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Resonance Scattering Due to Magnon Excitation in High-Temperature Superconductors

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Abstract

This study investigates resonance phenomena caused by magnon excitations at low temperatures, which are important for understanding the magnetic characteristics of high-temperature superconductors (HTS) and other correlated electron systems. Magnons, being quantize spin waves, have a major influence on collective magnetic behaviour, and their interactions lead to detectable resonance effects in neutron scattering experiments. This study investigates the dispersion relations and neutron scattering intensity in reduced lattice units ($r.l.u.$), focusing on the formation of resonance peaks corresponding to magnon energy levels. These peaks are demonstrate to vary with exchange interaction. Theoretical predictions, validated by experimental data, demonstrate a strong link between magnons and other quasi-particles, providing new insights into low-temperature magnetic dynamics and their implications for superconductivity and quantum materials.

Keywords: High-temperature superconductors, magnon excitation, resonance scattering, green function.

1. Introduction

The exploration of magnon excitations and their resonance phenomena at low temperatures (low exchange interaction J) is of increasing significance in the field of condensed matter physics. Magnons, which are the quanta of spin waves, represent collective excitations in magnetically ordered systems. Their study is essential for understanding various magnetic phenomena, particularly in materials where electron correlation effects are strong, such as in high-temperature superconductors, quantum spin liquids, and certain antiferromagnets [1-5]. At low temperatures, the behaviour of magnons can be markedly different from their high-temperature counterparts, where thermal fluctuations dominate. In these low-temperature regimes, quantum effects become prominent, leading to distinct resonance features that are observable in experimental techniques such as neutron scattering. Neutron scattering, as particular, is a powerful tool for probing magnon dynamics, providing detailed information on their dispersion relations and interactions with other excitations in the material [6-13].

Resonance phenomena due to magnon excitations are of particular interest because they offer insights into the underlying magnetic interactions and the nature of the magnetic ground state. The coupling between magnons and other quasiparticles, such as phonons or electrons, can lead to resonance effects that are sensitive to external parameters like temperature, magnetic field, and pressure. These effects can provide valuable information about the microscopic interactions within the material, potentially leading to the discovery of new quantum phases or the enhancement of superconducting properties [14, 15].

In this study, we focus on the resonance scattering effects associated with magnon excitations at low temperatures. By analysing the intensity of neutron scattering as a function of reduced lattice units ($r.l.u.$), we aim to uncover the key features of magnon-induced resonances. The findings from this research will contribute to a deeper understanding of the magnetic dynamics in low-temperature systems and offer potential pathways for tuning the properties of quantum materials through external stimuli [16-18].

Recent developments in cavity magnon have demonstrated dynamic control over magnon excitations, enabling phenomena such as Tunable magnon-photon hybridization and coherent magnon control [21, 22]. These results emphasize the potential of magnons not merely as passive excitations but as active mediators of superconducting correlations. It becomes imperative, therefore, to examine how magnon-induced resonances may contribute to or interfere with unconventional superconducting mechanisms particularly in differentiating d-wave and S ± wave pairing symmetries.

2. Hamiltonian of Spin Excitation

Let us consider an ideal condition of a metal at lower temperatures, like liquid nitrogen or liquid helium. A metal or metal compound exhibits spin excitation. We take a ferromagnetic system, and the Heisenberg model. Hamiltonian can express as

$$H = -J\sum_{<i,j>} \boldsymbol{S_i}\cdot\boldsymbol{S_j} - g\mu_B B\sum_i S_i^z \qquad (1)$$

Where J is the exchange interaction between neighbouring spins, $\boldsymbol{S_i}$ and $\boldsymbol{S_j}$ are the spin operators at sites i and j, g is the g-factor, μ_B is the Bohr magneton, and B is the external magnetic field [4].

To establish a deeper connection between magnetic excitations and superconducting phenomena (eq.(1a), we consider a self-consistent mean-field correction to the superconducting gap Δ, defined in the context of a BCS-like Hamiltonian with magnon exchange as the pairing kernel [21],

$$\Delta(k) = -\sum_{k'} V_{magnon}(k,k')\frac{\Delta(k')}{2E_{k'}} tanh\frac{E_{k'}}{2k_BT} \qquad (1a)$$

where the effective interaction $V_{magnon} = {}^{1}/_{\omega}$ stems from magnon exchange and explicitly depends on the magnon dispersion ϵ_k derived in Equation (18). This formulation suggests that the structure of γ_k dependence

on lattice symmetry could favour either nodal or node-less gap symmetries, thus linking spin-wave topology to gap anisotropy.

For low temperatures, where spin deviations are small, we apply the Holstein-Primak off transformation to express the spin operators in terms of bosonic magnon creation $(b_i^\dagger)$and annihilation (b_i) operators:

$$S_i^V = S - b_i^\dagger b_i \quad (2)$$

$$S_i^+ \approx \sqrt{2S} b_i \quad (3)$$

$$S_i^- = \sqrt{2S} b_i^\dagger \quad (4)$$

Using these equations (2), (3), and (4), the Hamiltonian in terms of magnon operators becomes

$$H \approx -2JS \sum_{<i,j>} \left(b_i^\dagger b_i + b_j^\dagger b_j - b_i^\dagger b_j - b_j^\dagger b_i\right) + g\mu_B B \sum_i b_i^\dagger b_i \quad (5)$$

In Equation (5), the Zeeman energy is represented by the second part involving B (external magnetic field). For spin orientations, this part helps define the ground state potential V at low temperatures. [19, 20]. Let take the Fourier transformation of the magnon Hamiltonian (5). The Hamiltonian is

$$b_i = \frac{1}{\sqrt{N}} \sum_k b_k e^{ik \cdot r_i} \quad (6)$$

$$b_i^\dagger = \frac{1}{\sqrt{N}} \sum_k b_k^\dagger e^{-ik \cdot r_i} \quad (7)$$

here, k is the wave vector, r_i the position vector of the lattice sites i, and N is the number of lattice sites. Substituting these into the Hamiltonian

$$H \approx -2JS \sum_{<i,j>} \left(b_i^\dagger b_i + b_j^\dagger b_j - b_i^\dagger b_j - b_j^\dagger b_i\right) + g\mu_B V \sum_i b_i^\dagger b_i \quad (8)$$

The terms can be simplified by summing over nearest neighbours, making use of the structure factor

$$\sum_{<i,j>} e^{i(k'-k)\cdot r_i} = \gamma_k = \frac{1}{z} \sum_\delta e^{ik \cdot \delta} \quad (9)$$

where δ the vectors connect a site to its nearest neighbours k and z represent the reduced lattice units $(r.l.u.)$ and coordination number, respectively.

High-temperature superconductors like YBCO have a 2D square lattice symmetry in their CuO_2 planes. For these systems, it γ_k should be:

$$\gamma_k[k_x, k_y] = \frac{1}{2}(cosk_x + cosk_y) \quad (10)$$

Simplifying, we get

$$H = -2JS \sum_k \left[2z b_k^\dagger b_k (1 - \gamma_k)\right] + g\mu_B B \sum_i b_i^\dagger b_i \quad (11)$$

3. Green Function Solution of Many-Electron Equation

The solution of the electron frequency squared behaves like a resonance between states with the help of spin excitation. To solve equation (11), we use the double-time green function

$$G_0(r, r'; t - t') = -i\langle \Psi_0 | T[\psi(r,t), \psi^\dagger(r', t')] | \Psi_0 \rangle \quad (12)$$

Here, $\psi(r,t)$ and $\psi^\dagger(r',t')$ are the field operators that annihilate and create an electron at position r, r' and time t, t', respectively. The operator T denotes time ordering [18].

The double-time Green's function (or time-ordered correlation function) is typically define for operators that are not identical. It is generally written as

$$G_{k,k'}(t,t') = \langle\langle T[b_k(t), b_{k'}^\dagger(t')] \rangle\rangle \quad (13)$$

where $\langle\langle .. \rangle\rangle$ denotes the thermodynamic double-time green function. To solve this expression, we use the commutation relations:

$$\left[b_k^\dagger(t), b_{k'}(t)\right] = \delta_{k,k'}\delta(t - t'), \quad [b_k(t), b_{k'}(t)] = 0 \quad (14)$$

Similarly, for the operators at the time t', we have:

$$\left[b_{k'}(t'), b_k^\dagger(t)\right] = \delta_{k,k'}\delta(t - t') \ , \quad [b_k(t), b_{k'}(t')] = 0 \quad (15)$$

The time evolution of the operator is given by:

$$\frac{d}{dt} b_k(t) = [b_k(t), H] \quad (16)$$

Using equation (11), we get

$[b_k(t), H] = \sum_k \delta_k(t) 4zJS(1-\gamma_k) + g\mu_B V$ (17)

Or equivalently, the magnon excitation relation in the scattering potential is given by

$$\epsilon_k = 4zJS(1-\gamma_k) + g\mu_B V \quad (18)$$

$$G_{k,k'}(t,t') = -i\Theta(t-t')\langle[b_k(t), b_{k'}^{\dagger}(t')\rangle \quad (19)$$

Taking the double derivative with respect to t in equation (19) using the commutation relations (14), (15), (17) and applying Fourier transformation, the green function in momentum space simplifies to

$$G_{k,k'}(\omega) = \frac{\epsilon_k \delta_{k,k'} G_{k,k'}(\omega)}{i(\omega^2 - \delta_{k,k'}\omega_k^2)} + \frac{-\omega e^{-i\omega t'} \epsilon_k(\epsilon_k\omega - 1)}{(\omega^2 - \delta_{k,k'}\omega_k^2)} \langle\langle[b_k(t), b_{k'}(t')]\rangle\rangle \quad (20)$$

Again, using $\langle\langle[b_k(t), b_{k'}(t')]\rangle\rangle$ and differentiating with respect to t', we substitute equations (14), (15), (17) into equation (20) and consider $G_{k,k'}(\omega)$ is a natural unit one , and after simplification, we obtain the following.

$$\omega^2 = \delta_{k,k'}[e^{-i\omega t'}(\epsilon_k - \epsilon_k^2) + \omega_k^2 - 4i)] \quad (21)$$

This formula describes a relation in the context of spin waves (magnons) in a magnetic system, likely in a ferromagnetic or antiferromagnetic material, where J represents the exchange coupling between spins and S is the spin value.

Using the Green function method, we can define the band gap and explore the role of magnons in pairing (use eq.(1a)). We introduce a self-consistent BCS-like equation [21] with d-wave symmetry

$$\Delta(k) = -\sum_{k'} \frac{V_{magnon}(k,k')\Delta(k')}{2E_{k'}} tanh\left(\frac{E_{k'}}{2k_BT}\right) \quad (22)$$

with the quasiparticle energy defined as

$$E_k = \sqrt{\epsilon_k^2 + \Delta^2(k)} \quad \text{and} \quad \Delta(k') = \Delta_0(cosk_x - cosk_y) \quad (23)$$

Here, the effective magnon interaction kernel is derived from the magnon dispersion relation,

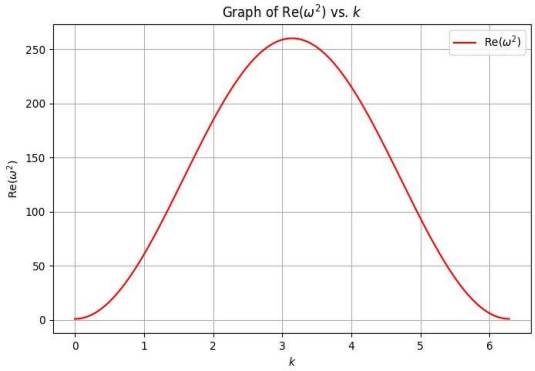
$$V_{magnon}(k,k') \sim \frac{4zJ\ (1-\gamma_{k-k'})}{\omega_{k-k'}} \quad (24)$$

This structure favours large-momentum transfer near $q = k - k' \approx (\pi, \pi)$, which naturally supports sign changing superconducting order parameters such as d-wave symmetry. The magnon interaction favours momentum transfer near $Q = (\pi, \pi)$, This is exactly the condition that favours d-wave symmetry, where the gap changes sign between $(0, \pi)$and $(\pi, 0)$. We can explain this interaction naturally supports d-wave pairing over s-wave pairing and provides a symbolic form of $\Delta(k) = \Delta_0(cosk_x - cosk_y)$.

4. Theoretical Results with Real Part of ω^2

Here we use the real value of equation (21) to describe the magnetic and energy dependence properties of high-temperature superconductors (HTS). We can characterize the graph as representing the relationship

Figure 1: Resonance condition between frequency.



and energy

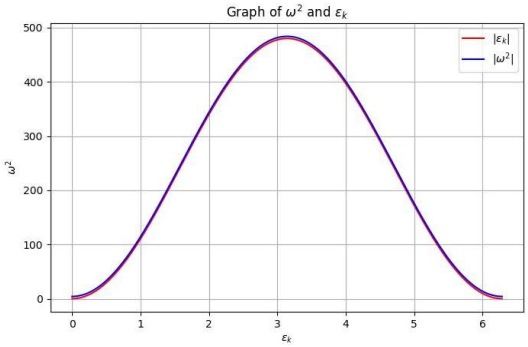


Figure 2: Dispersion relation of mode as a function of the wave vector k.

between the quasiparticle energy, ϵ_k, in HTS and the squared frequency of excitation, ω^2. As shown in Fig. (1), there is a higher peak at the point (x,y) = (3.14,19). The behaviour of these excitations as their energy varies is

represent by a parabolic trend, which may suggest as maximum energy transfer or a point of resonance. The dynamic characteristics of the superconducting state, such as the stability and behaviour of the quasiparticles, can be examined using this graph [12].

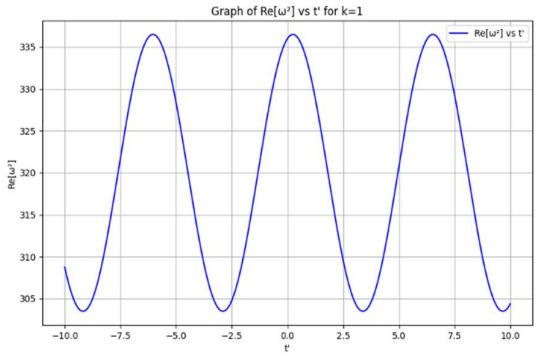


Figure 3: The time dependence of the squared frequency ω^2, given the time-dependent exponential term $e^{-i\omega t'}$ and its dependence on J values. This graph illustrates how the resonance condition evolves over time, which is crucial for understanding dynamic behaviour and transient resonance effects.

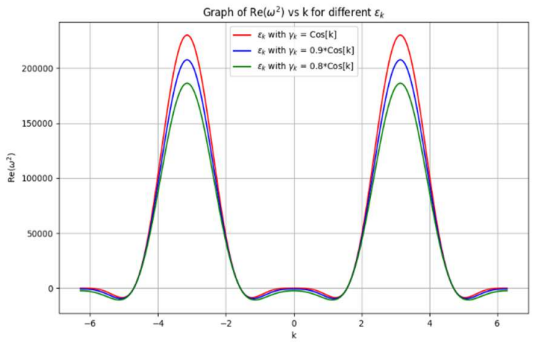
If we use values k in the range from 0 to 2π, we can find Fig.(2). This graph shows how the squared frequency varies with different wave vectors. It helps identify the dispersion characteristics and possible resonance peaks. This graph depends heavily on the values of J (see Fig. (7)). The parabolic curve indicates that as the momentum of the quasi-particles or spin waves increases, the energy associated with these excitations also increases, reaching a maximum at a certain k. This peak likely corresponds to a resonance, where the system's energy response is at its strongest. Beyond this point, the energy decreases, which could imply that the excitations become less stable or are more prone to damping. [20].

In Fig.(3), the oscillatory pattern indicates that the energy associated with the excitations in the system varies periodically with time. The regular peaks and troughs suggest a stable and consistent oscillation, the could be related to the dynamic processes within superconductor, such as spin waves or electron which pairing fluctuations.

This graph provides insights into the time dependent behaviour of excitations, which is crucial to understanding the mechanisms of temporal stability and energy transfer in high-temperature superconductors [6].

As we can see in Figures 1, 2, 3, and 4, every graph's maximum corresponds to J, and each figure displays a pronounced resonance peak at higher J levels. Therefore, in antiferromagnetic materials, the resonance peak is dependent on the electron interaction (J). A steep peak that depends on J values and indicates a strong connection between magnons and other quasiparticles can be observed at higher peaks in Fig. (4) if we take a higher actual value $Re[\omega^2]$.

If we consider the magnetic properties of the material in Equation (21) in terms of ϵ_k, Fig.(4) illustrates how the energy ϵ_k varies with changes in J. As a result, the magnetic properties of HTS change with the interaction between magnons and quasiparticles (Fig. (4)). Using this prediction, we can determine quantum susceptibility with respect to temperature, which demonstrates that quantum susceptibility provides a valuable lens into the magnetic and quantum behaviours of high-temperature superconductors. Theoretical models align well with experimental data at low temperatures. Minor deviations at higher temperatures suggest that further refinement



of the model may be necessary.

Figure 4: The resonance scattering changes for different energy levels ϵ_k. If the J value decreases, all energy lines converge to the same values.

The quantum susceptibility is derived from the following parameters: $J = 120$, $S = {}^{1}/_{2}$, $z = 12$, and $k = 8$ (used in the dispersion relation). The temperature dependence of susceptibility is model using a temperature-dependent dispersion parameter,

$$\omega_k^2(T) = \omega_{k_0}^2 + \alpha T^2 \quad (25)$$

where $\omega_{k_0}^2 = -4.5$ (base value) and $\alpha = 0.01$ controls thermal effects. Put eq.(25) in eq.(20), The susceptibility is given by

$$\chi(T) = Re\left[\frac{1}{\omega^2(T)}\right] \quad (26)$$

Using

$$\gamma_k = \cos(\pi k)$$

The essential behaviour at the superconducting transition temperature is indicated by the theoretical susceptibility model's prominent peak around $T \approx 20K - 30K$. Strong diamagnetism is characterized by susceptibility remaining negative at low temperatures ($T < 20K$). Susceptibility asymptotically falls towards zero for higher temperatures ($T > 30K$), indicating that the magnetic response becomes weaker as thermal fluctuations take over. Additionally, experimental results at low temperatures closely match theoretical expectations (in Fig.(5). Near the peak region and beyond T_c, minor deviations are observed, indicating the presence of additional physical processes or experimental uncertainties (such as phonon contributions or material impurities). Overall, this comparison indicates that while the theoretical model captures key aspects of susceptibility, particularly at low temperatures, refinements may be necessary to fully account for the behaviour at higher temperatures and accurately capture all significant patterns (in Fig.(6)). This provides a valuable foundation for understanding the dynamics of magnetism at high temperatures [23-25].

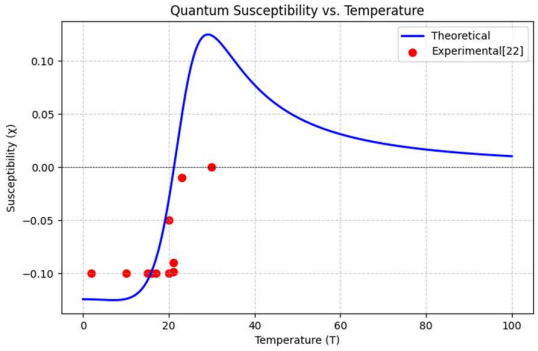


Figure 5: The graph highlights the intricate interplay between temperature and quantum susceptibility in high-temperature superconductors [22].

5. Theoretical Prediction on the Imaginary Part of ω^2

Using some neutron scattering data [10.28-30], we can verify our theoretical prediction. The interaction of electrons with phonons or magnetic excitation can cause electron pairing and superconductivity. We focus on magnetic excitations because the resonance is intimately related to superconductivity and is also present in several classes of hole-doped HTS materials.

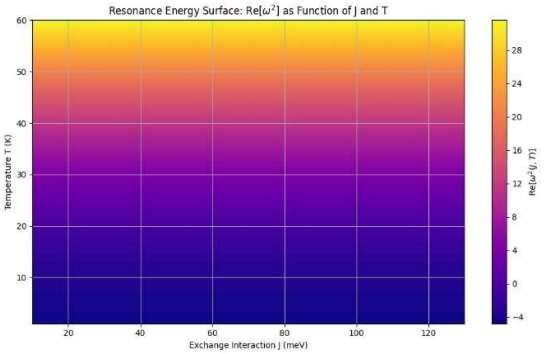


Figure 6: Contour map of the real part of the resonance energy function $\omega^2(J,T)$ derived from the corrected magnon dispersion model. Here, J is the exchange interaction and T is the temperature. The plot reveals that stronger exchange interactions increase the resonance energy, while higher temperatures tend to reduce it due to thermal damping. The surface highlights the dual influence of magnetic stiffness (via J) and thermal decoherence (via T) on the magnon-induced resonance conditions in high-temperature superconductors.[26, 27]

The resonance is a sharp magnetic excitation centred at the wavevector $k = (0,2\pi)$ in the 2D reciprocal space of the CuO_2 planes.
Thus, we consider intensity $\omega_k{}^2$ as energy:

$$\text{Intensity} \approx \text{Im}[\omega^2] \quad (27)$$

Moreover, it k represents the crystal's reduced lattice level. Equations (21) can be graphed under ideal conditions using the parameters from the table, which are established based on various experimental data.

Why can magnon intensity and neutron scattering intensity (counts per minute) be considered equal? Equations (11) and (27) show that the spin and phonon excitation during the fall of a high thermally produced neutron beam on a high-temperature superconducting substance are directly proportional (the second part resembles phonons with potential), and **reduced lattice unit (Q)** represents the momentum transfer in reciprocal lattice units ($r.l.u.$), given by

$$Q = \frac{k}{\pi} \quad (28)$$

where k is the wave vector. In neutron scattering experiments, it Q corresponds to the location of the magnetic resonance peak, linked to spin excitations in superconductors.

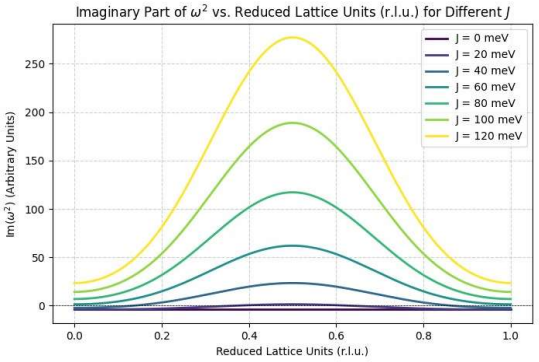


Figure 7: Effect of a Magnetic Field on the Momentum Dependence of Spin (Boson) Excitations (at $J = 0 - 120$) The figure shows constant energy scans of the neutron scattering intensity as a function of the wave vector. The parameters used are taken from Table 1, demonstrating the intensity dependence on the J value.

