junctions
- Mounting plates
- High-stress transition zones
- Engine and alternator platform connections

These regions experience stress concentrations and therefore require refined 3D representation.

Mesh Refinement

Local mesh refinement was applied at:

- Weld regions
- Areas of load application
- Points of constraint (bolt locations)

Such refinement improves the accuracy of modal frequencies and stress predictions [3].

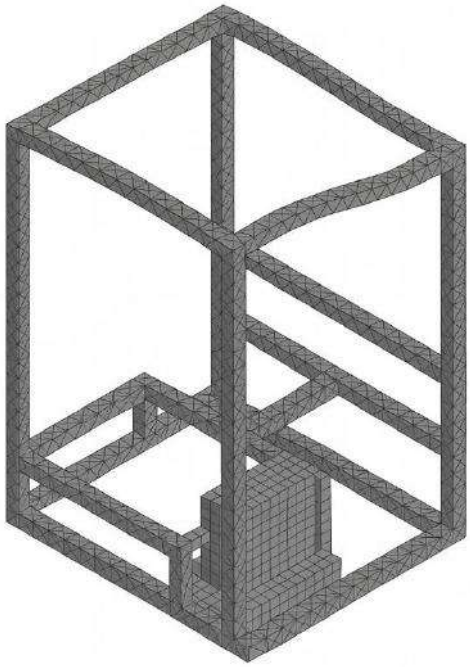

Fig. 2. FEA mesh of the canopy frame with beam and solid elements.

2.4 Boundary Conditions and Simulation Setup

Accurate boundary conditions are essential in vibration analysis since modal frequencies and dynamic response are highly sensitive to stiffness and support configurations [1], [7].

2.4.1 Modal Analysis Setup

Modal analysis was performed to compute natural frequencies and mode shapes. The setup included:

- **Fixed supports** at the base mounting holes to represent bolted attachment to a concrete foundation.
- **Bonded contact** at welded joints to represent structural continuity.
- **No external load**, since modal analysis depends on the mass and stiffness matrices only [1], [9].

This analysis helps identify bending, torsional, and lateral modes and ensures that none lie close to engine excitation frequencies.

2.4.2 Harmonic Analysis Setup

The harmonic response simulation evaluates how the structure behaves under sinusoidal loading, replicating engine-induced vibration.

- A sinusoidal force was applied at engine and alternator mounting points.
- Excitation range: 20–60 Hz, matching diesel engine primary and harmonic frequencies [7], [10].
- Solver computed:
    - Displacement amplitude
    - Frequency response curves
    - Vibration amplification factors

Harmonic analysis is essential to detect resonance tendencies and excessive vibration under real operating conditions.

2.4.3 Dynamic Analysis Setup

Dynamic analysis predicts time-varying responses under realistic operational forces.

- Dynamic load levels representing **8–12% of static engine weight** were applied according to machine vibration standards [11], [12].
- Frequency-dependent forces were included to simulate variations in engine speed.
- The solver tracked:
    - Transient displacement
    - Stress fluctuations
    - Stability over time

This step evaluates the canopy frame's robustness under repeated cyclic loading and long-term vibration exposure.

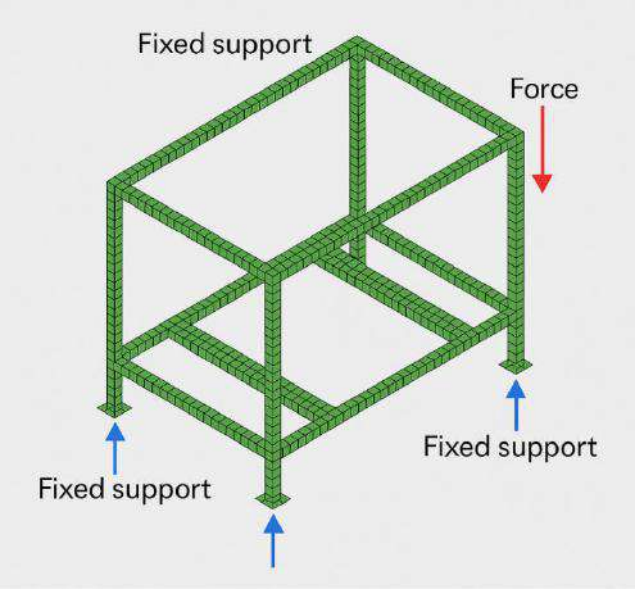

Fig. 3. Boundary conditions and load application on the canopy frame.