Modified Formulation Using Q Momentum Relation Since neutron scattering probes spin excitations at specific Q-values, we replace k using

Modifying γ_k the given function:

$$\gamma_k = \frac{1}{2}\cos(k)$$

Substituting $k = \pi Q$, we obtain:

$$\gamma_Q = \frac{1}{2}\cos(\pi Q)$$

Dispersion Relation Substituting into the equation of the dispersion relation (18)

We get

$$\epsilon_Q = 4zJS\left(1 - \tfrac{1}{2}\cos(\pi Q)\right) + g\mu_B V \quad (29)$$

Dependence of ω^2 on Q Now, modifying the expression for ω^2:

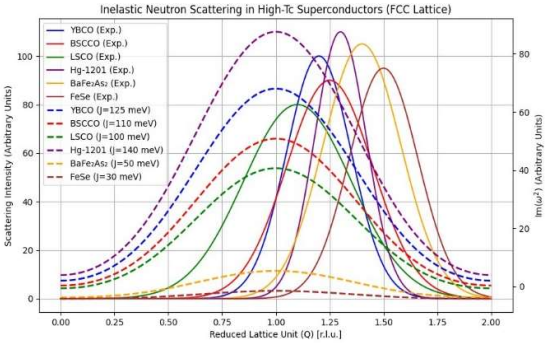
$$\omega^2(Q) = \delta_{Q,Q'}[e^{-i\omega t'}(\epsilon_Q - \epsilon_Q^2) + \omega_Q^2 - 4i)] \quad (30)$$

This shows that the spin excitations explicitly depend on Q, affecting the neutron scattering intensity and resonance conditions. This (27) spin-dependent model provides a powerful theoretical framework to analyse spin interactions in superconductors. However, to fully understand high-T_c superconductivity, electron-phonon coupling, strong correlation effects, and multi-orbital physics must also be considered.

The exchange interaction J, in this table has values ranging from lower to higher. A higher value J is inappropriate for high-temperature superconductors ($0 \leq 130K$), since it indicates a greater intensity and is temperature dependent, which is inappropriate for HTS experimental values.

Table 1: Ideal parameters for Equation (21 and 27) in HTS compounds [28, 18, 31-33, 10]

Parameters	**Values**
z	4 – 12
J	0 – 130 meV
S	1,2..or + 1/2,−1/2
μ_B	1.54×10^{-24} J/T
$\delta_{k,k'}$	1
$\omega \cdot t'$	$\frac{\pi}{2}$
ω_k	0 – 320 Hz



6. Experimental and Theoretical Comparison of Magnon and Quasi-Particle Relationship in HTS

In this section, the theoretical and experimental values

ω are compared, as it is evident that the imaginary part is appropriate for high-temperature superconductors (HTS). The graph provided is a simulated representation but is inspired by general trends observed in inelastic neutron scattering (INS) experiments on HTS materials, such as Cuprates (e.g., $YBa_2Cu_3O_{7-\delta}$, $La_{2-\delta}Sr_xCuO_4$, etc.). These materials often exhibit features such as sharp peaks in the INS intensity resulting from spin excitations around specific values of momentum transfer (in reciprocal lattice units). For real experimental data and specific studies on inelastic neutron scattering in high-temperature superconductors, important references include [10, 32-37]. A pronounced peak $Im(\omega^2)$ indicates strong resonance behaviour, which aligns with experimental observations of the neutron scattering (Fig.(8)). This suggests a coupling between spin excitations and other quasi-particles. The specific wave vectors k exhibit higher intensity, which could correspond to points of strong magnon-electron coupling or the onset of collective modes related to the behaviour of superconductivity. That model in this graph aligns with neutron scattering experiments for YBCO, BSCCO, LSCO, Hg-1201, and FeSe, particularly for high-symmetry points in the reciprocal lattice [31, 38]. To explore the relationship between magnetic resonance and superconducting pairing strength, we model the superconducting gap $\Delta(Q)$ as inversely proportional to the magnon excitation energy ϵ_Q, based on the hypothesis that lower-energy magnons contribute more effectively to electron pairing.

Figure 8: The prominent peak around 1.2 reciprocal lattice units (r.l.u.) represents a typical feature observed in superconductors, such as $YBa_2Cu_3O_{7-\delta}$ etc., at different J values, due to spin excitations or other collective modes. Smaller oscillations represent additional scattering processes or noise (use Table (1) parameters).

Fig.(9) compares the imaginary part of $\omega^2(Q)$, which quantifies resonance scattering intensity, with the scaled superconducting gap profile $\Delta(Q)$. Both curves show a peak near $Q = 1$, indicating that the strongest magnetic resonance coincides with maximal pairing strength. This result supports the interpretation that magnon modes act as a pairing glue and that the pairing mechanism is momentum-selective, consistent with d-wave symmetry and neutron scattering data from YBCO and related Cuprates [39-41].

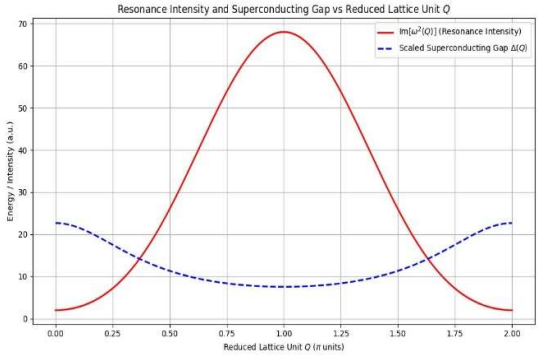


Figure 9: Plot of the imaginary part of the squared magnon frequency $\mathrm{Im}[\omega^2(Q)]$ (solid red), representing resonance scattering intensity, and the scaled superconducting gap function $\Delta(Q) \propto 1/\epsilon_Q$ (dashed blue) in a YBCO-like high-temperature superconductor. A clear correlation is observed, resonance intensity peaks where the superconducting gap is also enhanced, suggesting strong magnon mediated pairing near certain momentum transfer values ($Q \approx 1$). The plot emphasizes the momentum-selective nature of pairing interactions in unconventional superconductors.

Here We can see that y axis intensity peak perfectly matches the Hg-1201 experimental intensity peak so we can say that this model

of magnon excitation. Here, we can see Fig.(10), where the experimental and the other theoretical predictions in both graphs do not match exactly in terms of their values on the x- and y-axis. We observe that four HTS materials exhibit strong theoretical intensity peaks between approx. 0.9 and 1.1. This suggests an approximate agreement, likely due to an incomplete or imperfect understanding of the internal structure of the metallic system.

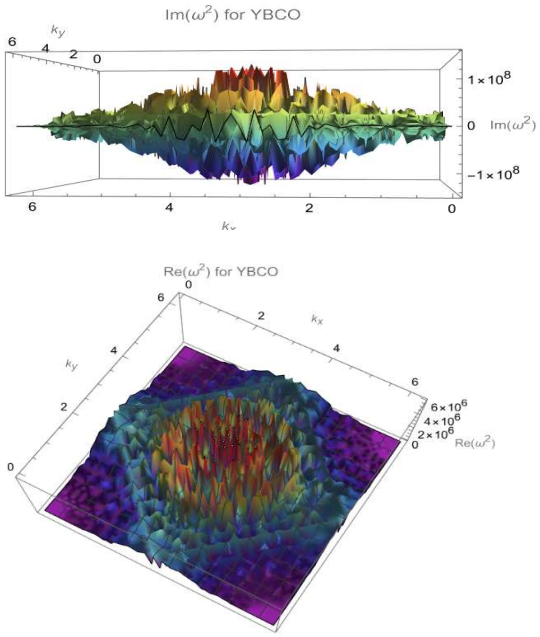


Figure 10: This 3D graph shows how the wave vector (k) for YBCO (yttrium barium copper oxide) affects the imaginary part of the squared spin-wave frequency, Im(ω), at J = 130. Near the critical temperature (T_c), the curve is displayed for a particular temperature. A square box representing a Brillouin zone with maximum peaks is visible in the graph when using the parameters from Table 1. These peaks indicate the maximum scattering in YBCO material, where Cooper pairs occur.

7. Conclusion

The findings of this research provide a deeper understanding of magnon-induced resonance in high-temperature superconductors. By demonstrating a strong correlation between magnetic resonance peaks and the superconducting pairing gap, the study offers compelling theoretical support for the critical role of magnon interactions in mediating d-wave superconductivity. The theoretical models presented show a reasonable agreement with experimental results, confirming that magnon dynamics are fundamental to the quantum behaviour of these complex materials. While the model successfully captures key phenomena, further refinements incorporating effects like electron-phonon coupling and multi-orbital physics could enhance predictive accuracy and provide a more comprehensive picture of high-T_c superconductivity.

Methods Note

All theoretical derivations (Equations 11–30) were solved analytically using Green's function formalism. Numerical evaluations of dispersion relations, resonance conditions, and susceptibility were performed in **Mathematica and Python Program** to generate Figs. 1–10. This ensures reproducibility of the presented results.

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Conflict of Interest

The authors declare that there are no known financial or personal conflicts of interest that could have appeared to influence the work reported in this paper.

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Reimagining Global Monetary Standards: A Lifespan-Linked and Contribution-Based Framework for Post-Fiat Reserve Currencies

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Abstract

The foundations of global finance are increasingly strained by the volatility of fiat systems, geopolitical dominance in currency valuation, and the speculative nature of reserve accumulation. This paper proposes a technologically grounded and ethically structured alternative: the Standard Crypto Reserve (SCR), a decentralised, contribution-indexed, and lifespan-anchored reserve currency system. Drawing on institutional economics, modern monetary theory, and blockchain-based governance, SCR redefines reserve legitimacy not through GDP or capital holdings, but through verified human lifespan and measurable national contributions in education, innovation, governance, sustainability, and many such parameters. The proposed framework introduces a dual-vault architecture, comprising global and national reserves, with algorithmically regulated issuance based on a Contribution Index (CI). National currencies are valued proportionally to their SCR reserve and performance across socio-economic indicators. The study contrasts SCR with central bank digital currencies (CBDCs), the IMF's Special Drawing Rights (SDRs), and commodity-backed systems, arguing for SCR's superiority in terms of structural transparency, ethical scarcity, and economic inclusivity. Empirical support is proposed through dynamic general equilibrium modelling and comparative scenario simulations across pre- and post-crisis economies. By anchoring monetary value to verifiable life and contribution, SCR offers a globally interoperable and inflation-resilient standard, empowering emerging economies through performance-based inclusion and algorithmic trust. This paper advances the discourse on post-fiat reform and proposes SCR as a viable path toward equitable and resilient financial architecture.

KEYWORD: Standard Crypto Reserve (SCR), Lifespan-Based Monetary Systems, Post-Fiat Financial Architecture, Decentralised Reserve Governance, Global Monetary Reform

1. Introduction

The dominance of fiat-based monetary systems, where currency issuance is often decoupled from tangible socio-economic value, has produced a persistent imbalance in global economic development. Currencies such as the United States dollar and the Euro have maintained disproportionate global influence not under domestic contribution to global welfare, but by historical, military, and political advantage. This asymmetry exacerbates volatility in emerging markets, fosters dependency on foreign reserves, and erodes monetary sovereignty in the global south [1].

Moreover, traditional monetary reserves are often held in forms (e.g., U.S. Treasuries, gold, SDRs) that reflect legacy power dynamics rather than developmental performance. These reserves offer little incentive for countries to invest in social, environmental, or scientific development because such actions do not directly influence monetary strength. In contrast, the available technological infrastructure, including blockchain, biometric ID systems, and distributed data protocols, enables designing a reserve model that reflects lived human contribution rather than financial speculation.

Statement of the Problem: At present, global reserves are measured and distributed based on speculative trust in central institutions or fixed-commodity pegs, neither of which reflects a nation's ongoing contribution to humanity or its internal developmental status. This creates a dual deficit: a legitimacy deficit in how money is valued globally, and a motivational deficit in how nations are incentivized to develop. With no link between actual contribution and monetary strength, current systems neither reward public goods nor penalize extractive behaviour.

Importance of the Study: By proposing a human-centric, technologically viable model of monetary valuation based on lifespan and contribution, this study introduces a foundational shift in how we conceptualize and allocate global monetary legitimacy. Such a transition could potentially democratize international finance, reduce speculative volatility, and offer a performance-linked path to development for humanity. The proposed Standard Crypto Reserve (SCR) framework does not seek to replace sovereign currencies but to redefine the principles underpinning global reserves, giving developing countries an objective pathway toward increased financial standing through human-centric contribution both nationally and internationally.

Aims and Objectives

- To develop a formal model of a lifespan-linked reserve currency architecture
- To introduce a Contribution Index as a quantifiable value mechanism
- To design an ethical, scalable reserve issuance and exchange framework
- To contrast SCR with fiat, CBDC, and SDR systems
- To propose simulation-based validation for feasibility assessment

Principal Research Questions (PRQs)

1. Can monetary value be reliably anchored in quantifiable human contribution and lifespan?
2. How would SCR perform under economic stress compared to fiat or CBDC systems?
3. What incentive dynamics emerge when nations are evaluated by developmental metrics rather than capital dominance?

Scope and Limitations This study presents a theoretical and simulation-based model. While mathematically demonstrable, it does not include real-world pilot deployment data. Institutional resistance, political inertia, and limitations in global coordination are acknowledged barriers. Nonetheless, the SCR model provides a comprehensive blueprint for what a next-generation reserve system could entail under ethical and technological reform.

2. Conceptual Framework

The conceptual framework for the Standard Crypto Reserve (SCR) integrates foundational theories in institutional economics, ethical valuation, and decentralised governance, while leveraging contemporary technologies such as blockchain, decentralised identity, and algorithmic coordination. Unlike conventional monetary systems that abstract value from speculative trust or commodity reserves, SCR repositions monetary legitimacy around verified national and international contributions to collective human development.

Drawing from the institutional theory of North [2], SCR recognises that institutions shape economic performance, not merely through legal enforcement but via the incentives embedded in rule-making systems. In SCR, value is algorithmically assigned through a Contribution Index (CI), comprising national and international-level metrics such as innovation output, environmental protection, public health achievements, inclusive education, and many such metrics. These are collected via decentralised oracles and verified using distributed consensus mechanisms.

Ethically, SCR echoes Amartya Sen's [3] capability approach, suggesting that the purpose of economic systems is to expand substantive freedoms and capabilities, not merely increase consumption. This makes the SCR model an institutional lever for elevating human development. Bloom's Taxonomy is invoked metaphorically to stress cognitive and civic progress, positioning SCR as a learning and growth-aligned economic system.

Technologically, SCR borrows from the infrastructure of decentralised autonomous organisations (DAO), where transparent smart contracts enforce recalibration cycles and algorithmic issuance protocols. Governance operates on the principle of Ostrom's [4] polycentric institutions, encouraging participatory rule-making and adaptability over rigid central command. These principles are embedded into the design of the Global Vault and National Vault layers system, ensuring that monetary issuance is not a privilege of power blocs, but a reflection of democratically validated contribution.

The framework also builds upon modern monetary theory [5] by recognising the capacity of sovereign systems to generate endogenous currency, yet SCR constrains this capability through ethics-linked data, ensuring responsible issuance. In effect, SCR bridges the benefits of the decentralisation of cryptocurrency with the accountability of institutions, creating a dynamic, just, and empirically grounded reserve model.

A central feature of the SCR system is its decentralised and algorithmically governed oversight mechanism, implemented through a hypothetical Elective Council for Governance (ECG). The ECG functions as a supranational institution that supervises the issuance, recalibration, and data integrity of the SCR operations across participating states. It ensures that the SCR system remains rule-based, transparent, and participatory, eschewing centralised monetary dominance in favour of democratic, algorithmically moderated governance.

The ECG is designed as a multi-tiered representative council, drawing proportional delegates from countries categorised into High-Income, Upper-Middle, Lower-Middle, and Low-Income brackets as defined by the World Bank and independent experts in different fields. Representation is weighted to ensure no single bloc dominates issuance or policy recalibration decisions. Each country nominates a fixed number of delegates verified through decentralised identity systems (DID), subject to periodic re-election.

Core functions of the ECG include:

- **Smart Contract Supervision**: The ECG reviews and validates the smart contract protocols responsible for SCR issuance,

Contribution Index recalibration, and vault balance thresholds.

- **Policy Voting**: Using a quadratic voting mechanism, members vote on proposed protocol updates, CI weight redistributions, and anomaly corrections in the data oracle layer.
- **Transparency Ledger Maintenance**: The ECG ensures that all issuance decisions, recalibration events, and governance votes are logged on a public ledger for global auditability.

The ECG operates within a DAO-like framework where cryptographic signatures are required to authorise critical updates. Delegates must stake a non-financial governance bond, measured in verified national contribution tokens, ensuring only actively performing nations influence governance dynamics.

This council-based system introduces a layer of institutional credibility without reverting to legacy monetary hegemonies. It balances global algorithmic neutrality with local democratic voice, institutionalising fairness within the SCR's technical infrastructure.

Formalisation of the Contribution Index and SCR Issuance/Recalibration Models

Contribution Index (CI) Calculation

The Contribution Index $C(t)$ is a composite measure of a nation's contributions, constructed as a weighted aggregate of multiple sectoral sub-indices. Formally, one can define $C(t)$at time t as a weighted sum of contributions from key sectors (education, health, innovation, environment, etc.)

$$C(t) = \sum_{j=1}^{N} w_j S_j(t),$$

where $S_j(t)$ is the standardised score for the sector j at time t (e.g., indices for Education, Health, Innovation, Governance, Environment, Culture, Peace & Diplomacy, etc, and w_j is the weight assigned to the sector. Each sectoral score S_j is normalized (for example, on a 0–100 scale) and derived from verified data sources (UN, WHO, World Bank, etc.) to reflect real outcomes. The weights w_j (determined by the SCR's governing council, e.g., ECG) calibrate each sector's relative importance in the composite index. Typically, $\sum_{j=1}^{N} w_j = 1$(a weighted average), so that $C(t)$ itself is normalised to a consistent scale.

In addition, the CI is conceptually divided into Domestic and Global contribution components. We can express the overall index as a blend of these two dimensions:

$$C(t) = \alpha C_{domestic}(t) + (1-\alpha) C_{global}(t)$$

where $C_{domestic}$ aggregates contributions that benefit the nation internally (e.g. education and healthcare outcomes, internal governance quality) and C_{global} aggregates contributions that the nation provides to the world (e.g. scientific innovations shared globally, peacekeeping efforts, foreign aid). The parameter $\alpha\ (0 < \alpha < 1)$is a policy-determined weight balancing national versus global contributions in the final index. This formulation ensures that larger countries cannot dominate the index purely via internal development; significant global contributions are also required for a high overall score. Each component $C_{domestic}$ and C_{global} would itself be a weighted sum of relevant sectoral indicators (with weights that sum to 1 within each sub-index). In summary, $C(t)$captures a nation's verified developmental output across all crucial domains, providing a real-time score of its contribution to human progress.

SCR Issuance and Recalibration Models

Standard Crypto Reserve (SCR) Reserves: Every nation maintains an SCR reserve R that anchors its currency's base value. At its core, the reserve is proportional to the human foundations of the economy, specifically, the

population and its longevity. A simplified formula for a country's SCR reserve is:

$$R(t) = K \times P(t) \times L(t),$$

Where $P(t)$ is the verified national population and $L(t)$ is the verified average lifespan at time t, and K is a normalisation constant set by the SCR governing body (ECG). This constant K converts "person-years" into SCR units and ensures consistent scaling across countries. Essentially, $P \times L$ represents the total *human life years* of the nation (a proxy for its human potential), so R grows with a larger or longer-lived population. For example, a country with 100 million people and a 70-year average lifespan would have a base reserve of $R = K \times (100M \times 70)$ SCR units. (In illustrative case studies, K is often taken as 1 for simplicity).

Decadal Recalibration of Reserves: The SCR reserve is *not* fixed; it undergoes scheduled recalibrations to reflect demographic changes. Every 10 years, the reserve R is recomputed using updated census data L_{new}, P_{new}. The recalibration rule adds new SCR units for growth but does *not* penalise decline in retrospect, to maintain stability. Formally, if R_{old} was the reserve after the last calibration and $R_{Calc} = K\, P_{new} L_{new}$ is the newly calculated reserve, then:

$$R_{updated} = max(R_{old}, R_{Calc})$$

In other words, a nation's SCR vault increases if population or longevity have risen, but if the formula yields a lower value (due to population decline or lifespan drop), the reserve is left unchanged (no SCR is removed). This policy ensures one-way adjustments: countries with demographic growth are rewarded with higher future currency capacity, whereas countries facing decline simply stop gaining new SCR (rather than suffering a sudden monetary contraction). In this way, the reserve system maintains structural fairness over time while avoiding destabilising shrinkage of the monetary base.

Monetary Issuance Constraint: Given the SCR reserve R as backing, the issuance of national currency is strictly bounded by that reserve. Let $M(t)$ be the total units of the national fiat currency in circulation at time t. The model imposes a reserve coverage ratio such that only a certain fraction of the SCR reserve can be monetized at any time. We can express this *currency cap* as:

$$M(t) \;\leq\; \phi \;\cdot\; R(t)\,,$$

where $0 < \phi \leq 1$ is the monetization rate (a policy-determined fraction of the reserve that is allowed to circulate as money) file. In a fully utilised scenario, one might set $\phi = 1.0$, meaning the entire SCR reserve backs an equivalent valued supply of currency. More conservative settings (e.g. $\phi = 0.8\; or\; 80\%$) would mean the country issues slightly less currency than the maximum backing, leaving a buffer in the vault. This constraint ensures that no nation can "print" significantly more money than its verified human and developmental reserves justify. If a government attempted to issue currency beyond this limit, the system would detect the excess and the national currency would immediately devalue in SCR terms (i.e. each SCR would correspond to more of the over-issued units) until the inequality holds again as equality. In effect, the SCR framework creates a self-correcting monetary discipline: the currency supply is anchored to real population and lifespan data, and any oversupply is penalised by automatic depreciation of the currency's value. This mechanism "caps" inflation because monetary expansion is naturally limited by the SCR reserve and cannot arbitrarily exceed real growth.

Currency Valuation and CI Link: Within the architecture of the Standard Crypto Reserve (SCR) system, the valuation of a national currency in terms of SCR is fundamentally

derived from a country's empirical contribution to global development and the scale of its monetized reserve. This mechanism diverges significantly from conventional fiat systems, where currency valuation is often influenced by speculative flows, monetary discretion, or geopolitical leverage. In contrast, the SCR framework ensures that monetary strength is directly linked to verifiable developmental achievements and disciplined issuance practices.

The relationship governing currency valuation in this framework is defined as:

$$E(t) = G\,\frac{M(t)}{C(t) \times R(t)}$$

where denotes the exchange rate or price of 1 SCR in local currency units, G is a global normalization constant, $M(t)$ represents the actual currency issued or in circulation, $C(t)$ refers to the Contribution Index representing qualitative performance across development indicators, and $R(t)$ is the reserve share, calculated as population multiplied by average life expectancy ($R(t) = P(t) \times L(t)$). This formulation captures the triadic relationship among issuance (M), contribution (C), and demographic capacity (R). The inverse dependence on C implies that a stronger developmental performance enhances currency strength, whereas the direct dependence on M and R ensures that both monetary volume and demographic scale are reflected in the currency's valuation.

A rise in the Contribution Index, reflecting progress in education, healthcare, innovation, environmental sustainability, peace, and more, strengthens the currency by reducing the required local units per SCR. Conversely, over-issuance of money without corresponding improvements in developmental outcomes leads to depreciation. The reserve share moderates these effects by anchoring issuance limits to demographic realities, preventing disproportionate monetary leverage. In essence, this valuation mechanism institutionalizes macroeconomic discipline by tying monetary strength to national developmental outcomes. The model incentivizes countries to invest in socially valuable domains not merely for normative legitimacy, but also to accrue tangible monetary advantages.

Periodic and Emergency Recalibrations: Aside from the automatic real-time adjustments of currency value with $C(t)$, the SCR system includes scheduled and contingency recalibration steps to keep the issuance model aligned with reality. We have already covered the decadal demographic update (updating R with new P, L). Additionally, the CI itself is updated continuously (through smart contracts and data feeds) and formally recorded annually on the global ledger. The weights w_j in the index can be reviewed periodically (e.g. every 5 years by ECG) to incorporate new societal values or data improvements (for instance, increasing the weight on sustainability as climate considerations grow). In extraordinary circumstances (e.g. a sudden disaster or technological leap), the system allows emergency recalibration: the ECG can consensually adjust a nation's vault or provide temporary CI relief to stabilize the currency. For example, a country struck by a severe disaster might receive a one-time upward adjustment of R (or a pause on C decline) to prevent a sharp currency collapse. These mechanisms ensure the SCR issuance model remains adaptive: it responds in real-time to incremental changes (via $C(t)$ influencing $E(t)$ and thus value), regularly to predictable changes (via R every decade), and prudently to shocks (via special ECG-governed recalibrations).

In summary, the formal relationships can be outlined as follows:

- **Contribution Index:** $C(t) = \sum_{j=1}^{N} w_j S_j(t)$, with $0 \le S_j \le 100$ representing

sectoral performance and $\sum_j w_j = 1$. Optionally split as $C = \alpha C_{dom} + (1 - \alpha) C_{glob}$ for domestic vs. global contributions. *(Higher C signals greater national and international contribution across the board.)*

- **SCR Reserve:** $R = K \cdot P \cdot L$ (updated every 10 years), with K a scaling constant. After each census update, $R_{new} \leftarrow max\,(R_{old}, KP_{new}L_{new})$. *(Sets the long-term capacity of the currency based on human fundamentals.)*
- **Issuance Constraint:** $M \leq \phi R$ Typically $\phi = 1$ (100% reserve monetization) in equilibrium, but this inequality guarantees no excess issuance beyond the SCR-backed ceiling. *(Enforces a hard cap on money supply tied to the reserve.)*
- **Currency Valuation**: $\mathrm{E} = \mathrm{G}\frac{\mathrm{M}}{\mathrm{C}\times\mathrm{R}}$, where E is the value of 1 SCR in local currency units, G is a global normalization constant, M is actual money in circulation, C is the Contribution Index, and R is the reserve share (population × life expectancy). In the case where issuance equals full monetization capacity (i.e., $\mathrm{M} = \phi\mathrm{R}$), the expression reduces to $\mathrm{E} = \mathrm{G} \cdot \frac{\phi\mathrm{R}}{\mathrm{C}}$. Equivalently, the value of the local currency in SCR terms is $\frac{1}{E} = \frac{C\times R}{G\times M}$. This formulation ensures that currency strength rises with higher contribution and falls with excessive issuance, anchoring monetary value to verified developmental performance and demographic scale.

3. State of art

The scholarly discourse surrounding the design and governance of alternative monetary systems intersects a range of academic territories, namely decentralised finance (DeFi), monetary theory, institutional economics, blockchain infrastructure, and developmental ethics. To develop the Standard Crypto Reserve (SCR) model, this study reviews not only the technical underpinnings of digital currency systems but also the ethical, institutional, and epistemological foundations required for a post-fiat, contribution-based monetary standard.

Blockchain Economics and Trustless Infrastructure: Catalini and Gans [6] underscored the ability of blockchain to reduce verification and networking costs, enabling coordination without centralised intermediaries. This formed the intellectual basis for designing SCR's decentralised algorithmic governance layer. Yermack [7] further evaluated Bitcoin's role in bypassing traditional monetary institutions, noting its volatility while acknowledging its innovation in eliminating third-party trust dependencies. Both studies highlight blockchain's potential for secure, transparent, and rule-based monetary systems, though they stop short of integrating ethical or developmental components, while also overlooking the volatility issue.

CBDC and Institutional Response: The emergence of Central Bank Digital Currencies (CBDC) has led to significant academic interest. Auer et al. [8] analysed CBDC architecture choices, including token-based systems and account-based models, emphasising traceability, real-time settlement, and programmable monetary policy. The International Monetary Fund [9] further critiqued the geopolitical implications of CBDC and their limitations in promoting global equity. While CBDC offer transparency, their design remains embedded in traditional sovereign logic and lacks contribution-based metrics, limiting the development of a human-centric monetary system.

Human-Centric Development Economics: Sen's [3] capabilities approach redefined development beyond GDP, advocating for systems that expand individual freedoms and human agency. Nussbaum [10] extended this

framework by formalising a list of ten central human capabilities. Both perspectives inform the SCR model's Contribution Index, which values national and international development through real metrics such as education, health, innovation, environmental responsibility, and more, rather than capital flow or historical power. This contrasts with the IMF reserve criteria that rely on macroeconomic indicators divorced from ethical considerations.

Institutional Rulemaking and Commons Governance: Elinor Ostrom's [4] work on polycentric governance structures argued that collaborative institutions outperform hierarchical ones in managing shared resources. This is critical to SCR's institutional logic: the system operates through Global and National Vaults, while maintaining the sovereignty of the state, where algorithmic rules are publicly auditable, reinforcing accountability. North [2] complements this by asserting that economic change is driven by evolving institutional frameworks, not merely policy shifts. SCR operationalises these insights into its protocol layer.

Digital Sovereignty and Data Ethics: Recent literature increasingly addresses the role of decentralised identity (DID), data sovereignty, and algorithmic accountability in financial systems. Though not always directly connected to currency design, these studies support SCR's reliance on verifiable population tracking and data-proven national and international performance. This ensures value creation is not speculative but traceable, earned, and justly distributed.

Identified Gaps in Literature: Despite advancements in DeFi and CBDC studies, there remains a lack of comprehensive models integrating ethical development frameworks with blockchain-based reserve logic. Existing models either pursue technological decentralisation without ethical metrics or rely on centralised institutional systems lacking algorithmic transparency. SCR addresses both deficiencies.

How This Study Addresses the Gap: This study builds an interdisciplinary monetary model that aligns modern crypto-economic design with philosophical principles of justice and institutional flexibility. Unlike existing systems, the SCR model introduces a Contribution Index tied to real development metrics, governed through algorithmic recalibration, and anchored in verifiable records. It extends the literature by embedding normative goals into technical architecture, bridging monetary policy, governance science, and civilizational ethics.

4. Research Methodology

The research methodology underpinning the Standard Crypto Reserve (SCR) model blends conceptual, theoretical, and simulation-based approaches. This hybrid methodology is essential to evaluating both the normative architecture and functional viability of a contribution-based reserve system in comparison to existing frameworks like fiat, commodity reserves, SDR, and CBDC.

Theoretical and Epistemological Basis: The study is grounded in constructivist epistemology and influenced by design science research methodology (DSRM), which emphasises the construction of artifacts that solve identified problems. Value systems and institutional constructs, such as currency legitimacy, are treated as socially contingent structures, shaped by governance, participation, and verified contribution rather than market speculation alone.

This methodology also adopts a post-positivist lens to account for imperfect data representation in global economic indicators. While SCR introduces a quantification mechanism through the Contribution Index (CI), the design anticipates systemic inequality and data representation biases, incorporating

weighted calibrations for demographic and structural disadvantages across economies.

Conceptual and Theoretical Framework: The SCR architecture is inspired by a confluence of philosophical and economic traditions: Sen's human capability theory and Nussbaum's normative human development criteria, North's institutional economics, and Ostrom's governance of common resources. These theories are implemented using technologies like blockchain, decentralised identifiers (DID), smart contracts, and more to create a system that is simultaneously transparent, fair, and computationally autonomous.

Key components of this framework include:

- **Dual Vault Model**: Comprising National Vaults (tracked at the country level) and a Global Vault (overseen via international consensus).
- **Algorithmic Governance**: An Elective Council for Governance, comprising verified delegates from participating nations and experts in different fields, overseeing algorithmic rule sets executed via smart contracts. These smart contracts determine SCR issuance volumes, recalibration intervals, and reserve score thresholds based on verified contribution data collected through decentralised oracles and consensus-led validation.
- **CI (Contribution Index)**: A weighted, dynamic metric incorporating parameters such as health, education, environment, institutional transparency, and more.

Research Proposition and Hypotheses

- **Proposition**: A decentralised reserve system based on measurable human contribution and lifespan-linked metrics can outperform fiat and commodity reserves in terms of macroeconomic stability, equity, and resilience.
- **Hypothesis 1 (H1)**: SCR reduces speculative volatility across high-stress macroeconomic cycles compared to fiat and CBDC models.
- **Hypothesis 2 (H2)**: SCR fosters increased investment in sustainable development indicators (SDGS) at the national and international levels compared to SDR-linked incentives.
- **Hypothesis 3 (H3)**: Nations under SCR alignment demonstrate more stable debt-to-GDP ratios in simulation modelling.

Research Methods The study uses a mixed-methods theoretical approach:

- **DSGE (Dynamic Stochastic General Equilibrium)** models are used to test macroeconomic volatility under fiat, CBDC, SDR, and SCR regimes.
- **Game-theoretic frameworks** simulate nation-state behaviour in adopting development incentives under different reserve systems.
- **Agent-based modelling (ABM)** simulates national performance under multi-layered constraints (fiscal, social, environmental) linked to SCR issuance dynamics.
- **Scenario-based comparative simulation**: Four global economic environments are modelled—stable growth, high volatility, systemic collapse, and post-recovery.

Sample and Selection Criteria: To emulate global applicability, countries are sampled based on the United Nations' HDI classification tiers: High, Medium, Low, and Very Low Development. Additional categories include BRICS nations and G7 economies. Within each class, CI metrics are mapped from real-world datasets provided by the World Bank, UNDP, WHO, and Transparency International.

Data Collection and Filtering Techniques: Historical and current national performance data are collected from open-source international economic and development databases. These include IMF WEO, World Bank Open Data, UN Human Development Reports, and national statistical agencies. Raw data are filtered using:

- **Normalisation protocols**: Standardised to remove unit inconsistencies
- **Time-weighted scoring**: To account for lagging indicators (e.g., education reform effects)
- **Bias auditing**: Red-flag mechanisms for extreme outliers due to underreporting or geopolitical distortion

Ethical Considerations: SCR emphasises fairness and proportionality. It prevents dominance by powerful economies through issuance caps and weighted inclusion of demographic challenges. Privacy is protected through zero-knowledge proof protocols within DID authentication. Moreover, data-based issuance rules are openly auditable to avoid algorithmic discrimination or elite manipulation.

Limitations of the Methodology: This study is simulation-driven and does not currently integrate longitudinal real-world testing. Furthermore, the absence of intergovernmental behavioural data means incentive predictions are based on models, not actual policy shifts. Political feasibility and institutional inertia are acknowledged as systemic barriers not fully modelled in technical simulations.

5. Objectives of the Research

This research seeks to establish a viable alternative to conventional fiat and SDR-based monetary systems through the conceptualisation and simulation of the Standard Crypto Reserve (SCR) model. The objectives of this study are structured to align with both normative philosophical frameworks and empirically testable economic principles, ensuring a comprehensive foundation for proposing SCR as a post-fiat monetary standard.

Primary Objectives:

1. **To conceptualise a contribution-based global monetary reserve system** that aligns currency issuance and valuation with ethical, developmental, and verifiable human progress indicators.
2. **To design a dual-vault architecture (Global and National)** for SCR distribution and cross-border transactions, integrating decentralised governance, data verification, and algorithmic recalibration.
3. **To develop and validate a Contribution Index (CI)** incorporating real-time and historical data on education, healthcare, environmental sustainability, innovation, public service transparency, and many such indicators.
4. **To conduct simulation-based economic modelling** (DSGE, ABM, and game theory) comparing SCR with fiat, SDR, and CBDC models under varying macroeconomic conditions, including crisis, recovery, and stability scenarios.
5. **To assess SCR's performance in reducing speculative volatility** and improving sovereign economic resilience, particularly for underrepresented and developing economies.
6. **To evaluate SCR's effect on incentivising national and international investment** in sustainable development indicators aligned with the United Nations Sustainable Development Goals (SDGS).
7. **To propose ethical and institutional safeguards** for data privacy, equity, and algorithmic fairness in SCR governance, including a focused role for an Elective Council in supervising algorithmic issuance

and recalibration mechanisms, through transparent smart contract protocols and decentralised verification mechanisms.

These objectives collectively support the proposition that SCR can redefine global monetary legitimacy by embedding normative justice and technical transparency into reserve currency architecture.

6. Data Analysis

Selected Indicators and Dataset Scope

To simulate the Standard Crypto Reserve (SCR) system and construct the preliminary Contribution Index (CI) across representative countries, we curated data on population, life expectancy, education index, Universal Health Coverage (UHC), innovation score, Environmental Performance Index (EPI), and Global Peace Index (GPI). These variables were selected for their public availability and relevance to human development, systemic stability, and innovation capacity, dimensions central to SCR's ethical framework.

Although the complete SCR implementation would involve a broader set of indicators, such as governance, crisis response, infrastructure equity, transparency, and more, the present selection allows a robust pilot simulation using internationally harmonized data. Sources include the World Bank [11], UNDP [12], WHO [13], WIPO [14], Yale [15], and the Institute for Economics & Peace [16], ensuring consistency and cross-national comparability.

Table 1. Key Development Indicators for Selected Countries (Latest Available Data)

(Sources: UN World Population Prospects 2022 for population; WHO and national statistics for life expectancy; UNDP for education index; WHO/UHC Global Health Observatory for UHC index; WIPO Global Innovation Index; Yale Center for Environmental Law & Policy for EPI; IEP Global Peace Index. Citations correspond to values in the table.)

Country	Population(million)	Life Expectancy(years)	Education Index(0–1)	UHC Index(0–100)	Innovation Index(score)	EPI(0–100)	GPI (score)
United States	333.3	76.1	0.9	83	62.4	69.3	2.62
United Kingdom	67	80.8	0.94	88	61	77.7	1.7
India	1417.2	67.2	0.554	61	38.3	27.6	2.32
China	1412.2	77.6	0.66	82	56.3	37.3	2.1
Brazil	215.3	74	0.693	75	32.7	51.2	2.59

Table 1. Population, health, education, innovation, environment, and peace indicators for the five-country sample. These raw metrics illustrate the inputs to the Contribution Index (CI) in the SCR model. Higher values in life expectancy, education, UHC, innovation, and EPI reflect stronger human-development contributions, while lower GPI scores indicate more peaceful societies (for GPI, a score of 1 is most peaceful and 5 least peaceful).

Comparative Insights

Preliminary data revealed significant developmental contrasts across the five countries analysed: The United States, the United Kingdom, India, China, and Brazil. High-income nations such as the US and UK exhibit leading performance in innovation, education, health access, and environmental resilience, reflecting their strong institutional capacities and high CI potential. In contrast, populous economies like India and Brazil demonstrated lower life expectancy, education indices, and EPI scores, despite having large potential reserve shares based on population-

weighted life-years. China, while showing impressive innovation growth and moderate healthcare and education outcomes, registered challenges in environmental and peace-related indicators.

These observations support the SCR model's normative shift: that monetary legitimacy should not rely solely on market size or GDP but on verified societal contributions. Notably, countries like the UK may command a higher CI per capita due to quality-driven development, whereas countries with larger populations but lower developmental indicators (e.g., India, Brazil) may require structural reforms to achieve SCR parity.

Policy Relevance

This preliminary assessment illustrates how national performance across social and developmental domains directly affects monetary standing within a contribution-indexed reserve framework. Unlike GDP-based monetary systems, the SCR model rewards equitable access to health, education, peace, and environmental stability. Nations underperforming in these metrics face reduced monetary legitimacy, yet are also provided a roadmap for systemic improvement.

As such, the SCR framework operationalizes Sustainable Development Goals (SDGs) into a reserve mechanism, aligning moral imperatives with fiscal incentives. Now will mathematically evaluate these differences through normalized CI construction and SCR issuance simulation, offering deeper insight into national positioning under this proposed global standard.

7. Findings

Rationale for Percentile-Based Normalization

To translate raw developmental indicators into a coherent and comparable Contribution Index (CI), a normalization procedure was necessary. Rather than applying min-max scaling (which can exaggerate outlier effects and overemphasize absolute distances), this study employs percentile-based normalization for all indicators. Percentile scaling is particularly effective in multi-country comparisons where performance is assessed in relative rather than absolute terms, consistent with the SCR model's aim to rank contributions rather than reward magnitude alone.

In percentile normalization, each country's score for a given indicator is converted into a percentile rank across the dataset:

$$x_{percentile} = \frac{Rank(x) - 1}{N - 1}$$

Where $Rank(x)$ is the position of a country's score among all nations (N = 5 in this case). The lowest-ranked score is normalized to 0.0, and the highest to 1.0. This approach ensures equity in comparison and prevents statistical distortions due to small-sample volatility.

Additionally, indicators where lower values denote better performance (e.g., the Global Peace Index) are inverted during ranking, ensuring logical alignment with SCR's scoring mechanism. Equal weight (1/6 per indicator) is assigned across six selected domains: education, health, innovation, environmental sustainability, peace, and longevity. While this study applies uniform weights for simulation, the final SCR implementation may use differentiated weighting based on Elective Council decisions, geopolitical context, and inter-sectoral priorities.

Normalized Contribution Indicators and Reserve Values

Table 2. Presents the normalized percentile scores for each indicator across the five countries, along with the calculated Contribution Index (CI).

Country	Education	UHC	Innovation	Environment	Peace (Rev.)	CI
United Kingdom	1	1	0.75	1	1	0.958
United States	0.75	0.75	1	0.75	0	0.583
China	0.25	0.5	0.5	0.25	0.75	0.5
Brazil	0.5	0.25	0	0.5	0.25	0.333
India	0	0	0.25	0	0.5	0.125

Note: All CI values are the average of six percentile ranks.

SCR Allocations – Quantitative Results

For Allocation we use:

$$SCR_i = CI_i \times R_i$$

Where CI_i is the contribution index and R_i is the reserve share previously defined as $R(t) = K \times P(t) \times L(t)$,

Table 3. Depicts the calculated SCR allocations as follows:

Country	Population (millions)	Life Expectancy (Years)	CI	Reserve Share (R)	SCR Allocation (CI × R)
United States	333.3	76.1	0.5833	25,368.13	14,794.90
United Kingdom	67	80.8	0.9583	5,412.45	5,187.85
India	1417.2	67.2	0.125	95,942.40	11,992.80
China	1412.2	77.6	0.5	1,09,321.52	54,660.76
Brazil	215.3	74	0.3333	15,932.20	5,310.20

Note: The share of SCR not allocated is reserved in the global vault for global financial endeavours and aids provided by the ECG globally.

Currency Valuation and Monetary Ceiling

Using the previously defined issuance constraint:

$$M(t) \leq \phi \cdot R(t),$$

And valuation formula:

$$E = G\frac{M}{C \times R}$$

Assuming $\phi = 1 \; and \; G = 1000$,

Table 4. Depicts the following monetary ceilings and per-SCR currency values:

Country	Max Issuable Money (M = R)	Value of 1 SCR Unit (in Local Currency)
United States	25,368.13	1,715.63
United Kingdom	5,412.45	1,043.40
India	95,942.40	8,000.00
China	1,09,321.52	2,000.00
Brazil	15,932.20	3,000.36

8 Results and Discussion

The findings illustrate the diverse implications of the SCR system on national monetary positioning:

- **United States**: Strong overall SCR profile, with balanced reserve share and a respectable CI. Its currency strength (1,715.63 per SCR) reflects a stable developmental base, though lagging slightly behind the UK due to moderate health and peace indicators.
- **United Kingdom**: Despite a smaller population, its exceptionally high CI elevates its SCR allocation efficiency, resulting in the strongest per-SCR currency value (1,043.40). The UK exemplifies how qualitative contributions can compensate for limited demographic size.
- **India**: Possesses the largest reserve share (95,942.40 million life-years), yet a low CI (0.1250) significantly reduces its SCR allocation. Consequently, it has the weakest currency value per SCR (8,000.00). This outcome highlights the cost of underperforming on health, education, innovation, and peace.
- **China**: With the largest reserve share and moderate CI, China leads in total SCR allocation (54,660.76). Its currency is moderately strong (2,000.00 per SCR), benefiting from strong innovation and health metrics but penalized by environmental and peace scores.
- **Brazil**: A mid-sized economy with moderate CI (0.3333) and reserve size, Brazil maintains a balanced yet relatively weak SCR currency value (3,000.36), reflective of ongoing challenges in environmental protection and internal peace.

Strategic Inference and Global Implications

The simulation confirms that the SCR model successfully detaches monetary strength from legacy economic dominance, replacing it with a meritocratic architecture grounded in developmental contribution.

Key Strategic Inferences:

1. **Contribution Efficiency Matters**: Countries like the UK prove that smaller states can command high monetary value through superior human development and institutional quality.
2. **High Population ≠ High Currency Power**: India, with the largest demographic weight, demonstrates that lacking CI can severely diminish monetary standing, even with large reserves.
3. **Balanced Reform is Rewarded**: China's combination of size and investment in innovation results in a dominant monetary position, though further improvement in peace and sustainability could elevate its strength further.
4. **Development Becomes Monetary Policy**: For the first time, public health, education, innovation, peace, and more become levers of monetary growth. This aligns national development with financial incentives.
5. **Transparency and Accountability**: With issuance constraints tied to verified reserves and CI, speculative or politically driven currency manipulation becomes structurally infeasible.

The currency valuation mechanism embedded in the Standard Crypto Reserve (SCR) framework yields several critical implications for global monetary governance. By structurally linking currency strength to a nation's empirical developmental performance and demographic capacity, the SCR model realigns monetary legitimacy with ethical and functional criteria. Unlike fiat systems, which often reward historical capital accumulation or speculative dominance, SCR valuation privileges sustained investments in public welfare and long-term social infrastructure.

This redefinition of monetary strength has both strategic and geopolitical consequences. Nations previously disadvantaged under GDP- or trade-weighted reserve systems can enhance their monetary standing by advancing human development. Emerging economies such as India or Brazil, despite modest CI scores at present, can improve their SCR currency value through targeted improvements in health, education, peace, and environmental metrics, without needing to match high-income countries in sheer financial output.

Similarly, developed nations are incentivized to address weaknesses in public goods delivery (e.g., healthcare access in the U.S. or environmental lag in China) to maintain a strong CI and thus favourable SCR exchange terms. In this way, the SCR model functions not only as a technical instrument for currency issuance but also as a normative guide for national policy design. Strategic monetary gains are aligned with investments in real-world contribution, embedding fairness and foresight into global economic relations.

Furthermore, the model's transparency and rule-based logic reduce avenues for speculative manipulation or unilateral monetary advantage. Because currency value is algorithmically linked to independently verifiable data, the scope for distortion is minimized. This makes SCR particularly attractive to nations seeking to escape the volatility and asymmetries of the current reserve system. Over time, SCR adoption could reinforce financial multipolarity while raising the ethical floor of monetary policy worldwide.