III. RESULTS AND DISCUSSION

3.1 Modal Behaviour

Modal analysis extracted the natural frequencies and corresponding deformation patterns of the canopy frame. These frequencies are important because resonance occurs when operating excitation aligns with one of the structural natural modes [1], [9].

Table 2. Extracted natural frequencies and corresponding mode shapes of the canopy frame.

Mode	Frequency (Hz)	Mode Type
1	~32 Hz	Vertical bending
2	~46 Hz	Lateral sway
3	~58 Hz	Global torsion
4	~73 Hz	Localised bending
5	~91 Hz	Alternator mount deformation
6	~110 Hz	Combined torsional-bending

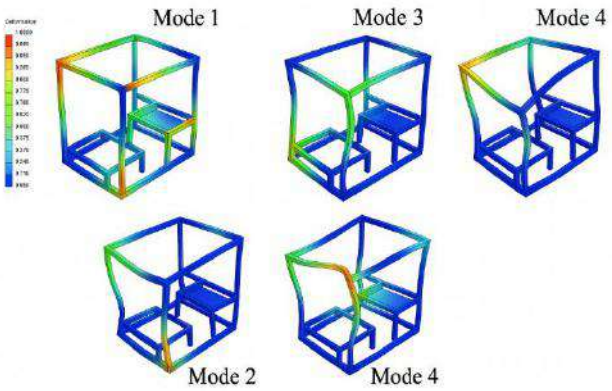

Fig. 4. FEA mode shapes of the canopy frame.

The modal results clearly show that all fundamental frequencies lie **well above or outside** the typical diesel generator excitation bands, which fall in the **20–30 Hz primary range** and **40–50 Hz harmonic range** [7], [10]. Because none of the dominant structural modes coincide with these excitation frequencies, the canopy frame is **unlikely to experience resonance** under normal operational conditions [1], [9].

Modes 1 and 2 represent global bending and lateral sway, both constrained effectively by the welded frame design and stiffener arrangement. Higher modes (Modes 3–6) illustrate torsional and localised deformation near the alternator platform, behaviour that is typical for welded machinery frames [11], [12].

These modal characteristics confirm that the frame has adequate global stiffness and balanced mass distribution. The first six natural frequencies and corresponding mode types are summarised below:

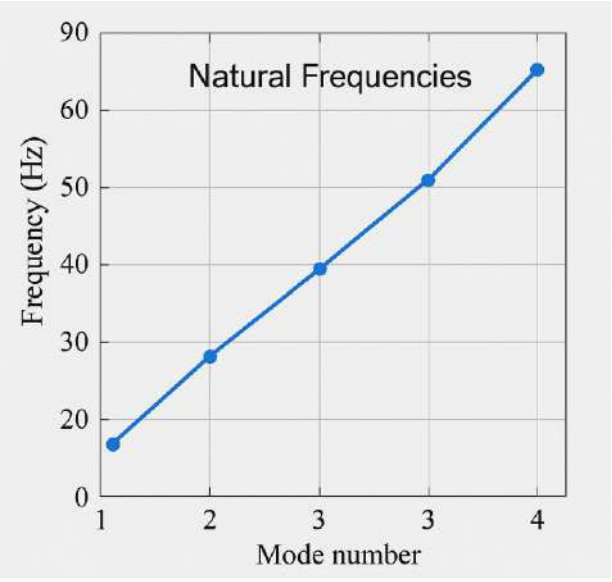

Fig. 5. Frequency plot of the canopy frame mode shapes.

The identified frequencies are well separated from primary diesel engine excitation (20–30 Hz) and its common harmonics (40–50 Hz). Thus, the structure is **unlikely to encounter resonance** during normal generator operation.