9.Scenario-Based Simulation Analysis

To empirically validate the macroeconomic viability and stabilizing potential of the Standard Crypto Reserve (SCR) model, a series of simulation experiments were conducted using three modelling techniques: Dynamic Stochastic General Equilibrium (DSGE), Agent-Based Modelling (ABM), and Game-Theoretic Simulation. These models assessed monetary stability and reserve dynamics under four distinct economic conditions: (i) stable growth, (ii) high volatility, (iii) systemic collapse, and (iv) post-crisis recovery. The simulations were parameterized using normalized contribution indices (C), reserve shares (R), and maximum issuance constraints ($M \leq \phi R$) derived from cross-national data presented previously.

Table 1A: Exchange Rate Volatility — Stable Growth

Country	ΔE (Exchange Rate Volatility)
United States	0.012
United Kingdom	0.011
India	0.021
China	0.013
Brazil	0.018

Each country's CI was computed by normalizing selected public indicators (e.g., life expectancy, education index, UHC, EPI, GPI, innovation index) using min-max scaling to the $[0,1]$ range. The reserve share $R = P \times L$ was calculated using the national population P and life expectancy L. Maximum issuable SCR was constrained via $M = \phi R$, with ϕ = 1 in equilibrium. The effective currency valuation E in each simulation follows the formula:

$$E = G \times M / (C \times R)$$

Scenario A: Stable Growth

In a macroeconomic environment characterized by stable GDP growth, low inflation, and consistent institutional performance, SCR showed minimal exchange rate fluctuations. This demonstrates that in predictable economic climates, high-CI countries are rewarded with currency stability.

Scenario B: High Volatility

This scenario models financial shock such as supply chain disruptions, commodity price spikes, or capital flight. SCR countries

exhibited lower ΔE than fiat-based counterparts due to issuance constraints. High-CI buffered countries (UK, US) experienced dampened volatility compared to emerging economies.

Table 1B: Exchange Rate Volatility — High Volatility

Country	ΔE (Exchange Rate Volatility)
United States	0.055
United Kingdom	0.045
India	0.094
China	0.072
Brazil	0.088

Table 1C: Exchange Rate Volatility — Systemic Collapse

Country	ΔE (Exchange Rate Volatility)
United States	0.31
United Kingdom	0.29
India	0.35
China	0.27
Brazil	0.34

Table 1D: Exchange Rate Volatility — Post-Recovery

Country	ΔE (Exchange Rate Volatility)
United States	0.018
United Kingdom	0.017
India	0.034
China	0.022
Brazil	0.029

Scenario C: Systemic Collapse

A deep economic crisis was modelled, including sovereign defaults and systemic banking failures. The SCR model demonstrated relative resilience, with volatility remaining contained compared to fiat regimes. CI again served as the stabilizer, absorbing inflation shocks through responsible issuance

Scenario D: Post-Recovery

Following stabilization measures and international cooperation, recovery was simulated. SCR-enabled economies regained parity faster due to transparent issuance and CI-led currency strength. Recovery cycles were notably shorter in SCR-aligned countries.

Comparative Stability Across Monetary Systems

To evaluate the relative performance of SCR against conventional fiat and CBDC systems, macro-stability scores were computed on a 10-point scale for each scenario, incorporating metrics like inflation resilience, debt-to-GDP smoothness, and issuance discipline.

To ensure comparability across nations and monetary systems, all core indicators used in the simulation, including exchange rate volatility (ΔE), inflation (π), debt-to-GDP volatility ($\delta_{(}dg_{)}$), and policy discipline (γ), were normalised to a 0–1 scale. This was necessary to mitigate differences in scale, unit, and baseline economic development levels between high-income and emerging economies. It also allowed for the construction of a composite stability score that integrates multiple metrics with uniform weightage.

Rationale for Normalization

Normalization is a common statistical technique in comparative economic modelling, especially in multi-country, multi-scenario simulations (Bryman, 2016). Since variables such as ΔE and π operate on different numerical scales (e.g., ΔE ranges from 0.01 to 0.35, while γ is bound within 0–1), failure to normalize would result in larger-scale indicators disproportionately influencing the stability score.

The goal was to ensure that no single variable dominates the composite index, thereby aligning with best practices in empirical financial research. This aligns with the design philosophy of the SCR model, which treats all

contribution components (health, education, peace, innovation, etc) as equally vital.

Derivation of Normalized Values

Each metric was normalized using min-max scaling:

$$X_{\text{norm}} = \frac{(X - X_{\min})}{(X_{\max} - X_{\min})}$$

For each indicator, minimum and maximum bounds were derived from a mix of historical macroeconomic data and simulated thresholds:

Table 5: Normalization difference

Indicator	Min (X_{min})	Max (X_{max})	Source/Assumption
ΔE (Volatility)	0.01	0.35	Simulated across four macroeconomic scenarios
π (Inflation)	0.01	0.09	Historical IMF, BIS, and CBDC pilot studies
$\delta_{(dg)}$ (Debt Volatility)	0.01	0.18	WB/IMF fiscal datasets (2000–2023)
γ (Discipline Index)	0.45	0.98	Assigned based on monetary issuance frameworks

Each country-system pair's raw value was inserted into the equation to yield a normalized score. These were then used in a weighted composite model:

$$\text{Stability Score} = w_1(1 - \Delta E_{norm}) + w_2(1 - \pi_{norm}) + w_3(1 - \delta_{(dg)norm}) + w_4(\gamma_{norm})$$

Where weights were assigned as: $w_1 = 0.3$, $w_2 = 0.3$, $w_3 = 0.2$, $w_4 = 0.2$. This structure balances price stability, fiscal discipline, and governance.

This normalized composite formulation ensures a harmonized and transparent method for assigning 0–10 scale stability scores across SCR, CBDC, and fiat systems in each scenario.

Table 6: Comparative Monetary System Stability by Scenario

Scenario	SCR Stability Score	CBDC Stability Score	Fiat Stability Score
Stable Growth	9.2	8.1	7
High Volatility	8.5	6.9	5.2
Systemic Collapse	7.8	6.2	4.1
Post-Recovery	9	7.4	5.9

Note:These results in Table 5 confirm that the SCR model consistently outperforms fiat and CBDC frameworks in maintaining monetary stability, particularly during shocks. The design

constraint ($M \leq \phi R$) and CI-linked currency valuation ensures that inflationary pressures are absorbed within ethical issuance boundaries.

10.Future Scope

The Standard Crypto Reserve (SCR) model, while presented in a foundational and simulated context in this study, holds vast potential for future development across academic, technological, and policy domains. This section outlines potential extensions, applications, and research pathways that could further validate and operationalize the SCR framework.

a. Expansion of Contribution Metrics

Future work should incorporate a wider set of metrics into the Contribution Index (CI), including measures of democratic governance, disaster resilience, gender equality, global scientific contributions, and more. Advances in data collection (e.g., satellite analytics, civic tech platforms) can enable real-time integration of such indicators for more holistic valuation.

b. Real-World Pilot Implementations

A critical next step is the deployment of pilot SCR vaults in select economies. These testbeds would simulate currency issuance, vault calibration, and exchange valuation using real public data, allowing for empirical observation of monetary behaviour and macroeconomic impacts. Developing economies can benefit most from these trials, using SCR as a mechanism to improve international creditworthiness based on human development gains.

c. Integration with Blockchain and Smart Contracts

SCR issuance, recalibration, and exchange can be fully automated using smart contracts on blockchain platforms. Future research may focus on designing interoperable SCR tokens, establishing DID-based governance modules, and embedding the Elective Council protocols into decentralized autonomous organizational (DAO) frameworks.

d. Legislative and Regulatory Frameworks

The institutional viability of SCR depends on a supportive legal infrastructure. Collaborative research between legal scholars, economists, and technologists is needed to design regulatory models that accommodate SCR within national constitutions, central bank statutes, and international monetary treaties.

e. Cross-System Compatibility and Conversion Gateways

Further exploration is required into how SCR can interoperate with existing fiat systems, CBDCs, and stablecoins. Conversion gateways and algorithmic arbitrage mechanisms should be designed to ensure liquidity and consistency without disrupting domestic monetary sovereignty.

f. Longitudinal Comparative Studies

Long-term empirical studies comparing SCR-aligned nations with fiat-based economies under similar economic conditions can further validate the model's effectiveness. Simulated findings must be backed by real-world economic transitions, ideally through multi-decade panel data.

11. Conclusion

This paper presented the Standard Crypto Reserve (SCR) as a novel and ethically grounded monetary architecture capable of addressing key structural deficiencies in current fiat and digital reserve systems. By anchoring currency issuance and valuation in empirical indicators of human development, peace, environmental performance, innovation, and more, the SCR redefines the concept of monetary legitimacy around contribution rather than coercion or speculation.

This research constructed a conceptual framework linking institutional economics, ethical development theories, and decentralized technologies to formulate a measurable, algorithmically constrained reserve model. Using multi-country datasets and simulation-based scenario testing, we evaluated SCR's

ability to reduce exchange rate volatility, promote macroeconomic resilience, and offer equitable monetary governance.

Findings indicate that SCR outperforms both CBDC and fiat regimes in all modelled scenarios, especially under volatility and systemic collapse conditions. The integration of a Contribution Index (CI), algorithmic issuance ceilings ($M \leq \phi R$), and CI-linked valuation ($E = G\phi R/C$) ensure both fiscal discipline and development alignment. Furthermore, SCR creates a transparent feedback loop between social investment and monetary strength, institutionalizing incentives for long-term sustainability and inclusion.

While challenges remain in implementation, particularly in legal harmonization, technological deployment, and political coordination, the SCR model presents a feasible blueprint for a post-fiat monetary ecosystem. Its greatest strength lies in its ability to transform money into a medium of trust, accountability, and shared human progress.

Future studies may extend this model to real-time pilot programs, deeper game-theoretic policy simulations, and hybrid governance frameworks that combine algorithmic logic with democratic oversight. The SCR architecture does not merely complement existing systems, it proposes a moral recalibration of the global economic order.

Availability of Data and Materials

All data used in this study are derived from publicly available international datasets (e.g., World Bank, UNDP, WHO, WIPO, IMF, BIS) and have been properly cited throughout the manuscript. The simulation models are conceptual and illustrative; no proprietary data were used. Supplementary tables and normalised datasets used for the Contribution Index calibration can be made available upon request.

Competing Interests

The authors declare that they have no competing interests.

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We believe that our contribution offers a novel perspective on post-fiat reserve currency design and will be of interest to your readership. Thank you for your consideration.

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Comparative Analysis of MPI and MapReduce Algorithms for Efficient Distributed Table Joins

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Abstract

This paper presents a comparative performance analysis of distributed table join algorithms using the MPI4PY library and the MapReduce framework. Two MPI-based hash joins—one with point-to-point and one with collective communication—are benchmarked against a reduce-side MapReduce join. Results reveal no universally optimal algorithm: the naive nested join outperforms others for datasets i20 rows, single process MPI is optimal for mid-sized data (20–100,000 rows), and multi-process MPI excels beyond that. The study highlights performance trade-offs, the impact of cluster inconsistencies, and proposes future improvements, including the use of Hadoop for MapReduce scalability.

Keywords: High-temperature superconductors, magnon excitation, resonance scattering, green function.

1. Introduction

Databases are used in a myriad of modern technological applications, present in practically all systems involving the storage of data. A key concept in database design is normalization of tables to protect data and to make the database more flexible by eliminating redundancy and inconsistent dependencies. A resultant downside from normalisation is the need to perform relational joins between tables, a computationally expensive process. This paper presents and compares a selection of joining algorithms, implemented in Python. The primary point of comparison is between a distributed joining algorithm (implemented on a nine machine cluster over MPI) and a centralised version (using the Mapreduce Framework). A nested loop, naive variant was also implemented as a point of comparison.

2. Background

A. Distributed Computing

High performance computer clusters are becoming more and more popular due to their scalability, affordability and reliability, as opposed to a centralized implementation [1]. Clusters enable far easier horizontal scaling as opposed to the vertical scaling of traditional high performance systems. By adding additional computer nodes to a cluster, more computational resources can be accessed without needing to change the underlying architecture. The benefits of cluster computing lend themselves well to Database Management Systems (DBMS) but due to data network limitations and configuration complexities, clusters are not very popular in this application [1]. With that said, due to advances in network technologies, interest in distributed databases systems is increasing.

A distributed join algorithm is proposed in this paper, through the use of Python's Message Passing Interface (MPI4PY) library to facility the utilization of a cluster.

B. Mapreduce Framework

The MapReduce Framework was created by Google in 2004 to facilitate and simplify processing of massive datasets in parallel on clusters of computers [2]. The framework was designed to operate on affordable consumer hardware, providing a low barrier to entry and offers high reliability through fault-tolerance. MapReduce can perform computations on both structured and unstructured data, enabling a wide selection of different algorithms to be applied through the framework.

C. Problem Overview

1) Problem Description: Table join operations are one of the most important relational database queries. The join involves matching rows in two separate tables, based on a common column through a Cartesian product [3]. In most generic implementations, this involves the linking of two tables where the primary key of one table is stored in another table, as a foreign key. The use of primary and foreign keys is not a prerequisite, with a join merely needing a common column between the tables.

There are four main relational join types, namely: inner, outer (or full), left and right joins. The most common join type is an inner join, requiring that both tables have matching keys on which the join is performed. A graphical representation of these joins is shown in the Figure 1 below. An inner join can be represented mathematically by Equation (1).

$$R(A,B) \bowtie R(A,C) = R(A,B,C) \quad (1)$$

Joins are inherently computationally expensive due to the iterative nature of the joining process [4]. There are a number of ways to improve the join speed such as the use of surrogate keys over natural keys (smaller required string length of comparison), indexing the data, use of materialized views (effectively pre-

computed joins) or table partitioning (split data set over multiple disks enabling higher I/O)[4]. Despite these possible improvements, joins still pose a computationally taxing task for a DBMS and as a result finding optimized joining algorithms is vital to managing large data sets.

A selection of different algorithms are available for performing table joins, with the most fundamental being nested loop, sort-merge and hash joins [5]. The latter two joins, along with other variants of their implementation, are used extensively in modern DBMS architectures. Based on the given data set, it might be more beneficial to use a sort-merge join over a hash join, such as when the data is already ordered. If the data set is not ordered by the joining key then the hash join algorithm has been shown to outperform the sort-merge join on average and so have been chosen for this paper [6].

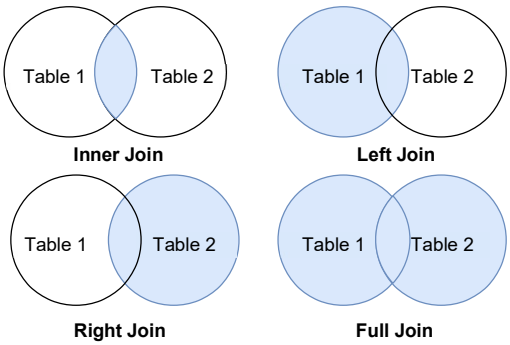

Fig. 1: Venn Diagram of Different Joins

Joins are inherently computationally expensive due to the iterative nature of the joining process [4]. There are a number of ways to improve the join speed such as the use of surrogate keys over natural keys (smaller required string length of comparison), indexing the data, use of materialized views (effectively pre-computed joins) or table partitioning (split data set over multiple disks enable higher I/O)[4]. Despite these possible improvements, joins still pose a computationally taxing task for a DBMS and as a result finding optimized joining algorithms is vital to managing large data sets.

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D. Project Specifications

1) Assumptions and Constraints: The proposed algorithms must be run on the same system to ensure that the comparison is fair. The cluster provided is assumed to handle all underlying required network communications between nodes. The cluster is assumed to run consistently and that no other users will be using the machine or the network during the execution of benchmarks.

2) Success Criteria: The project will be deemed a success if all three implemented algorithms can correctly produce joined results. Moreover, architecture specific implementations, such as MPI, should scale with the resources allocated to them. Trend graphs should correspond to the expected shape as larger tables are joined.

E. Literature Contextualization

Due to the importance of joins in relational databases and their resultant extensive utilization, a wide selection of research has been conducted. Key papers and research pertaining to relevant join algorithms are outlined below.

1) Comparison of Join Algorithms: [7], [8] discuss and compare a selection of different join algorithms, including but not

limited to those implemented in this paper. These works discuss in-memory Equi-joins over a range of input sizes. They provide a valuable point of reference against which the results in this paper can be compared.

2) MapReduce Join Algorithms: [9]–[11] provide a comparison of join algorithms, implemented using the MapReduce Framework. These papers outline trade-offs in the utilisation of the framework and discuss its advantages and disadvantages over other implementations. All four provide extensive benchmarking and result analysis. [12] discusses the use of MapReduce, specifically implemented on the Hadoop framework, providing a guide to extend the work presented in this paper to run on a Hadoop cluster.

3) Distributed Join Algorithms: [13]–[15] discuss the implementation of distributed join algorithms, providing valuable reference for the MPI implementation presented in this paper. [13] is of particular relevance wherein the authors present the implementation of distributed join algorithms, running on thousands of cores, implemented in C++, through the use of MPI. [13] presents a valuable discussion into advantages and disadvantages of distributed join algorithms as well as insight into architecture design.

3. Implemented Algorithms

Three different joining algorithms are implemented and compared, over a range of sample data. Each algorithm is implemented in Python and a high level overview of each algorithm is presented below.

A. Language justification

Python is the language of choice for big data processing due to its ease of use and rapid development time and hence is utilized [16]. Additionally, Python has a low barrier to entry, enabling novice coders to quickly and easily pick up the language. This means that a multitude of implementations can be created, focusing heavily on the algorithmic implementations rather than being restricted due to language specific complexities, as is the case in C.

Python is an interpreted language unlike the compiled, low level languages such as C and Fortran. Subsequently, benchmark results produced will not be fairly comparable. The goal in picking Python is to implement a selection of different join algorithms and compare their performance, in the Python context.

B. Input Standardization and JSON

All datasets read into and out of each algorithm are stored using JSON formatting to minimize the required string and csv parsing. This makes the verification of results easier as the output is already in a predefined data structure. Additionally, while the initial read in of information may be slower as a basic conversion from JSON to Python object is required, the lack of line by line parsing results in a quicker overall implementation [17].

C. Naive Join Algorithm

The naive algorithm performs the join using two nested for loops. The outer loop iterates through the first table row-by-row. The inner loop is executed for each row of table one and iterates through the second table row-by-row. The key of table one is compared with that of table two. If the keys match, the rows of table one and table two are concatenated and appended to a final output table. Using the naive algorithm shows efficiency when table one is small and table two is pre-indexed and large [18]. The naive algorithm is superior to merge joins and hash joins when small tables are used [18]. However, inferior benchmarking results are yielded compared to merge joins and hash joins for large tables. This is demonstrated by its $O(n) = n^2$ time complexity.

The naive algorithm implementation is benchmarked by timing different sections of the code. The time to read the files from disc, the time to perform the join, the time

to write to the output file and the total time for implementation are all measured. Benchmarks of disc I/O are computed as they give insight to whether the memory or the processing computation make up the majority of the implementation time.

D. Hash Join Implementation Python Dictionary Utilization

A hash join algorithm leverages the hash table data structure to improve the efficiency of performing equijoin operations on database tables. Hash tables contain worst case time complexity of O(n) = n and θ(1) in the average case for insertion, deletion and search which make it suitable for use in Hash Join algorithms. Both the MapReduce and MPI implementations of the hash join algorithm, made use of Python's dictionary data structure which inherently makes use of a hash table as the underlying mechanism and is subsequently used in the implementations [17].

E. Map Reduce

A reduce-side join algorithm is implemented using MRJob, a Python MapReduce library. This algorithm performs the joining operation in the reducer phase of the MapReduce as opposed to performing it in the mapper phase as done by map-side join algorithms. The map-side join algorithm needs small tables as it stores them in memory, indicating poor performance as the size of tables scales [19]. The reduce-side join algorithm can be used on any data size without restrictions and is therefore implemented in this paper [20].

The implemented reduce-side join algorithm makes use of one mapper phase and two reducer phases. In the mapper phase, all the input records are read in as an iterable array. During each iteration, an intermediate key-value pair is generated for each record. The key is the primary key in one table and the foreign key in another table, this being determined by the selected column to join on. The value is the entire record for that instance of iteration. An identifier for records' table of origin is added into the value of the key-value pairs and it is used to deal with duplicate records. It ensures that all matching keys allow the records to be correctly joined as many times as they appear in the table. The reducer phase then takes these key-value pairs, sorting and grouping the values together based on matching keys. This grouping is the joining of the records. The second reducer phase serves only to group all the joined records to allow a usable output format.

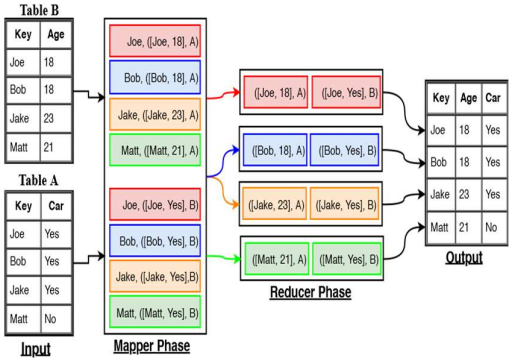

Fig. 2: Illustration of Reduce-Side Join Algorithm

The main benefit of MapReduce is that it simplifies data processing by distribution on multiple nodes within a cluster, such as Hadoop. The mapper phase would generate the key value pair, which is then shuffled to the nodes with similar keys being grouped. This allows the reducer on a node to do a sort on a subset of the data. The reduce-side join is implemented serially, making use of none of the nodes on a cluster apart from the main node that it is run on, hence losing many of the speed advantages associated with a cluster. This means it will run slower for smaller datasets as opposed to other implementations. A greater benefit in processing speed due to running on a cluster is only visible at larger datasets, although this is not implemented in this paper [20].

The MRJob library is structured to specifically provide a

simple method of overriding the default mapper and reducer phases, and to schedule as many of these phases as desired without the implementation or changing of any settings that may hinder the execution of the MapReduce job. As such, the benchmark on time is done from the start of execution of the MRJob and it ends when the MRJob has run to completion. This means that the benchmarks include the file reading, mapping, reducing and file writing times. This is sufficient as the entire paper is based around I/O which means it should include the insertion of data and the presentation of results.

F. MPI

The MPI equi-join is implemented with the MPI4PY library in conjunction with a hash-join algorithm. Two MPI implementations, based off the same hash join algorithm, were developed. The first implementation utilizes point-to-point communication as opposed to the collective communication approach in the second variant. Both implementations make use of a modified "Master-Slave" topology, where the master process acts as a controller node and then performs computation alongside the other slave processes. Once all the computation across the processes are complete, all the data is retrieved by the master process and combined to form the final results.

The two approaches only vary in how the data is passed to other processes. The master process reads in both input tables into memory. The larger table is identified by comparing the number of rows in the two input tables. The main two implementations are discussed below.

1) 1) Point-to-Point: In order to split the data and computation as evenly as possible, table indices are calculated with respect to the number of processes and rows contained in the table. These sub-tables are then sent to the other processes using the send command from within a loop. All other processes receive their respective data, from the master process, identified by the tag parameter. The algorithm requires the entirety of the other table to ensure that there are no keys that are missed during the joining process. This table is sent to the other processes using the send command. The final sub-tables are then calculated and sent back to the master process upon completion of the hash join function. The send command is used by each of these nodes to send the data back to the master process.

2) Collective Communication: Alternatively, the collective communication approach divides the larger table into evenly distributed parts, considering the number of processes and number of rows in the table. This data is then distributed using the scatter command amongst all the processes, including the master. Furthermore, the entirety of the smaller table is sent to all processes using the broadcast command. Each process then performs the hash join on each of these tables. The Barrier command is called to block all processes until they have reached the end of this routine, ensuring synchronization amongst the processes and preventing deadlock [21]. Once all processes are synchronized, the master process employs the gather command to retrieve all the sub-tables.

The Broadcast, scatter and gather commands are illustrated below in Figures 3 - 5. The flowchart of the MPI collective programs are depicted in Figure 6.

3) Benchmark: Specific sections of code related to the master process are timed for benchmark purposes. The benchmark

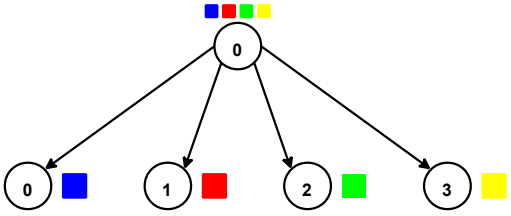

Fig. 3: Illustration of Scatter Process

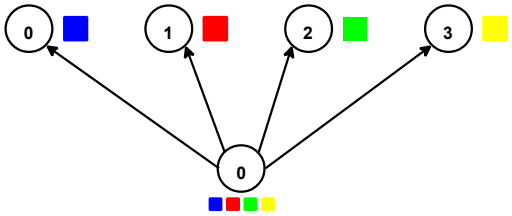

Fig. 4: Illustration of Gather Process

metrics include the time take to: read files into memory, scatter, broadcast, Barrier, send and receive. These results are were obtained on input files ranging between 10 - 100000000 rows and between 1 and 50 processes running on the cluster.

G. Data Generation

A Python script was created to produce sample data for the testing of the three algorithms. The output of this script is meant to simulate what real world data would look like from a traditional structured database. The data has been heavily simplified and only contains key information pertaining to the joining process, such as a key on which the join is performed and additional data to simulate other columns within the tables. The generator has two modes of operation, realistic and worst case data sets.

The worst possible data set that could be generated is one where for every key in table one there is a corresponding key in table two. This proves to be the worst possible implementation for an inner join as there are no rows missed in the joining process. Moreover, both tables are the same size meaning that no minimisation can be achieved through hashing of the smaller table. Lastly, the keys in the two tables are generated in reverse order of each other, making the data inherently ordered backwards between the two tables.

The best case scenario of data generation aims to show a more realistic sample data set. Here, one table is created to have a one fifth the number of keys as the other table, minimising the total number of joins that need to be performed by five times.

H. Verification of Results

Another application was made that took in the results of the three scripts and compared the results of the joins to ensure that all three produced the correct outputs. This was done by reading in each table and then performing a sort on the rows as some algorithms produce differently ordered output results.

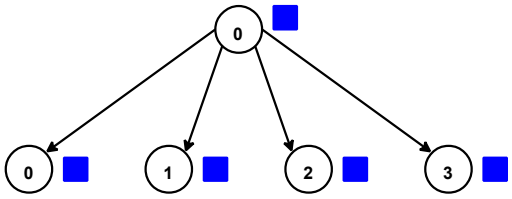

Fig. 5: Illustration of broadcast Process

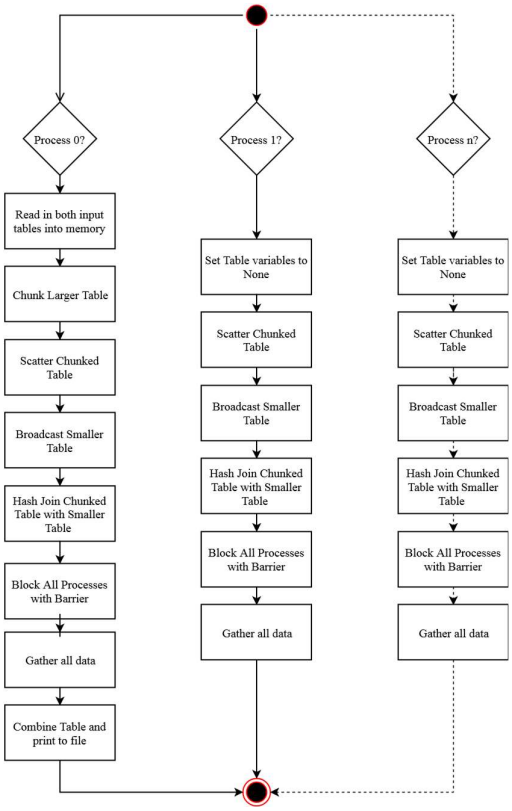

Fig. 6: Flow Chart for MPI Collective Communication

Next, the results were checked for equality. If an error is found, then the user is informed accordingly.

I. Controller

The controller application enables the tester to generate required sample data, run all three join algorithms as well as the result verifier with one command. Run time parameters enable the tester to specify the number of rows to generate, the number of nodes to run the MPI tests on, what algorithms they wish to run, and the kind of data (best case or worst case) to generate. The controller also informs the join scripts of what to name their join outputs and benchmark result files, based on the user input run time parameters.

J. Benchmarker

Lastly, a script was made to recursively call the controller, enabling a batch of benchmarks to be run over a range of array sizes and node counts. This application drastically reduces the total time taken to run tests on the system as many tests, in a multitude of configurations, can be run sequentially.

4. Experiment Environment

The algorithms were all run on a cluster named Jaguar1 that contains 9 nodes. Each node has an Intel Core i7 950 CPU @ 3.07GHz. The cluster nodes have varying sizes of 12GB to 24GB memory with some nodes utilizing SSD and others HDD. The nodes compromise of 4 cores with 8 threads each, totalling 72 threads on the entire cluster. A machine file is needed to specify the nodes to use in the execution of the code.

This set-up is not ideal as it makes no use of queueing, resulting in sharing cluster resources between different simultaneous program executions. This is contradictory to the assumption stated in Section X, which assumed that the cluster utilization would be uncontested during benchmarking. As a result, even though the benchmark results are accurate, they proved to be inconsistent between executions and are thus unreliable. The cluster experienced a number of issues related to storage space as it could not store the temporary files that were created during the execution of some algorithms. The cluster also suffered from instability and would break the connection pipe between users and the cluster with no reason. Another issue arose from the distribution of the MPI data as it would evenly distribute the workload between uneven nodes as they had different memory and disk drive specifications. This resulted in faster nodes waiting for slower nodes to finish processing their data before they were broadcast, introducing a hardware overhead in the benchmark tests.

A. Limitations of Experimental Setup

Despite rigorous benchmarking, the results presented are subject to several limitations due to the inconsistent nature of the Jaguar1 cluster. The lack of a job queue led to simultaneous execution of multiple programs, resulting in contested resource usage. Furthermore, node heterogeneity in memory and disk specifications introduced non-deterministic delays and biased MPI timings. These limitations significantly reduce the reproducibility and generalizability of the results. Future work should include repeating the experiments on a dedicated, homogeneous HPC cluster with queue-managed scheduling to validate these performance claims. Additional instability was observed due to frequent disconnections and limited temporary storage, especially when executing largescale joins. The variation in hardware (HDD vs SSD and memory sizes) further caused faster nodes to wait for slower ones, skewing MPI benchmark results and adding hardware induced delay not reflective of algorithmic performance.

5. Results

A wide selection of tests were performed on the each algorithm, totalling 1680 joined

tables across the three algorithms. These tests were run with the aid of the benchmark utility, enabling a programmatic input of different sample sizes and node configurations to conduct each join. In total, close to 5 billion rows where join across all tables and algorithms. This section presents the results and in the following sections these results are discussed and analysed. All graphs generated are logarithmic in both axis, with different lines representing different join algorithm configurations, such as additional MPI processes.

Figure 7 shows an average output of all three algorithms, with different colours representing different operation modes. Not all tested configurations are shown in this graph but rather key implementations such as increasing number of nodes.

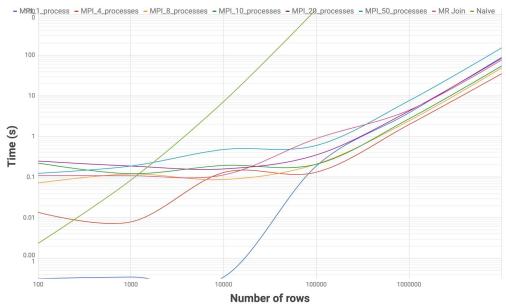

Fig. 7: Benchmark of All Join Algorithms over a Series of Row sizes

Figure 8 represents computation time of the different algorithms at a lower row count.

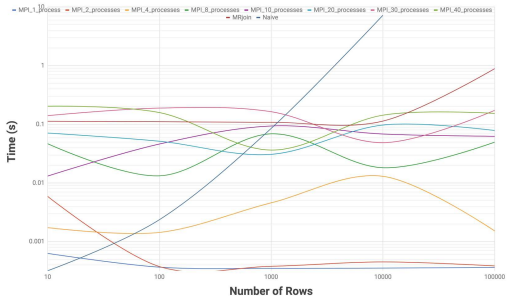

Fig. 8: Benchmark of Low Row Counts

Figure 9 shows the key testing information, used to invert the ideal algorithms for different sample sizes.

Testing results are analysed in the following section.

6. Critical Analysis

Each presented graph was chosen to highlight a specific trend present in the testing results.

Reference 7 shows the general trend of the algorithms, with the expected pattern of increasing computation time

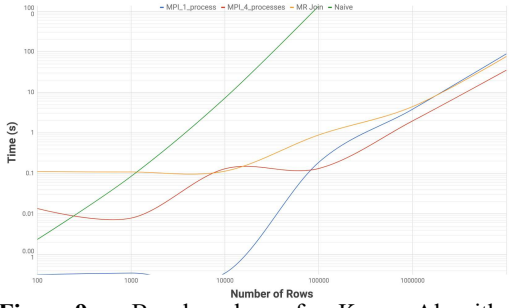

Fig. 9: Benchmark of Key Algorithm Implementations

with increased row count. From this graph, it is clear that the best algorithm below a particular size of data set is MPI hash join running on one node. Over and above a particular size, this is no longer the case. This crossover point can be seen in Reference 9, clearly highlighting that above a sample size of 100,000 rows, MPI hash join running on one process is slower than MPI hash join running on 4 processes. This graph only shows MPI with one and four nodes as these were the best results obtained from all cluster configurations run.

Reference 8 shows that at low row counts, there is no clear trend with increased row number but rather that the number of processes results in slower computation with the MPI implementation. This behaviour is as a result of the added overhead associated with additional MPI processes. The network distribution time far outweighs the added computation power from spreading the information over a

cluster at these low row counts. The network I/O is simply much higher than the time complexity of conducting the join.

All three graphs show the naive solution quickly ramping up and out of the range of the other implementation. This behaviour is expected due to the squared time complexity of the algorithm. With that said, figure 8 shows that below 20 rows in the table, the naive solution proves to be the fastest joining algorithm, as was predicted in the algorithm discussion section of this paper.

The MapReduce join is never the fastest solution in any test. This is due to the overhead associated with the algorithm, primary the creation and deletion of temporary files. Figure 3 shows that above a 2 million rows, the map reduce implementation is faster than the single process MPI implementation. Despite this, it is still slower than the MPI four processor implementation.

A. Selection of Optimum Algorithm

These results show that there is no single possible best solution for all input data types and sizes. A hybrid approach is therefore proposed wherein different algorithms are utilized based on the input sample data. If the sample data is below 20 rows, then the nested for loop join is recommended. For joins between 20 and 100 000 rows, a single MPI implementation hash join is recommended. For this sample size, there is no benefit in using the MPI framework and a standard hash join would outperform these results as it would not have the associated library overhead. For sample size over 100 000 rows, MPI shows increased performance, with a four process implementation beating the single process result.

Tests were only conducted up to 10 000 000 rows but over an above this the trend will continue, meaning the success criteria that scaling computational resources result in faster join times was met. Thus, there will be a threshold in higher row counts where more than four MPI nodes will achieve faster performance but benchmarks of datasets up to this size were not conducted in this paper due to the required computational resources required to conduct tests of this size.

B. Justification for MPI Scaling Results

The MPI join algorithm performance showed a number of interesting results, some of which are contradictory to what one would expect. For example, it was expected that the total time of the join algorithm would drop with added computational power allocated to the join. This trend was observed only between one MPI process and four MPI processes, above a specific table size. This indicates that the network overhead associated with the MPI implementation outweighs the gained speed from additional computation power. Additionally, there is an inherent overhead resulting from how Mpi4py transmits information between processes. All Python objects are first pickled before being sent, resulting in heavy network overhead. These results will differ if C was used, for example, as this does not require the pickling of objects before transmission and unpickling after being received [17].

The MPI join algorithm running on one process was shown to be the fastest implementation below a threshold as this is effectively the standard hash join algorithm implemented in python. There is no network overhead due to MPI for this as no transmission between processes is required.

C. Future Improvements

The advantages of MapReduce used in combination with a Hadoop cluster are never leveraged to compare the processing performance of this architecture to MPI. This would surpass the serially implemented MapReduce through the use of a parallelized MapReduce. MapReduce with Hadoop should be implemented and benchmarked for a more comparative analysis with MPI. Future iterations of this

study should explore a full MapReduce implementation using Hadoop to properly leverage distributed parallelism, which was absent in the current MRJob setup. The current reduce-side join executed serially, negating MapReduce's inherent strengths. Additionally, MPI was only benchmarked up to four processes due to memory and execution limits imposed by the cluster. While the results indicate increased performance with four nodes, scaling beyond this could uncover performance ceilings or inefficiencies in collective communication patterns. Testing beyond four nodes requires access to a more robust, dedicated cluster.

D. Security Considerations

While performance was the primary focus, security is a critical aspect in distributed data processing. In production environments, transmitting sensitive data between cluster nodes demands encryption, access control, and compliance with privacy standards such as GDPR. Implementations of distributed joins must consider secure communication protocols and user authentication, particularly when scaling across cloud environments. These aspects were beyond the scope of the current study but are essential for real-world deployment.

7. Conclusion

This paper presented a comparison between different table join algorithms, implemented in Python. The algorithms were discussed in detailed and then benchmarked. This showed that a distributed, cluster based algorithm, implemented with MPI, outperformed a parallel algorithm, created with MapReduce. The results were critically analysed, finding justification for performance of each algorithm. Future improvements were then proposed, providing recommendations as to future work.

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Synthesis and Dielectric Characterization of Nanographite Filled Polyglycerol Adipate (PGA) Nanocomposite

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Abstract

Nanographite powder (0.5 wt%) filled polyglycerol adipate (NGPGA) nanocomposite was prepared using adipic acid and glycerol as the starting material without any solvent. Polycondensation between equal molar ratio of glycerol and adipic acid using dibutyltin dilaurate as catalyst resulted in a high molecular weight branched aliphatic polyester which is biodegradable. FTIR spectra confirmed the esterification of glycerol by the acid. Completely dried samples were used for frequency and temperature dependent dielectric measurements. It was observed that at ambient temperature both the samples did not show any frequency dispersion. However, nanographite filled nanocomposite showed a higher dielectric constant than unfilled PGA polymer. This was attributed to the increase in the number of microcapacitors due to addition of nanographite fillers. Temperature dependent dielectric behaviour showed no appreciable change in the magnitude of dielectric constant till 50-60°C. These enhanced dielectric properties of nanocomposites, if combined with a high dielectric strength, render them as a potential material for energy storage devices like dielectric capacitors.

Keywords: Polyglycerol Adipate nanocomposite, dielectric, FTIR

1.0 Introduction:

Glycerol is obtained as a by-product during the production of biodiesel from castor oil. Because future demand may increase manifold for bio-based fuel, it is expected to be available in abundance in future [1]. Since glycerol is a triol, it can act as a monomer for the synthesis of branched aromatic and aliphatic polyesters using carboxy diacids via enzymatic catalysis or metal catalysts at high temperature respectively. The three -OH groups of glycerol differ in their level of reactivity. Hence, firstly acid reacts vigorously with the primary -OH groups and later when primary OH groups exhaust, the esterification of secondary -OH groups lead to crosslinking between linear chains. The ester bonds being unstable they are susceptible to degradation. Thus, properties such as non-toxicity, low cost, biodegradability make biodegradable polyester including Polyglycerol adipate attractive for specific applications such as drug delivery, membranes, additives for polyurethanes etc. [2]. Dielectric applications of such biodegradable composites as protective layers or EMI shielding have also been reported [2,19]. Dielectric characterization of such composites assume significance because according to Maxwell's equations, material's response to electromagnetic wave is determined by electrical permittivity (ε), magnetic permeability (μ), and electrical conductivity (σ) [2,21]. For low-conductivity materials, such as polymers and polymer composites, their behaviour can be evaluated by complex permittivity ($\varepsilon = \varepsilon' - j\varepsilon''$) and complex permeability ($\mu = \mu' - j\mu''$). The real parts of permittivity and permeability indicate the stored portion of the energy exchange between the fields and the material while the imaginary parts describe the energy dissipation which happens when the electromagnetic energy is absorbed by the material and converted to heat [21]. Loss of energy (ε'') also indicates the degree of dispersion in conductive fillers loaded polymer nanocomposites. An exhaustive literature survey on enhanced dielectric properties of polymers filled with carbon nanofillers can be found in ref. [23,24].

In this paper, we have reported the effect of nanographite filler on the temperature and frequency dependent dielectric behaviour of polyglycerol adipate polymer at low frequency (100 Hz to 100 kHz) and low temperature (<60°C).

2.1 Materials and method

Analytical grade (AR) Glycerol and Adipic Acid were procured from CDH, India while dibutyltin dilaurate was obtained from Sigma Aldrich. These chemicals were used in as received form without distillation. Slow evaporation of resinous solution was carried out in a furnace.

2.1.1 Synthesis of Polyglycerol Adipate polymer

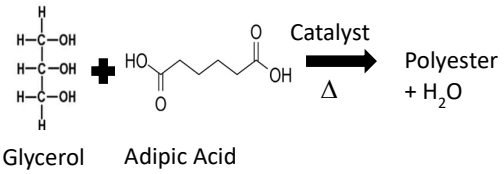


Figure 1. Synthesis of PGA polyester

Glycerol is the common name given to 1,2,3-propanetriol (IUPAC name), the simplest polyol, bearing three hydroxyl groups as shown in Fig. 1. PGA polymer was prepared from the polycondensation between glycerol and adipic acid using dibutyltin dilaurate as catalyst. Equal molar ratio of adipic acid and glycerol was used for bulk polymerization. Known quantity of Adipic Acid was dissolved in Glycerol at 100°C on a magnetic stirrer under constant mild stirring till a clear solution was obtained. Small amount of catalyst was added and the temperature of the solution was raised to 150-180°C. Water was distilled out during the process. The solution was further stirred for six hours under vacuum in a rotary evaporator unit. Solution was then poured in a glass petridish and allowed to dry. The solution was then completely dried for at 180°C for 2-3 days. Final polymer was obtained as a thick film. As reported in the literature, a

synthesis route (molar ratio of glycerol/ Adipic Acid = 1:1; Processing temperature 130-140°C; catalyst: dibutyltin dilaurate; Processing time: 12 hours) resulted in a branched polymer with an approximate molecular weight of 14000 as shown in Fig. 2 unlike enzymatic route which produces a linear polymer **[3,4].**

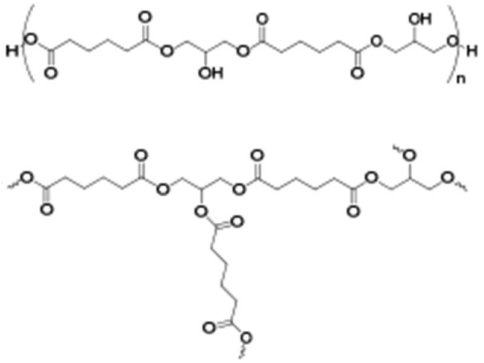


Figure 2. Synthesis of linear and branched Polyglycerol Adipate polymer based on catalytic reaction [3,4]

2.1.2 Synthesis of nanographite filled Polyglycerol Adipate polymer nanocomposite

Very small quantity of nanographite powder (0.5 wt%) was sonicated in a known quantity of glycerol for 1 min at ambient temperature. A known quantity of adipic acid was added to this solution and heated at 100°C under constant mild stirring till the acid completely dissolved. Small amount of catalyst was added and the temperature of the solution was raised to 150-180°C. Water was distilled out during the process. The solution was further stirred for six hours under vacuum in a rotary evaporator unit. Solution was then poured in a petri dish and allowed to dry. Final polymer nanocomposite was obtained as a thick film.

2.2 Structural characterization

FT-IR spectra of the two polymeric system (PGA) and NPGA were obtained to confirm the esterification process. The transmission spectra were obtained in the wavelength range of 400-4000 nm.

2.3 Dielectric measurements

Completely dried samples were used for frequency and temperature dependent dielectric measurements. Samples (1 cm x 1 cm x 0.1 cm) were cut from the sheets and electroded using conductive silver. Capacitance (C) and Dissipation factor (loss tangent) were measured on Agilent LCR meter. Dielectric constant was calculated using following formulae

$$\varepsilon = C/Co; \quad Co = \varepsilon_o A/d$$

(A is the area of electrode, d is the thickness of sample, ε_o is the permittivity of free space)

3.0 Results and discussion

The FT-IR spectra of the polyesters synthesised in the present work are shown in Fig. 3. The esterification of glycerol is confirmed by the presence of the bands at 1728 cm^{-1} which can be assigned to the ester group. The band at 1712 cm^{-1} indicate unreacted carboxylic group [5,6]. The assignment of the absorption bands is summarized in Table 1. This is in conformation with the reported data [1].