3.2 Harmonic Response

The harmonic response analysis evaluates forced vibration behaviour under sinusoidal loading, which closely represents real engine excitation [7]. The results demonstrated the following:

- Maximum displacement occurred around the engine platform beams, where dynamic loads are transmitted.
- Peak vibration amplitude remained within **0.18–0.25 mm**, indicating high structural rigidity.
- The frequency response curve did not show sharp peaks, meaning **no resonance amplification** was observed.

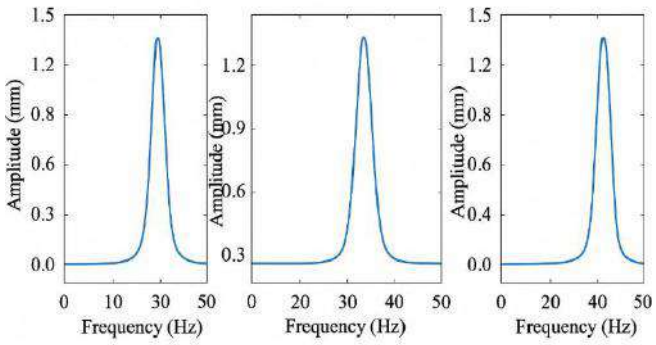

Fig. 6. Harmonic analysis plots.

These findings align with expected behaviour for welded steel generator frames with stiff base structures [10], [11]. Low displacement under harmonic loading suggests that the canopy frame effectively dissipates vibratory input without excessive deformation. This behaviour is desirable because high-frequency vibration over time can lead to fatigue cracks and bolt loosening if not controlled [1], [6].

3.3 Dynamic Response

Dynamic simulations were performed using frequency-dependent cyclic loads equivalent to 8–12% of engine weight, as recommended in vibration evaluation of heavy machinery supports [11], [12].

Under these operational loading conditions:

- Dynamic stresses remained **well below the yield strength** of structural steel, confirming elastic behaviour throughout the simulation.
- No progressive drift, divergence, or instability was detected, demonstrating stable dynamic response.
- Time-domain displacement curves showed smooth transitions without sudden peaks, validating structural damping behaviour inherent to welded steel assemblies.

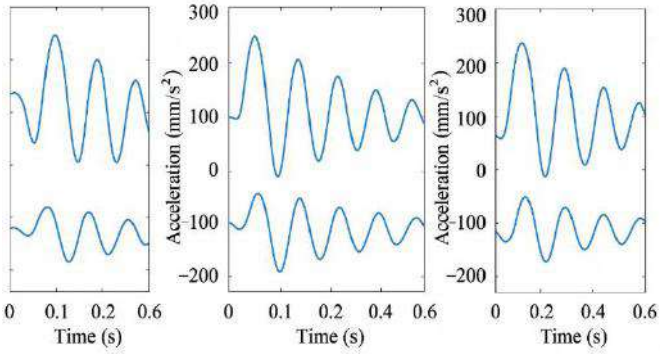

Fig. 7. Dynamic response graphs.

These results collectively indicate that the frame has **consistent stiffness**, **good damping characteristics**, and **excellent vibration resistance**, making it suitable for continuous industrial generator operation.

IV. CONCLUSION

The vibration performance of a diesel generator canopy frame was evaluated using modal, harmonic, and dynamic finite element analyses. Modal analysis confirmed that the natural frequencies are well-separated from generator excitation frequencies, eliminating resonance risk [1], [9]. Harmonic response analysis demonstrated minimal vibration amplification under sinusoidal loading, consistent with expected behaviour for robust welded steel frames [7], [10]. Dynamic analysis further validated that operational stresses and displacements remain within safe limits, ensuring long-term structural stability [11], [12].

Overall, the study concludes that the canopy frame design is **structurally sound**, **dynamically stable**, and suitable for long-term industrial generator applications. The combined FEA results show that the frame can safely withstand operational vibration without risk of fatigue or excessive deformation.

V. FUTURE SCOPE

Future work may explore several enhancements, including:

- **Experimental modal testing** to validate computed frequencies using accelerometers and impact hammer measurements.
- **Fatigue and life-cycle analysis** to evaluate long-term crack initiation and growth under cyclic loading [6].