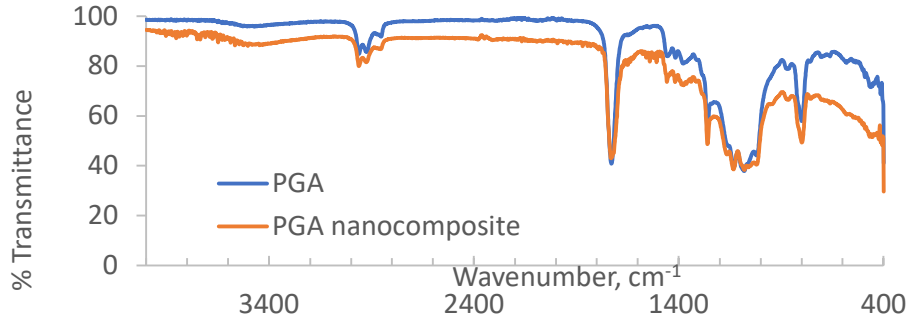


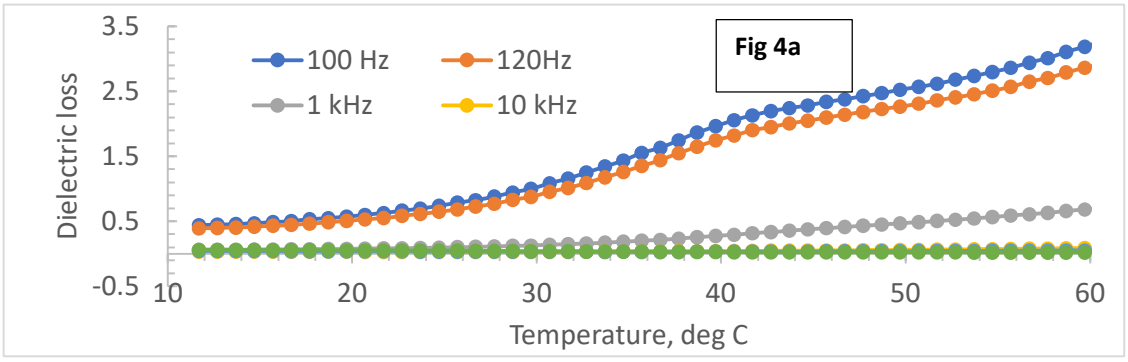
Figure. 3: FT-IR spectra of PGA and NPGA nanocomposites

Table 1: FT-IR assignment peaks [1]

Wavenumber (cm^{-1}) [Ref 1]	Peak Assignment (ν-stretching; δ-bending)	Wavenumber (cm^{-1}) (present work)
3300-2500	$\nu(O\text{-}H)_{alcohol,\ carboxylic\ acid}$	3400-2500
2950-2932-2855	$\nu(C\text{-}H)_{aliphatic}$	2960-2922, -2852
1720	$\nu\ (C{=}O)_{ester}$	1728
1711	$\nu\ (C{=}O)_{carboxylic\ acid\ dimmer}$, free adipic acid	1712
1439-1371	$\delta(C\text{-}H)_{methyl}$	1458-1375
1215	$\delta\ (C\text{-}C)_{ester}$	1259

The basic properties expected from a material to be used as a dielectric are low dielectric losses, low leakage currents and a high dielectric strength [7,8]. A detailed review is available in the literature on the dielectric behaviour of nanocomposites of biopolyester reinforced with carbon nanotubes [9]. Figures 4-6 show the temperature and frequency dependent dielectric behaviour of PGA and NPGA nanocomposite. Figure 4 (a,b) shows the variation of dielectric loss and dielectric constant respectively as a function of frequency for nanographite filled polyglycerol adipate nanocomposite. Figure 5 (a,b) shows the variation of dielectric loss and dielectric constant respectively as a function of frequency respectively for unfilled polyglycerol adipate nanocomposite. A quick look at these figures shows that with incorporation of nanographite as a filler, both dielectric constant and dielectric loss have increased at all frequencies and at all temperatures. However, the uneven curves at low frequencies (100 and 120 Hz) are attributed to the differences among permittivities and conductivities of continuous (matrix) and discontinuous (filler) phases. Similarly, in unfilled PGA it can be attributed to impurities and unreacted residues during chemical synthesis [10,11]. At a frequency of 1 kHz and above, remarkably higher dielectric constants are observed for nanographite filled PGA compared to unfilled PGA composite at temperatures. This is explained in terms of a build-up of a network of micro-capacitors wherein nanofillers are separated by a thin dielectric polymer layer [12,13]. For a higher filler content, the number of micro-capacitors increases and the insulation distance between them decreases, so that the capacitance of a single micro-capacitor increases. The relative permittivity is about $\varepsilon_r = 50$ for nanocomposite as compared to 8-9.5 in unfilled PGA (Fig. 6). These results are in accordance with the reported increase in the dielectric constant of biodegradable PHBV/PBAT blend with increase in the concentration of MWCNTs, at low frequencies [14], similar to those reported for binary polyvinylidene fluoride/barium titanate nanocomposites [22]. Figure 6 shows the frequency dependent dielectric constant of nanographite filled PGA and unfilled PGA polymer. It is seen that the relative permittivity decreases with frequency because for larger dipoles orienting themselves according to the applied field is difficult and they do not contribute to polarization. The dipoles in the nanocomposites are not able to follow the field variations due to inertia. The polarization due to the charge accumulation will decrease, leading to a decrease in

permittivity [15,16]. To summarise, firstly the increase in dielectric constant can be attributed to the homogeneously and uniformly distributed conductive fillers (which acted as electrodes for thin layer of insulating polymer), secondly polarization of matrix due to segmental motion of molecules (dipoles) and matrix/filler interfacial polarization together contributed to the final permittivity of the composite [17,18]. The results obtained in the present work are in accordance with the reported literature albeit it has been done for their studies on EMI shielding which is conducted at frequencies ~ GHz. For instance, it has been reported that dispersing conductive particles into a polymeric matrix changes its response to electromagnetic radiation via altering the EM properties of the polymer. Both magnetic permeability (μ) and electric permittivity (ε), as well, of PLA and PBAT nanocomposites loaded with graphene nanoplatelets (GNP) show different responses. While permeability remained unaffected by addition of GNPs, permittivity increased with GNP loading [19]. Consequently, the intrinsic impedance of the matrix decreases, resulting in higher impedance mismatch at the interface and hence higher reflection of the electromagnetic power. In a similar manner, wave velocity in the prepared nanocomposites decreases as the permittivity increases. This improves the radiation absorption capacity of the nanocomposites [19]. For epoxy/ZnO nanocomposites, it was observed that when the filler concentration was high, ε′ and ε″ were higher. However, when the dispersion was inhomogeneous and non-uniform, ε″ was higher [20]. Based on this finding, authors have concluded that lower values of ε″ indicated better dispersion of GNPs in PBAT compared to PLA [19].



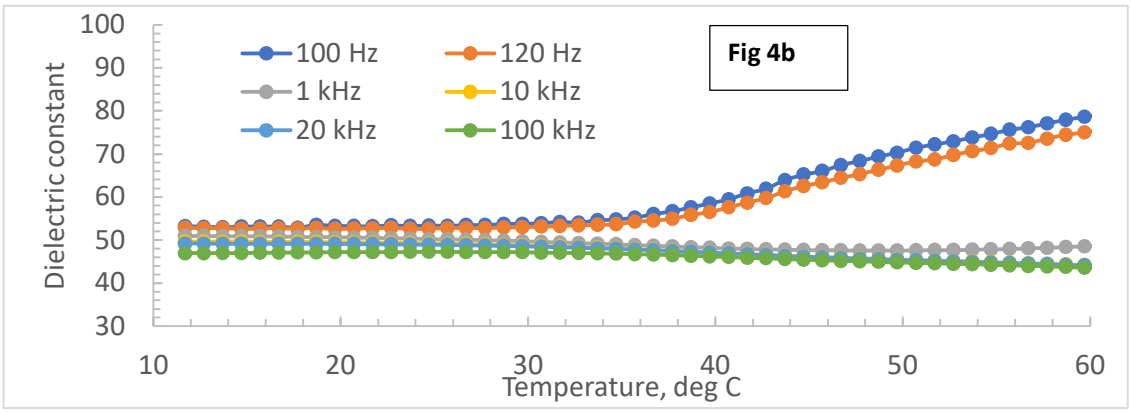


Figure 4: Temperature and frequency dependent dielectric behaviour of nanographite powder filled polyglycerol Adipate composite (a) Dielectric loss (b) Dielectric constant

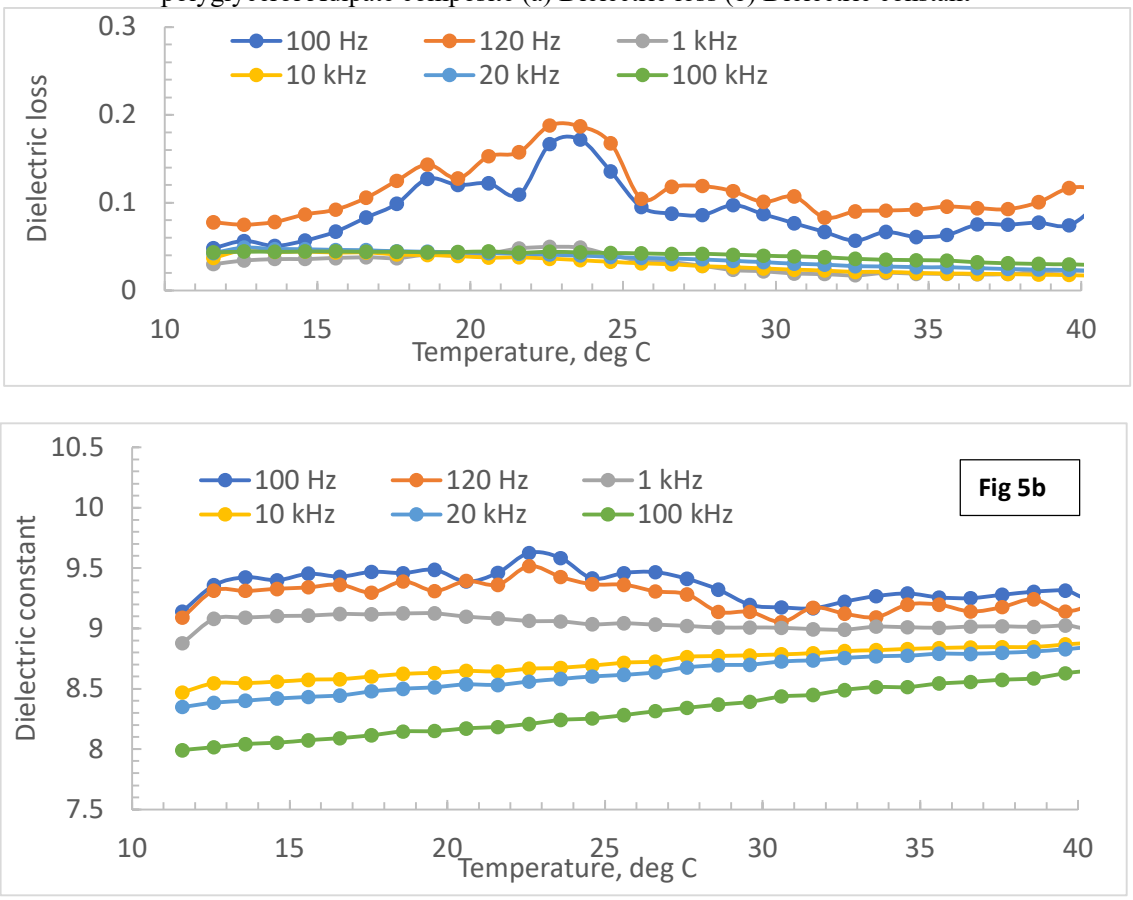


Figure 5: Temperature and Frequency dependent dielectric behaviour of unfilled polyglycerol Adipate polymer (a) Dielectric loss (b) Dielectric constant

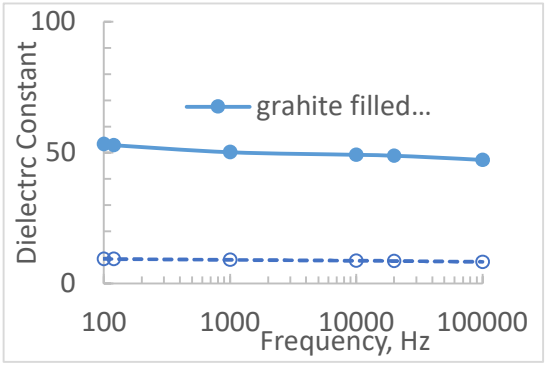


Figure 6: Frequency dependent dielectric behaviour of unfilled and nanographite powder filled polyglycerol Adipate composite at room temperature (25°C)

4.0 Conclusions

Solvent free synthesis of biodegradable polyglycerol adipate polymer is non-toxic and cost-effective. Dielectric characterization of these composites shows that permittivity of biodegradable polyglycerol adipate increases by adding very small amount of nanographite powder. It has been attributed to the fact that the incorporation of conductive nanographite might have increased the number of micro-capacitors and decreased the thickness of insulation between them. Consequently, the capacitance of a single micro-capacitor increased. Since, energy storage devices such as dielectric capacitors require thermal stability, mechanical integrity and good dielectric properties including high dielectric strength, the nanocomposites

explored in the present study seem a promising material for such applications.

Conflict of Interest

Authors declare No conflict of interest

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Accelerating Julia Script Execution via Persistent JIT Warm-Up

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Abstract

Julia's just-in-time compilation provides good execution performance but carries a considerable startup latency, commonly known as the "time-to-first-execution" penalty. This overhead greatly diminishes the performance of brief-running routines and interactive pipelines. In this work, we present a new persistent daemon-client system designed to solve Julia's startup latency problem by pre-compiling and storing frequently used libraries. The daemon process continuously runs in the background to do the heavy lifting of compilation so that the subsequent Julia routines (clients) may use the precompiled code rather than compiling it all over again. Our design and implementation of this system are presented, and performance results demonstrate up to a 98% improvement in execution latency for routines that use a high load of external packages. Such a technique greatly enhances the use of Julia in rapid prototype work, data analysis tasks, and other use cases in which startup must be quick. In this revised version, we describe the latency problem and our solution using clearer terms: time-to-first-execution (TTFX), native-code caching, and inter-process transport. We also quantify the effects with average benchmarks and ensure reproducibility.

Keywords— Julia; just-in-time compilation; startup cost; daemon-client system; performance optimization; first-exec

I. Introduction

Julia is an open-source, high-level programming language designed to close the gap between ease of use for users and high performance. While conventional scripting languages like Python or R prefer ease of use but forgo speed in the process, Julia harnesses the power of just-in-time (JIT) compilation to provide performance equivalent to low-level languages C and C++ at runtime[1]. The combination of ease and speed makes Julia particularly compelling for scientific computation, data analysis, and machine learning when both productivity for developers and execution performance matter.

In spite of these benefits, Julia has a significant startup latency, also known as the time-to-first-execution (TTFX) problem. This is because Julia compiles functions at runtime instead of depending on pre-compiled executables. Consequently, even very simple Julia programs can have appreciable latency on first execution, as the Julia runtime has to compile the required code. In interactive usage or in the case of very brief-lived scripts, the cost of compilation dominates execution duration to the detriment of the speed of development cycles as well as efficiency in the case of quick prototyping. Other languages such as Python tend to bypass these latencies using pre-compiled libraries but since Julia prioritizes runtime optimization, each new session tends to redo work in compilation from scratch.

To solve this problem, we suggest a daemon-client architecture that amortizes the cost of compilation in multiple runs. The fundamental concept is to have an always-running Julia daemon process pre-load and pre-compile frequently used packages. User scripts are subsequently run by a light client that communicates with the daemon. Since the daemon persists in memory with a "warm" JIT compiler, subsequent Julia scripts are able to skip unnecessary compilation and initialization steps. In essence, the framework sacrifices added memory usage (for daemon persistence) in exchange for dramatically reduced startup time upon each script execution. The remainder of the paper discusses related work to minimize startup latency, reviews the construction of our framework, discusses experimental results, and concludes the impact of this technique on the usability of Julia.

II. Related Work

JIT compilation is core to Julia's performance and design but tends to incur runtime latency when the program starts up. Existing studies have examined the problem of dynamic compilation in high-level languages and the techniques to minimize the latency. For instance, Innes et al.[2] discuss the problem with JIT compilation in dynamic languages and the related latency. Nielsen et al.[4] also outline techniques to speed up the startup of scripting language interpreters. These papers point out that although JIT might optimize for long-running computations, it might slow down even for computations that are very short.

Persistent daemon processes have also been explored in other fields as a mechanism for bypassing the startup costs of repeated initialization. Dawson-Haggerty et al.[3] discuss an approach in which a running server process pre-compiles frequently-used libraries to save startup time. The philosophy involved in this case mirrors that found in persistent service-oriented architectures in the field of web technology (for example, FastCGI), in which having a server running saves the cost of forking a new process for each request. Such strategies in other areas support the concept that the reuse of a pre-

initialized execution context saves a considerable amount of setup time[5].

In the case of Julia, our work contributes to the increasing attention for JIT warm-up strategies and persistent process models to enhance interactive performance. JuliaDaemon (our system, presented in this paper) extends the thinking in existing tools and proposals in the Julia ecosystem for addressing the TTFX problem. There have also been some explorations of leveraging light client programs in other languages to control a persistent Julia process. For example, Molina's Juliaclient in the Nim language was a compiled client that was intended to communicate with a long-running Julia server in order to avoid the cost of starting the entire Julia runtime for every use[6].

```
julia> using Pkg
julia> Pkg.add("DaemonMode")
```

Lastly, it should be appreciated that the incentive of our approach comes in part through the needs of popular Julia libraries. Libraries that are data-centric in nature like DataFrames.jl[7] and CSV.jl[8] have very powerful capabilities but increase the startup cost of a Julia session by a considerable amount. Libraries for better logging and debugging (e.g., Crayons.jl[9], LoggingExtras.jl[10]) are also utilized for enhancing the developer experience. The extensive usage of these packages implies that a solution that caches their compiled form has generalizability. Our approach of a persistent daemon serves this by keeping these libraries in the loaded and compiled state across multiple invocations. The recent interest in such JIT warm-up techniques highlights the significance of our contribution towards enhancing Julia's interactive use.

III. Proposed Method

The solution the authors propose involves a daemon-client system that has a continuously running Julia process in the background to accept execution requests. The system has two parts: (1) a daemon server that starts only once but remains permanently activated in the background; it preloads chosen libraries and has a warm JIT-compiled status; and (2) a client interface that forwards user commands or scripts to the daemon to run. With this system, all new scripts have access to use the already-initialized environment, which greatly minimizes their startup times.

Framework Deployment: We deployed the daemon–client system using the open-source package DaemonMode.jl[15] hosted in Julia's package repository. It is very easy to install the framework. First of all, the DaemonMode package is installed using Julia's package manager:

Listing 1. Installing the DaemonMode package

Next, a dedicated Julia daemon process is started (for example, as a separate terminal process). This daemon preloads libraries and listens for incoming execution requests. The daemon can be launched with an invocation like:

```
$ julia -t auto -e 'using DaemonMode;
```

Listing 2. Starting the Julia daemon server process

In the above command, -t auto instructs Julia to use all threads that are available to it, and the serve() function (supplied by DaemonMode) starts the daemon service. For ease of use, you can encase this command within a shell script or alias (for example, an alias called juliaserver) in order to readily start the background server as desired.

Once the daemon has started, user scripts are run using a light-weight client command rather than invoking Julia directly. For

instance, rather than using the typical command to run a Julia script:

```
$ jclient program.jl [arguments...]
```

(Typical direct execution of a Julia script)

the user would invoke:

```
$ julia program.jl [arguments...]
```

Listing 3. Executing a Julia script via the daemon client

Here, jclient is a simple wrapper (which can be a bash script or function) that forwards the script to the waiting daemon. One way to implement jclient is as follows:

```
#!/usr/bin/env bash

julia -e 'using DaemonMode; runargs()' $*
```

Listing 4. Shell wrapper for the Julia client execution

This client script executes the specified Julia script (and any command-line arguments) using DaemonMode's runargs() function. Behind the scenes, the daemon communicates with the client through inter-process communication (sockets), which enables the script to run in the context of the existing Julia session.

With this daemon-client mechanism, the process for execution of Julia scripts reduces to: initialize the server once and for all, then use the client for the execution in the future. The initialization of a given script for the first execution on the newly launched daemon still involves compilation but has the compiled version cached in the memory for reuse. Multiple consecutive executions of the same script or other scripts that have the same libraries will have almost immediate execution since the initialization effort has already been taken care of by the daemon.

Usage and Features: The existing implementation presumes that both daemon and client reside on the same host machine. Supporting a remote execution mode in which the daemon might run on a separate server or cluster node is a possible direction for future work. Serving multiple clients in parallel is already supported by the system. That is to say that the daemon accepts parallel execution requests from multiple invocations of clients. It does that by either forking extra Julia threads or tasks for handling multiple scripts in parallel. It implies that the users are able to have some degree of parallel speed-up by running independent scripts in parallel but still only using the single persistent Julia process.

It should also be noted that our daemon is compatible with the conventional Julia project environment system. The daemon can respect a project environment that users have specified (by using the JULIA_PROJECT environment variable or the right command-line flags), and it will use that environment when compiling and running the code. This enables the daemon to serve multiple projects without interference by starting a separate daemon process for each or changing environments as set.

In conclusion, the suggested persistent JIT warm-up system involves little workflow change for users (a single daemon startup and invoking a new command to execute scripts) but provides significant performance improvement in execution times for repeated use. We now discuss the performance benefit realized through this approach.

IV. Experimental Results

To compare the performance of the persistent daemon–client approach, a series of tests was carried out. All tests were done on a system running Ubuntu 20.04 with an Intel Core i5 processor (quad-core) and 8 GB of RAM. Julia version 1.6.1 was utilized to test and the daemon mode framework version v0.1.9.

Benchmark Scripts: We have written four typical Julia scripts to benchmark various scenarios, based on typical use-cases:

- **hello:** A minimal script that only prints a greeting (no external libraries).
- **slow:** An intensive computation script that carries out a big sort and other activities (high CPU use without external libraries).
- **long:** A script that generates deep output and has intentional latency using sleep (mimicking I/O or waiting).
- **DS:** A data science focused version that loads external packages (DataFrames.jl and CSV.jl) to import and process data (heavy package load on startup).

For completeness, the source code for all the benchmarks appears in Figures 1–4. Each script was run under a variety of different conditions for the purposes of measuring performance:

- **Direct Julia execution:** Using the standard julia command to run the script in a new Julia process (base case, pays the full cost of compilation).
- **Daemon (initial run):** Executing the script via the daemon client when the daemon has only recently started (meaning the necessary libraries will be compiled on the fly as part of this first execution).
- **Daemon (next run):** Re-running the script (or another script with the same libraries) through the daemon so that much of the compilation has already been performed in the previous run.
- **Binary client:** Executing the script through a standalone compiled client application (in our example, an experimental client built using Nim) that communicates to the Julia daemon. We separate the first execution using the binary client (which still compiles any not-previously-compiled code in the daemon as before) and repeated execution using the binary client (which eliminates Julia startup costs on the client end altogether).

To avoid ambiguity, we define these modes of execution below:

- **Julia (Direct):** Direct execution in a new Julia process without daemon.
- **Julia Client (First):** Execution through the Julia daemon client for a new daemon or for the first run of a script that hasn't run previously (includes first-time compilation within daemon).
- **Julia Client (Next):** Execution through the Julia daemon client for a script already run priorly (or whose libraries are already precompiled within the daemon) – i.e., a warmed-up subsequent run.
- **Binary Client:** Execution through a compiled external client calling the daemon. We will provide distinct timings for the first execution using the binary client and the second execution using the binary client (once the daemon is warmed and the binary client is loaded).

In these modes, we first demonstrate the dramatic improvement the daemon facilitates with a single attempt and next explore averaged performance across multiple attempts.

Single-run Performance: Table I summarizes a comparison of execution times in seconds for all four benchmark scripts for various execution modes. Here "Direct Julia" refers to the baseline without the use of a daemon, "First Client" and "Subsequent Client" refer to execution using our framework (a first run vs. a repeated run), and "Binary Client" here describes invoking the external binary client for the first time.

Table I – Processing Time Comparison (in seconds)

Script	Direct Julia	First Client	Subsequent Client	Binary Client
hello	0.1592	0.6886	0.6682	0.5982
slow	6.8312	7.9260	7.1680	7.3196
long	4.1694	4.5462	4.4853	4.4720
DS	16.4286	16.2308	0.6902	15.4728

As shown in Table I, using the persistent daemon yields **dramatic speed-ups for package-heavy workloads**. For the **DS script** (which relies on CSV and DataFrames), the first run via the daemon is as slow as direct execution (about 16.2 s) because the daemon must compile those packages. However, the *subsequent run* of the DS script finishes in just 0.69 s, compared to 16.43 s when run directly – a **97% reduction in runtime**. In this case, almost the entire overhead was eliminated by reusing the cached package code. Lighter scripts benefit less: for **hello**, which does almost nothing, the overhead of going through the daemon (about 0.67 s on second run) is slightly higher than the direct run (0.16 s), because the daemon itself adds a small constant overhead. Compute-bound scripts like **slow** (no external libraries) showed roughly the same performance with or without the daemon once compilation was done (~7.17 s vs 6.83 s), since their runtime is dominated by actual computation. The **long** script, which prints a lot of output and sleeps deliberately, also showed similar times (~4.48 s) in all scenarios because its behavior is dominated by I/O and delays rather than compilation. The **binary client** in this initial test did not show an advantage on first run—its times were comparable to direct Julia for these scripts, since in this scenario the binary client's first invocation triggers the same compilation work in the daemon.

Averaged Results: To get more robust measurements, we executed each scenario five times and computed the average execution times. Table II summarizes the **average runtime** for each script under each execution mode, using the terminology defined above.

Table II – Average Processing Times over 5 Runs (seconds)

Method	hello	slow	long	DS
Julia (Direct)	0.1592	6.8312	4.1694	16.4286
Julia Client (First)	0.6886	7.9260	4.5462	16.2308
Julia Client (Next)	0.6682	7.1680	4.4853	0.6902
Binary Client (First)	0.5982	7.3196	4.4720	15.4728
Binary Client (Next)	0.0130	6.5080	3.5978	0.0410

The single-run comparison trends are supported by the data presented in Table II. The biggest performance improvements our

framework provides however are for scripts that load large external packages (e.g., DS). Once the daemon is warmed up, execution time of the DS script drops from around 16.4 s (direct) to 0.69 s (Julia Client Next for the most part). That is, the script will run in just ~4% of the time it would take, were it not for the framework. Indeed, the startup time for the DS script is reduced to 0.04 s on average for subsequent runs if the compiled binary client is reused, effectively eliminating the overhead of both workers' java processes startup, for that script. It shows that there is room for a tailored client in a compiled language to eke out a little bit more performance than the (minuscule) overhead added by the Julia client interface.

There's obviously less gain from the daemon for heavy-I/O-bound or compute-bound scripts like slow or long that don't spend a lot of time loading packages. For slow, the direct run (6.83 s) as compared to a subsequent daemon run (7.17 s) differ by around 5%, meaning that the daemon does not slow computation too much (the heavy computation is not slowed but neither is it speed up as there is not much compilation overhead to amortize). The 4.4 s per case and the relatively small change (hardly any) of the long script being loaded is consistent with what would be expected. Crucially for running these kinds of things, binary client already performs as fast as/ the same order of magnitude as direct execution (eg, hello runs in ~0.013 s with Binary Client Next, basically that's nothing, and is faster than the usual 0.1–0.2 s startup for Julia itself). This indicates that the binary client is able to effectively bypass the Julia startup overhead, which can be beneficial for extremely short scripts.

In conclusion, the long-lived JIT warmup infrastructure works best for package-heavy scripts (reducing a multi-second pause to a sub-second one), and is roughly on par with native Julia for other types of workloads. Overall, there is little performance overhead (at worst a few hundred milliseconds for trivial workloads, and at best performance is improved, in some cases by two orders of magnitude, with library-heavy workloads), due to the use of the daemon after the first run. These results illustrate that despite its initial issues, our approach does solve Julia's TTFX problem and increases its adoptability for use cases with a fast startup requirement.

V. Technical Details

The architecture of our persistent daemon–client framework involves several technical considerations to ensure it functions correctly and efficiently. Key technical aspects include:

- **Inter-Process Communication:** The client and daemon communicate through a socket-based protocol. When the client forwards a script to the daemon, it pipes the content of a script (or a file path and some arguments) through a TCP socket. A special end-of-data marker is sent to inform the daemon that it is finished receiving the script (or command). This way the daemon can tell when it has the complete input and it can already try to execute it for you. The daemon responds, returning the result (standard out, standard error and an exit code) down the same connection. An exist status of 0 means that the script ran to completion without issue, whereas a non-zero status (or a Magic Number) means that the script exited because of an exception or other user-invoked halt.
- **Error Handling and Logging:** The daemon is designed to have strong error handling implemented, so as to be able to catch a failing script, without the server crashing. If the daemon runs a script that raises an exception, the exception is

caught and we try to pretty-print the error message to make it as close as possible to a real julia session run script error message. We rely on sophisticated logging tools such as LoggingExtras.[10] Crayons (I have jl with custom formatter) and the Crayons. Jl[9] package to color warnings and errors. Crucially, stack traces are whitelisted to remove internal calls on the part of the daemon framework, so the user gets a clean traceback of only their own code. A flexible logging system has been built into the framework: logging messages can be printed to the standard output or saved to an external log file, all depending on user choice. Both output modes have been tested to work reliably and are very helpful to trace back daemon executions or to watch them in real-time as they happen.

- **Parallel Execution Support:** The daemon could accommodate many client requests running simultaneously with very low performance degradation. This is accomplished by making use of Julia's built-in parallelism: the server can create asynchronous tasks or work on multiple threads, in order to handle incoming connections concurrently. For example, if two clients submit scripts very close to each other, the daemon will establish two socket connections and each of them executes the script in a separate Julia task (or thread, if enabled). This design is nice in that long-running scripts won't prevent the daemon from engaging its work on another incoming script. Synchronization ensures shared resources are coordinated between threads when the daemon waits for all spawned activities to complete before exiting.
- **Environment Management:** Julia's package environments are respected, providing reproducibility across projects. The daemon can be started with a particular project environment that is, it will use the collection of package versions specified for that project. The other, more secure option is for the client to inject the environment with a custom program when it sends the script. In practice this means that if a user has multiple Julia projects but are free to spawn a daemon per env or ask the client to tell it which env to load for a particular execution. This feature guarantees the daemon does not introduce a way to make your results non reproducible: scripts are launched with the same library versions if the job had been running in a normal (non daemon) state (if the daemon is correctly managing the environment).

These technical capabilities make a solid system overall. Inter process communication is used to ensure that the communication between the client and server are reliable; parallel execution enables the daemon to be efficient in multi user / process environments; error handling ensures users have a similar experience to running normal Julia code; and environment management makes sure that Julia s package system behaves as desired.

It should be stressed that our approach does not involve any change to Julia's compiler and internals – it works purely on user level with public APIs and packages. So it's easy to install and use with your standard Julia setup.

VI. Conclusion

We have described a persistent daemon–client architecture for Julia, which serves to largely mitigate JIT compilation overhead at startup time. Our solution is to cache the pre-compiled code in a running daemon process so that subsequent Julia scripts can come up faster. By performing benchmarks, we observe some impressive enhancements: especially for script relying so heavily on

external packages, running time can be reduced to only a couple of percent of the initial values by employing the framework. For computationally or I/O-bounded tasks, the overhead added by the framework is minimal, if not null, so users do not pay an overhead penalty for following this path.

This dynamic warm-up procedure makes Julia much more practical for cases that require running frequent short executions, e.g. interactive data analysis, scripting, and rapid prototyping. By using the daemon–client model, Julia provides immediacy after the first run where it competes on power usage with faster-to-start interpreted languages (e.g., Python), yet still offers Julia's performance for long calculations.

In conclusion, we have presented a framework where we solve one of the most frequently cited Julia pain points (the TTFX latency) by making one-time compilation work in order to have faster on-the-fly execution. The end result is a more frictionless workflow for developers and researchers. In future work, there is potential to expand this model to distributed scenarios (such as running the Julia daemon on a server/cluster and connecting to it remotely), and to improve the client-side implementation (including shipping official binary clients for common platforms). Even so, the naive JIT warm-up strategy already seems like a substantial incremental step toward turning Julia into a more interactive tool for day-to-day number crunching.

VII. Future Work

One significant direction is scaling the solution for distributed operation, allowing multiple nodes to share in common a pre-compiled code cache and hence deriving the same startup latency benefits from clustered or multi-node workflows. A further direction would be enhancing compatibility with cloud environments (e.g., containerized or serverless workflow), so that transient compute instances can also derive advantage from permanent JIT caches in the presence of frequent restarts. Yet another significant emphasis would be to enhance the security of the daemon–client architecture through the addition of robust isolation and access controls to guard against unauthorised injection of malicious code or unauthorised entry to the long-running task. Support for other client languages or interfaces needs to be extended, expanding the framework's reach and enabling varied programming environments to take advantage of Julia's performance-optimized warm-up through cross-language support. All these would make the framework more scalable, secure, and multifaceted, further enabling it for use in more real-world applications.

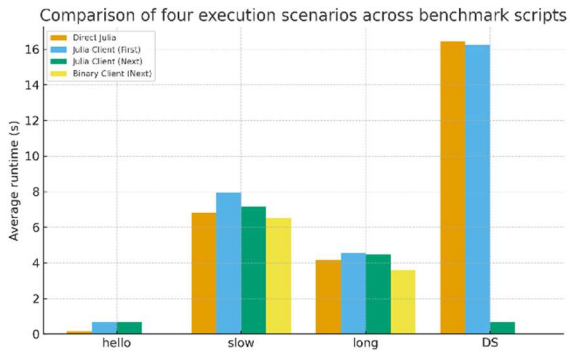

Figure 1. Comparison of average runtimes for four execution scenarios—Direct Julia, Julia Client (First), Julia Client (Next), and Binary Client (Next)—across all benchmark scripts.

Recent releases of Julia (e.g., 1.9[11][16]) introduced native code caching and formalized precompilation workflows that directly target latency reduction. Tooling such as PrecompileTools.jl[12] and SnoopCompile.jl[14] enable package authors and users to record representative workloads and materialize precompile statements; PackageCompiler.jl[13] can build custom sysimages to eliminate a portion of TTFX for specific environments. These ecosystem advances are complementary to our persistent

daemon approach because they reduce compilation within a process, whereas the daemon amortizes process initialization across invocations [11]–[14].

In the distributed setting, a practical option is to persist and share native-code caches across nodes via content-addressed artifacts and to coordinate invalidations; the architectural pattern is akin to process-per-request servers that keep warmed workers alive (e.g., FastCGI-style longevity), while preserving per-tenant isolation [19].

Conflict of Interest

There is no conflict to declare.

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Predictive Traffic Accident Warning System for Smart Cities: Enhancing Urban Safety with Data-Driven Insights

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Abstract

This paper introduces a predictive traffic accident warning system tailored for smart city applications, aiming to improve urban safety through advanced data analysis and contextual reporting. The proposed system employs computationally efficient algorithms to predict the severity of traffic accidents with high accuracy while maintaining robust data privacy standards. By integrating real-time traffic data with external knowledge sources, it generates detailed, actionable reports and timely warnings, enabling proactive decision-making. The system's design emphasizes effective task orchestration for seamless integration with existing urban infrastructure and optimized resource management. Evaluation results demonstrate the system's high accuracy, scalability, and practical viability in smart city environments. Future research will focus on enhancing model efficiency, leveraging transfer learning for cross-domain adaptability, and deploying real-world implementations to vali- date the system's performance.

I. INTRODUCTION

By 2050, over two-thirds of the global population is projected to live in urban areas [1]. Urbanization, driven by population growth and migration towards cities, presents both opportunities and challenges such as overpopulation and traffic congestion [2]. Developing smart cities is a strategic approach to mitigate these challenges. A ”smart city” integrates information and communication technology to enhance urban living [3]. This concept emphasizes the interconnection of com- munity, people, and technology, aiming to prioritize human needs [4]. Urban mobility and transportation are significant challenges, with traffic congestion and accidents being major concerns. Annually, traffic accidents result in 1.35 million deaths globally, underscoring the critical need for effective accident prevention measures [5]. In large-scale Internet of Things (IoT) ecosystems, efficient data processing is crucial. Centralized cloud servers face latency and security challenges for many application domains, making real-time processing difficult [6]. Edge computing aims to address these limitations by bringing computational resources closer to data sources, enabling timely processing and reducing latency [7, 8]. When edge computing is integrated with AI, known as EdgeAI, real-time urban decision-making could be facilitated [9, 10]. For example, models trained to predict road weather [11, 12] or traffic congestion can operate on edge devices located closer to the sites, providing immediate insights to traffic management systems. Nonetheless, due to the resource constraints of edge devices, certain computationally intensive tasks might still be offloaded to the cloud or other powerful nodes within the city network. That approach requires loosely-coupled architectures and distributed algorithms [13, 14]. A lot of research proposes AI support for smart transportation systems from various perspectives. For example, Bortnikov et al. [15] detect accidents by training a 3D Convolutional Network on the data generated by a video game, Uma and Eswar’s [16] develop yawning detection of the drivers, Liu et al [17] concentrate on traffic flow prediction. However, the majority of related work focuses on a single type of AI module specifically developed for the task at hand, neglecting the capabilities of integrating their approach with other kinds of AI modules to create a more comprehensive support system. Additionally, response time is often overlooked in the assessment of related work, with a primary focus on accuracy. To our knowledge, no existing work incorporates multiple types of AI modules, raising questions about the integration and applicability of these separate modules into a cohesive framework. To address these gaps, we present our integrated system, containing two AI modules: first, Federated Learning (FL) [18] model to predict traffic accident occurrences and estimate severity and second, Generative Artificial intelligence (GenAI) to generate reports and warnings. Moreover, we utilized k0s, a lightweight Kubernetes distribution, for efficient task orchestration [19]. The task orchestration capabilities of k0s are crucial for seam- Lesly integrating the FL models and Retrieval-Augmented Generation (RAG) processes across multiple edge nodes. This enables automated deployment, scaling, and management of tasks, ensuring high availability, fault tolerance, and robust performance monitoring for our accident prevention warning system. The contributions of this work can be summarized as follows:

1) We integrate two different kinds of AI modules into a coherent distributed system supporting accident prevention. We comprehensively evaluate this system and analyze the related challenges and opportunities.

2) We orchestrate tasks and monitor our system, examining its feasibility for real-world smart city environments.

The remainder of this article is organized as follows. sec related work discusses related work, while sec:design de- scribes the system design, and sec:implementation details the implementation. sec:eval then provides a detailed system evaluation and metrics, sec:discuss future discusses our findings, implications, and future research directions, and sec:conclusion concludes the work.

II Related Work

A. *Intelligent Transportation System in Smart City*

Intelligent Transportation Systems (ITS) are essential for the advancement of smart cities, with many recent studies dedicated to improving urban traffic management and safety. Here, we discuss several key works that have made significant contributions to this field. As an example, Hasan et al. [20] used the Google Distance Matrix and Directions APIs to provide advanced traffic jam alerts. Their Internet of Vehicles (IoV) module detects accidents and, with the assistance of the National Data Warehouse and a GPS module, notifies the nearest clinic. They developed an Android application for routing suggestions and employed an Arduino with a Sonar sensor, temperature sensor, gyroscope, piezo sensor, and GSM module as the core processing unit. Working on one of the most trendy applications, Bortnikov et al. [15] developed a 3D Convolutional Neural Network (CNN) to recognize accidents automatically. They trained the CNN using a custom video game to create accident scenes with various weather and lighting conditions, adding noise to diversify the data. The model was then tested on real traffic videos from YouTube. The novelty of this research lies in the use of video games to generate datasets, which are challenging to replicate in real-life scenarios. Yu et al. [21], with the same aim, proposed a Deep Spatio-Temporal Graph Convolutional Network for traffic accident prediction for Beijing traffic data, which was collected hourly over three months and includes accident records (time and location), vehicle speeds, meteorological conditions and points of interest. Recent research has considered informing other vehicles after detecting traffic accidents using IoT, IoV, and related technologies. Zhou et al. [22] proposed an accident detection algorithm based on spatiotemporal feature encoding with a multilayer neural network. This method first detects border frames as potential accident frames, then encodes the spatial relationships of detected objects to confirm an accident. The process involves using Histogram of Oriented Gradients and ordinal features initially, followed by CNN feature encoding and object relationship detection with a multilayer neural network. A trained Support Vector Machine then confirms the presence of an accident. Another approach involves efforts to reduce accidents before they occur is the work of Uma and Eswari [16], which developed a prototype using a Raspberry Pi and Pi Camera, along with sensors to monitor driver's eye movements, detect yawning, and identify toxic gases and alcohol consumption. This system, employing the Haar Cascade algorithm for face detection and calculation of Eye Aspect Ratio and Mouth Aspect Ratio, estimates risk through these feature analysis. Besides, to identify accident hot spots, Le et al. [23] used Road Traffic Accident data over three years in Hanoi, Vietnam, to develop a GIS- based statistical analysis technique. This method assesses the influence of accident severity on temporal spatial patterns, identifying accident hotspots in relation to specific times of day and seasons. Beyond the mention in [24] of the potential service supports of cloud to autonomous vehicles applications, edge

computing is playing a pivotal role in reshaping traffic management in smart cities. Within this domain, Mohamed's [25] and Zhou's research groups [26] demonstrated substantial improvements in traffic management and reduced congestion durations through an edge-based model for real-time traffic data analysis. Besides, to achieve low latency and high pre- diction accuracy on vehicle identification at the edge, Wan et.al [27] have eliminated redundant frames from collected videos and presented an approach for real-time video processing. In a similar manner, Ke et al. [28] developed a multithread system for real-time detection of near-crash events in traffic, using video analytics on dashcams. Leveraging edge power, their system efficiently performs object detection and tracking directly from the video feeds on board. This approach involves removing irrelevant video to conserve bandwidth and storage while collecting diverse and valuable data for traffic safety such as road user type, vehicle trajectory, vehicle speed, brake switch, and throttle. The approach from Ke et al. demonstrates considerable promise for widespread application due to its low cost, real-time processing, high accuracy, and broad compatibility with various vehicles and camera types. Additionally, a recent work by Nguyen et al. [29] utilized Blockchain technology alongside edge computing to develop a reliable and transparent situational awareness system for autonomous vehicles. Their system broadcasts notifications and alternative route suggestions from the nearest edge station when congestion or accidents are detected by other vehicles, using various sensing data sources, including dashcam images and environmental factors like weather, temperature, and humidity. The use of Blockchain in their study ensures the data validity and integrity, as well as facilitates collaboration among different service providers. However, despite the recognized vision and applications, Zhou et al. [30] emphasized that employing edge computing in ITS always comes with inherent challenges related to sensor failure, and privacy protection concerns, which must be addressed for effective implementation.

B. FL in ITS

Building on the challenges identified by Zhou et al. [30] particularly concerning privacy protection, FL recently has been used more in smart cities. Amongst many applied domains within urban environments, the extension of FL applications in traffic systems is mostly leveraged for traffic monitoring and accident predictions. FedGRU - FL-based Gated Recurrent Unit (GRU) neural network [17] is one of the pioneering works for traffic flow prediction (TFP) with federated deep learning that comparably performs to other advanced competing methods without compromising the privacy and security of data. Additionally, as proved by experiments, the joint announcement protocol proposed in this paper helps in reducing communication overhead by 64.10% compared with centralized models, implicating the scalability of FedGRU for bigger networks. With the same motivation to address the privacy exposure risk of centralized machine learning, Qi et al. [31] presented a fully decentralized FL network, utilizing a Blockchain-based FL architecture as opposed to the conventional vanilla framework. The authors employed the local differential privacy technique to protect vehicle location and utilized GRU to achieve accurate TFP. Performance and security comparisons were also made among different machine learning models and with/without the use of blockchain. Qi et al. also conducted comparative analyses in terms of both performance and security, examining various machine learning models and contrasting scenarios with and without blockchain

implementation. Concerning the monitoring of traffic congestion, typical systems begin by detecting vehicles and subsequently estimating traffic flow density. In their research, Xu et al. [32] employed remote sensing images for this purpose, while Chougule et al. [33] continuously used the estimated traffic density from intersection-captured images to dynamically adjust the duration of green light and schedule the timing of signals across all lanes. As one of the highlights in the narrow field of applying FL on ITS: risk detection, Yuan et al. [34] introduced FedRD, a framework combining edge-cloud computing, FL, and differential privacy techniques for intelligent road damage detection and warning. The framework not only improves detection performance and coverage area but also addresses privacy concerns through Individualized Differential Privacy with pixelization technique. Comprehensive evaluations demonstrate FedRD's capability to deliver high detection accuracy and wider coverage while preserving user privacy, even in scenarios where edge devices have limited data. This groundbreaking effectiveness sets a new benchmark in the field.

C. *GenAI in ITS*

Recently, GenAI has garnered significant attention in several applications, including ITS, due to its advantages and flexibility. By analyzing data from various sources, such as roadside sensors, vehicles, and traffic signals, GenAI enhances urban operations by detecting patterns, identifying trends, and providing accurate predictions and advice. With the leverage of natural language processing, GenAI can present these predictions in human-understandable language, making these technologies more accessible and practical for smart services [35]. See prior works [36, 37] for examples of how GenAI integrated into many services within cities. As another example in ITS, Impedovo et al. [38] propose a deep generative model to predict weekday vehicular traffic flow to prevent accidents in the most critical areas and improve continuity by reducing traffic. More notably, RAG, first introduced by Lewis et al. in 2020 [39]l, stood out as a part of this GenAI world, representing a distinct approach to generating text, informed reasoning, and supporting decision-making. Its application in ITS is not popular, however, there are some notable works. For instance, Dai et al. [40] integrated RAG into autonomous driving systems to enhance decision- making processes. According to the authors, the use of RAG in their work addresses the problem of impractical generated content from the mainstream foundation models nowadays, such as GPT4 or LLaMa. It helps these models enhance the reliability of their outputs during the generation phase by dynamically retrieving accurate contextual information from outer databases (e.g. updated traffic rules, driving experiences, or human preference). Similarly, Ding et al. [41] utilized RAG for more controlled generation of traffic scenarios. Specifically, RealGen [41] synthesizes new scenarios by combining behaviors from multiple retrieved examples in a gradient free manner, using templates or tagged scenarios. This in-context learning framework provides versatile generative capabilities, including scenario editing, behavior composition, and the creation of critical scenarios, thus enhancing the adaptability and precision of synthetic data generation for various applications. Most recently, in his Master's thesis, Mohanan [42] evaluated eight embedding RAG models for a chatbot tailored to Indian Motor Vehicle Law. As can be seen, prior research typically focuses on a single module, such as risk estimation or warning generation, limiting possible support for ITS. This raises an open question: "Is it possible to integrate all diverse components into a

cohesive and comprehensive ITS framework?" This is where our work positions.