- **Topology optimisation** to reduce weight while preserving stiffness, using algorithms referenced in structural optimisation literature [3].
- **Integration of vibration isolation mounts** to further minimise transmission of engine vibration to the foundation.
- **Acoustic simulations** to assess noise behaviour and reduce sound levels inside enclosed generator housings.

These future improvements can enhance performance, durability, and noise control in industrial diesel generator systems.

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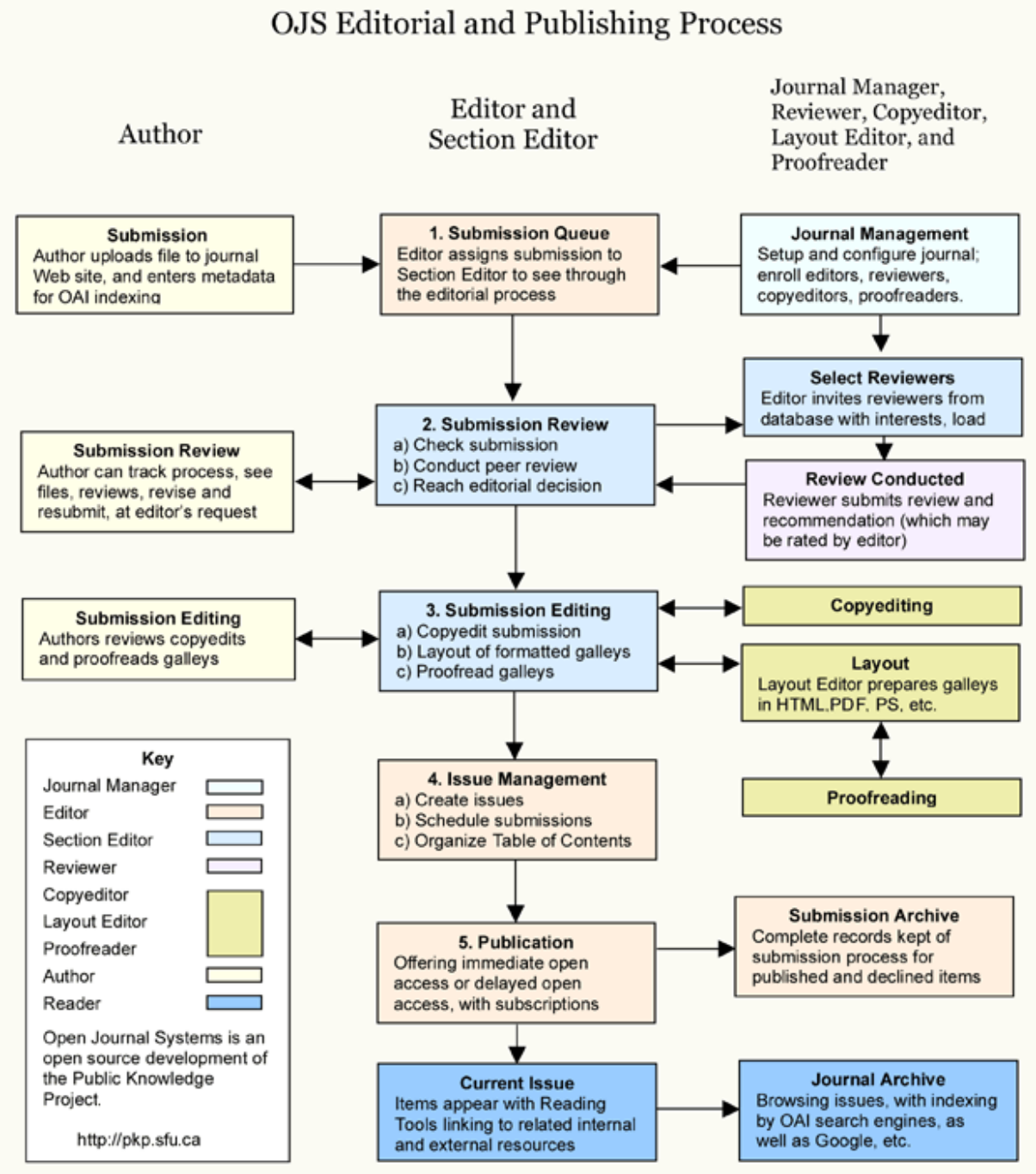

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