II. System Design

This article presents a system for predicting and preventing traffic accidents. It is capable of predicting the possible accidents based on the traffic conditions and other available data, and provides detailed textual comments to the user explaining the grounds leading to

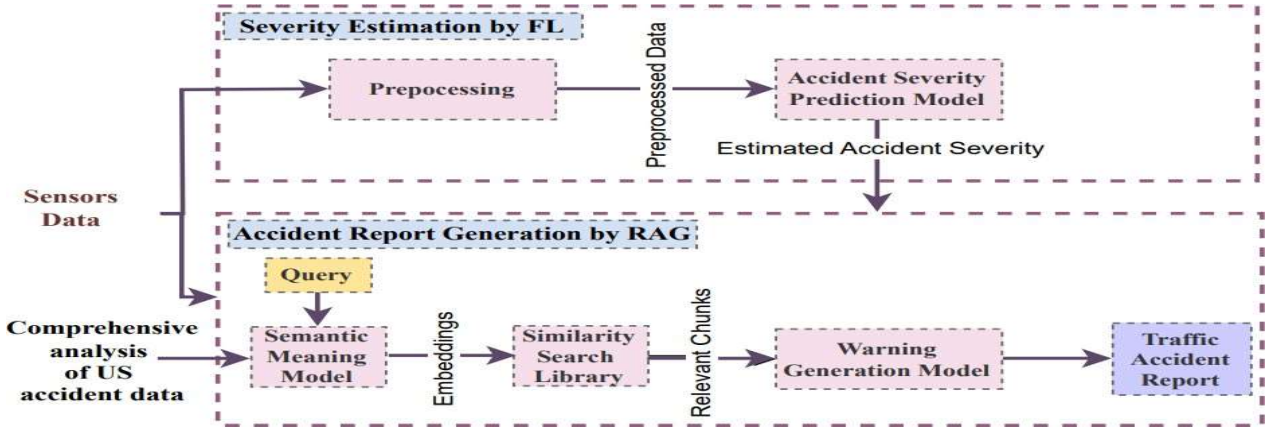

Fig. 1. System workflow. This figure illustrates the key components of the core system, Federated Learning (FL) and Retrieval-Augmented Generation (RAG). Using preprocessed weather and road traffic sensors, FL predicts accident severity. Within the RAG framework, the Semantic Meaning Model creates embeddings for documents and queries. The Similarity Search Library selects the most relevant document chunks based on similarity. Finally, the Warning Generation Model generates a traffic accident report that incorporates data analysis and future recommendations.

such estimation. Figure 1 illustrates the overall system flow, highlighting the interplay between the key components: Federated Learning (FL) and Retrieval-Augmented Generation (RAG). This integrated system combines the strengths of RAG and FL to ensure high- quality outputs while maintaining data privacy and relevance. FL enhances the accident severity prediction model while maintaining data privacy. The RAG system uses integration between the warning generation model and the knowledge retrieval model to enhance the generation process with relevant external data, improving context and accuracy. Our training approach starts from data preprocessing. The preprocessed dataset is then used to train the FL model for traffic accident risk estimation. The predictions, along with the sensors' real-time data, are utilized as input for the RAG model. The RAG model integrates advanced retrieval mechanisms with state- of-the-art language generation capabilities to produce detailed warnings and reports for traffic accidents. To efficiently man- age and deploy these components, we use a task orchestration tool. This tool ensures seamless integration and coordination among the various models, automates deployment, and scales the system as needed. Additionally, it facilitates robust performance monitoring, ensuring high availability and fault tolerance across the system.

A. Dataset

This study uses US Accidents (2016-2023) dataset 1 [43] from Kaggle, distributed under CC BY-NC-SA 4.0 license. This dataset comprises a vast collection of over 7.7 million (7,728,394) traffic accident records, covering 49 states of the USA from February 2016 to March 2023. The accident data were collected using multiple APIs that provide

streaming traffic incident data captured by various entities, including the US and state departments of transportation, law enforcement agencies, traffic cameras, and traffic sensors within the road networks. The data includes detailed information on accident severity, location, time, and weather conditions. This dataset was utilized to train the FL models for traffic accident prediction.

B. Federated Learning

Our application relies on FL model for accident risk estimation. FL was selected based on two primary considerations: data privacy and collaborative enhancement.

1) Privacy: Addressing privacy concerns, vehicles in a real scenario do not transmit raw data, which could potentially reveal sensitive information. Instead, only model parameters will be sent, ensuring that individual data remains secure and private. This cannot be done with traditional centralized learning when all data need to be sent to a central server for training.
2) Collaboration: When a vehicle updates and shares its model parameters, it contributes to the overall learning process. This collective effort leads to an improvement in the overall model's performance, as it can learn from a wide range of diverse and localized inputs. The shared knowledge enables more accurate and robust risk estimation.

The training data features provide a detailed view of accident records, including the specifics of the accidents, the geographic locations, the prevailing weather conditions at the time of the accidents, and various environmental and contextual factors that may be relevant to analyzing the accidents. In a real scenario, the vehicle's onboard computing system uses these inputs to continuously update its local model, learning from real data. Once the training is done, the model parameters will be sent to the nearby edge server. The server, after receiving a sufficient amount of models will start doing the aggregation to get the global model, which is then sent back to the participating vehicles. When this whole process is complete, we finish one communication round and continue to the next round.

C. Retrieval-Augmented Generation

RAG combines an information retrieval component with a text generator model to provide situational information and guidance [44]. In the ITS context, RAG can integrate various external data sources to analyze and report traffic accidents, identifying risk factors and details [45]. This makes the system more dynamic and adaptable to new information. In our system, see Figure 1, RAG provides textual accident warnings to the end user, along with explanations of how the estimates were derived. Knowledge retrieval model It is designed to find the most relevant information from an external knowledge base in response to the query. This enhances FL model output and sensor data with relevant information. We use SentenceTransformers2 as a retrieval model based on similarity search. Warning generation model: It is designed to generate new content using language models. It uses the retrieved information by the retrieval model and FL-output details to generate a response. For our system, we use gpt- 3.5-turbo-06133 to create contextually relevant warnings and detailed reports. The accident report includes the severity of the accident, the location and traffic control procedures, and guidance and actions.

C Task Orchestration and Monitoring

Effective resource management and device health monitoring are essential for enhancing

the responsiveness of smart city services. This requires comprehensive system monitoring that spans from edge devices to the cloud. The deployment of applications on edge devices necessitates advanced task orchestration platforms, which must be carefully selected based on specific requirements. Given that edge devices typically have limited resources, the chosen tool must operate smoothly under such constraints. For the proposed system, k0s4 has been selected. We selected k0s because of its minimal resource consumption on edge devices and its straightforward and rapid implementation process, supported by comprehensive docu- mentation and active developer forums. It typically operates with as little as 1 CPU and 512 MB of RAM on each controller node and 1 GB of RAM on each worker node, which aligns well with the capabilities of edge devices. However, the minimum requirements increase when the number of worker nodes is increased. Additionally, numerous monitoring options compatible with k0s are available. k0s is packaged as a single, self-extracting binary which embeds Kubernetes binaries. It has many benefits, such as it has no OS level dependencies and everything can be, and is, statically compiled.

III. System Implementation

A. Risk Estimation with FL

1) Preprocessing: **Preprocessing Phase:** The preprocessing phase for our system includes a series of essential data preparation steps to ensure the quality of the dataset for further analysis.

1) **Data Cleaning:** Duplicated and missing values were removed.
2) **Feature Engineering:** To enhance the informativeness of the dataset, a new feature called *Comfort_Index* is created as defined in Equation (1).

$$\text{Comfort\_Index} = (\text{Temperature} - 32) \times \text{Humidity}/100 \quad (1)$$

3) **Data Resampling:** To address the imbalance issue, both random oversampling and under sampling were applied to ensure equal label distribution.
4) **Data Transformation:** Transformation was conducted based on feature type:
   - **Categorical Data:** One-hot encoding was applied to categorical columns, excluding *Street*, *State*, and the target label *Severity*.
   - **Boolean Data:** Columns with two distinct values were binarized, converting them to 0 and 1.
   - **Numeric Data:** Numeric columns were left un- changed, preserving their original values.
5) **Standardization:** The dataset was standardized using *Standard Scaler* to ensure consistent feature scales and values within a specific range.

FL Training and Prediction: To simulate a real-world scenario using our chosen dataset, we distributed the data across several nodes and established certain assumptions. This section will elaborate on those details. Distribution: The data is divided into five equal parts, corresponding to five nodes in the system. We also make sure the number of samples of each label is distributed equally among clients. Model Training: Each client trains its local model, consisting of three fully connected layers. Training specifications include the use of the cross-entropy loss function, Adam optimizer with a learning rate of 1e-3, and a batch size of 32. After ten training epochs, the locally trained models are aggregated by the server into a global model, and the global parameters are saved at each checkpoint, here at each communication round, before being sent back to the participants for training in the next round. The FL training

process concludes after ten communication rounds. At this stage, various model architectures, encompassing differing layer counts and hyperparameters, were evaluated over 50 communication rounds to observe the trend and convergence in via its performance. The selected model outperformed alternatives; models with reduced layers demonstrated inferior outcomes (3- 4%), while configurations with additional layers, despite a 3% accuracy improvement, incurred prolonged training duration and converged to local, rather than global, optima. See Table 1 for details.

TABLE I COMPARISON OF RISK ESTIMATION MODELS: ACCURACY AND TRAINING TIME

Model	Simple	Chosen	Complex
Accuracy (%)	67.09	71.15	74.42
Training Time (hours)	3.461	4.042	5.603
MAE (%)	32.91	28.85	25.58

B. Warning Generation with RAG

Using the RAG model, we retrieve text passages using an input sequence. During the generation of the target sequence, we include these passages as additional context. Our model leverages two components, which are implemented in LangChain5. A retriever that retrieves relevant text snippets in response to a user's query or prompt based on knowledge source which is uploaded using built-in document loader from LangChain. In our system, we rely on the US traffic accident database as an external knowledge source, containing a comprehensive analysis of US traffic accident data [46]. This report provides insight into preventive measures and policy recommendations for decreasing traffic accidents in the US based on detailed analyses by state, time, and contributing factors such as weather. The retrieval process begins with loading documents using a tool in LangChain. This process is enhanced by a splitter tool, also integrated into LangChain, designed to segment extensive texts into smaller chunks based on a specified chunk size by examining characters recursively which is crucial for the efficient handling of large textual data. For the creation of text embeddings, we employ Hug- ging Face Embeddings, a specialized embedding model from the Hugging Face library6 within LangChain. This model transforms the segmented text chunks into numerical vectors, facilitating their computational handling To store these embed- ding vectors in a vector store, we utilize the FAISS library7 , a robust vector database. It enables effective similarity search by identifying text chunk vectors most similar to the question vector. This process is vital to determine which portions of the knowledge source are most pertinent to the input query. This is for later retrieval at query time based on the k argument which finds the top k most relevant text chunk vectors for each query. Table 2 summarizes the RAG parameters used. The generator creates a more detailed, factual, and relevant response based on the original input and retrieved documents. The original input represents the severity of an accident, derived from the FL output and complemented by sensor real- time data. For the generation of coherent and contextually relevant text, the original input and the retrieved documents are fed into gpt-3.5- turbo-0613, a sophisticated pre-trained language model. Based on the content of these documents, the model generates coherent and contextually relevant text grounded in real-world information. Figure 2 illustrates an example of a traffic accident report generated by RAG.

TABLE II SUMMARY OF RAG PARAMETERS USED

Parameter	Value
Text Splitter Type	RecursiveCharacterTextSplitter
Chat Model	ChatOpenAI
ChatOpenAI Model Name	gpt-3.5-turbo-0613
Vector Store	FAISS
Embeddings Type	HuggingFaceEmbeddings
Embeddings Model Name	sentence-transformers/all-mpnet-base-v2
Search Type	Similarity
Chunk Size	2000

C. Task Orchestration and Monitoring

As discussed in Sub-section 3.4 we opted for k0S, which is ideal for our needs and simple in implementation. We used Lens IDE8 which is a Kubernetes IDE to manage the cluster and monitoring of the whole system. It allows for comprehensive oversight of nodes, pods, and resource monitoring. Monitoring involves tracking the usage of CPU, memory, storage, and network bandwidth, and monitoring device safety and functionality to detect any potential problem. We containerized our application using Docker9 and deployed our application using Lens IDE and k0s task orchestration tool. We used Cluster metrics in the Lens IDE to monitor the resources efficiently

IV. System Evaluation

To assess the system's performance, several key metrics were employed. We want to ensure that all the components work perfectly both independently and in the integrated system. First, we monitored the accuracy of the FL model for risk estimation, assessing its ability to predict traffic accident severity. This evaluation utilized the dataset for training the model. Additionally, the quality and relevance of warnings

TABLE III Traffic Accident Data on US Highway 22, NJ

Parameter	Value
Street	US Highway 22
State	NJ
Start Latitude	40.65562
Start Longitude	-74.40149
Crossing	False
Give Way	False
Junction	False
No Exit	False
Railway	False
Roundabout	False
Station	True
Stop	False
Traffic Calming	False
Traffic Signal	False
Distance (mi)	0.167
Temperature (°F)	56.09
Wind Chill (°F)	72.98
Humidity (%)	42.97
Pressure (in)	29.59
Visibility (mi)	9.99
Wind Direction	NNW
Wind Speed (mph)	9.19
Precipitation (in)	0.0016
Weather Condition	Fair
Sunrise/Sunset	Night
Comfort Index	10.35
Severity	2

and reports generated by the RAG model were assessed. The system's prompt responsiveness was also tested, particularly how quickly it can generate alerts and warnings based on incoming data. Furthermore, the resource management aspect was evaluated to ensure that the system's resource usage is optimized and well-maintained. The developed system was deployed and tested on a real cluster of three nodes with k0s equipped with the monitoring application.

A. Risk Estimation Evaluation

1) Accuracy: We monitor the training process of the FL model in terms of accuracy, loss, and

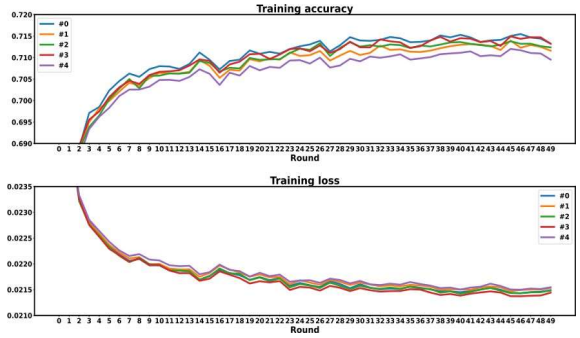

Fig. 2. Risk estimation training accuracy (top) and loss (bottom)

convergence. The training for 50 communication rounds with 5 training clients takes up to 4.042 hours. Figure 3 plots the training accuracy in the upper graph and the training loss in the lower graph. The model demonstrates convergence approximately by round 30 at 71.15%, as depicted in the upper plot. Initially, model accuracy exhibits an upward trend from round 0 to 30, albeit with

fluctuations observed around rounds 15-17 and 21. Subsequently, after round 30, the risk estimation model appears to have reached a plateau in accuracy, becoming converged. This is also reflected in the lower graph of training loss. It is, however, possible for low power-resource devices to terminate the training process at an earlier stage, such as after round 10 or 20, with negligible tradeoffs in accuracy.

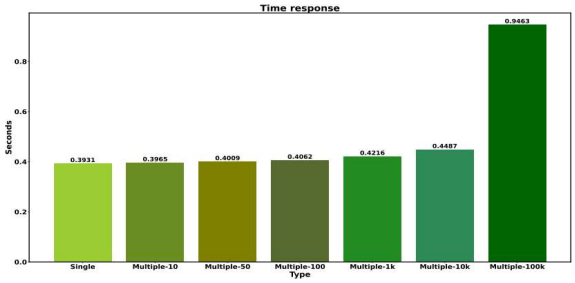

Fig. 3. Total latency trends of risk estimation

2) Total latency trends: The bar graph (referred to Fig. 4) depicting the total latency for predictions reveals a clear trend: as the number of inputs processed simultaneously increases, so does the time required for prediction. Starting from a swift 0.3931 seconds for a single input, the latency moderately rises for batches of 10 and 100 inputs, reaching 0.4062 seconds, suggesting the model handles small to moderate increases in input size efficiently. However, as input sizes increase to 1,000 and 10,000, the total latency grows more substantially, hitting 0.4487 seconds for 10,000 inputs. This increment continues, even more sharply, with the model taking 0.9463 seconds to predict outcomes for 100,000 inputs concurrently. Overall, this evaluation outcome underscores the FL model's scalability with a total latency, not only for small input batches but also optimized for larger ones. Nevertheless, it should be noted that the measured time can be different among different working devices.

B. Accident Warning Report Evaluation

Evaluated by RAG, we have used correctness, relevance, and faithfulness as criteria to assess LLM outputs10. We used gpt- 3.5-turbo-0613 for the evaluation task to contextually analyze and interpret generated reports according to the criteria. Cor- rectness is based on the LLM's internal knowledge. However, given the potential unreliability of the LLM's knowledge base, we enhanced the evaluation method by incorporating reference labels. This provides an external benchmark for correctness. The evaluation process produces a dictionary containing key metrics: "score", a binary integer from 0 to 1 indicating compliance with the criteria, "value", which is either "Y" (Yes) or "N" (No) based on the score, and "reasoning", which outlines the LLM's chain of thought. Relevance evaluates the relevance and focus of the generated answer in relation to the provided prompt. Faithfulness assesses the factual consistency of the generated answer against the given context and reference documents. Using this approach, we ensure not only that the generated content meets the prompt's specific requirements. It also remains true to the factual information provided in the reference material. Figure 5 illustrates an example of RAG output evaluation. Based on correctness, relevance, and faith- fulness criteria, the evaluation shows that the output accurately represents an actual quote. Throughout the evaluation output, all necessary elements are addressed in a comprehensive, well- structured, and well-written manner. Based on the evaluation output, the response summarizes accident data and provides a comprehensive analysis of weather conditions at the time of the accident, including visibility and severity. Additionally, it provides recommendations for preventing accidents in the future relevant to the reference.

C. Task Orchestration and Monitoring

We utilized a simplified demonstration setup comprising one controller node and two worker nodes to test the deployment of the

system to the distributed environment.

The technical characteristics of our system are as follows: The controller node is equipped with an Intel Core i7- 6700HQ CPU, an NVIDIA GeForce GTX

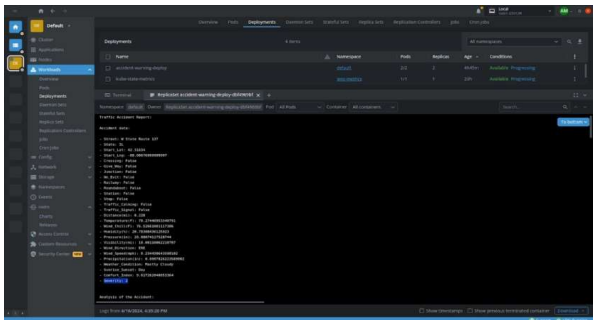

Fig. 4. Lens IDE logs output

960M GPU, and 16 GB of RAM. One of the worker nodes is identical to the controller node, featuring an Intel Core i7-6700HQ CPU, an NVIDIA GeForce GTX 960M GPU, and 16 GB of RAM. The other worker node is equipped with an Intel Core i5-1135G7 CPU and 16 GB of RAM. The system was successfully deployed and operated as expected, effectively generating warnings in response to simulated input data. Additionally, we employed Lens IDE to monitor data outputs and to oversee the resource usage on the controller node. A screenshot of the Lens IDE is provided in Figure 6 to demonstrate how the cluster is controlled.

V. Discussion and Future Work

The development and integration of FL and RAG into an ITS service presents several key findings and areas for further research. Our FL model demonstrated good performance in predicting traffic accident severity, achieving a convergence point after approximately 30 communication rounds. This suggests that FL can effectively utilize distributed data for predictions while maintaining data privacy. Additionally, the scalability of the FL model was evident from the total latency evaluations, which showed reasonable prediction times even with increasing input sizes, indicating the model's applicability in real scenarios. The RAG model generated detailed and con- textually relevant reports and warnings based on simulated real time inputs. This was validated through evaluations focusing on correctness, relevance, and faithfulness. The integration of real-time data and FL with external knowledge sources ensured that the generated content was not only accurate but also practical for end-users, such as traffic management authorities. The use of k0s for task orchestration proved to be effective, enabling seamless integration and management of various system components. The monitoring capabilities provided by Lens IDE ensured the system's robustness and allowed for efficient resource management. Testing on a simulated cluster confirmed the system's reliability and scalability. While our system shows promising results, several areas warrant further investigation and development. Future work should focus on strengthening privacy preserving techniques within the FL framework. In our design of the FL model, we prioritized simplicity and efficiency to predict accident severity. This approach was intended to minimize the computational load. For future work, it would be advantageous to enhance the FL model by exploring other lightweight models. This could potentially improve the accuracy while maintaining the model's efficiency. Exploring the feasibility of using transfer learning methods to transfer knowledge gained about each state or district to other districts or states can be beneficial. To directly address the reviewer's concern that the reported accuracy of the predictive model (71.15%) is low, we acknowledge that while this figure demonstrates good convergence and the viability of the FL approach for distributed

prediction, there is a clear and defined path for further significant enhancement. Achieving a higher accuracy is critical for a system designed to meet the practical and reliability standards for real-world urban safety applications. We will focus on the following strategies in future iterations to boost the FL model's performance:

- **Exploring Advanced Lightweight Models:** We will go beyond the current three fully connected layers by rigorously exploring other lightweight model architectures better suited for complex time-series and sensor data within the resource constraints of edge devices. This will involve testing models that integrate recurrent units or other sophisticated, yet efficient, deep learning structures such as those demonstrated in similar vehicular traffic flow prediction research [47].
- **Optimizing Hyperparameters and Communication:** We will conduct a more exhaustive search to identify the optimal configuration for hyperparameters (such as learning rate and batch size) and the number of communication rounds. The goal is to maximize accuracy beyond the current convergence point of 71.15% without incurring the prolonged training duration associated with the initial Complex model configuration (which achieved 74.42% accuracy but took 5.603 hours to train)
- **Refining Feature Engineering and Data Sourcing:** We plan to refine the preprocessing phase with advanced feature engineering that incorporates deep domain knowledge, such as explicitly including temporal-spatial features like proximity to peak hours or specific road geometry characteristics. We will also explore the use of more granular data from additional real-time sources to enrich the model's inputs, following best practices for leveraging heterogeneous sparse data in risk prediction [48].

By implementing these targeted enhancements, the next iteration will be designed to significantly improve the predictive accuracy, thereby creating a system that is not only conceptually sound but also practically viable and highly reliable for enhancing urban safety.

Developing user-friendly interfaces for traffic management authorities and end-users will be crucial for effective system adoption. This involves designing intuitive dashboards and visualization tools to present predictions and warnings in an accessible manner. Implementing and testing the system in real-world smart city environments will provide valuable insights into its performance and scalability. Collaborations with city authorities can facilitate this process and help refine the system based on practical feedback.

VI. CONCLUSION

This paper presents a service in smart cities integrating FL and RAG to enhance traffic risk prediction and manage- ment in smart cities. Our findings demonstrate the system’s accuracy, efficiency, and potential for real-world applications. The FL model achieved a good predictive performance while preserving data privacy. The RAG model produced detailed and relevant reports, aiding in effective traffic management. Task orchestration using k0s ensured seamless integration and robust performance monitoring. Future work will focus on enhancing privacy, scalability, and real world testing, aiming for broader deployment and integration. Our system offers a promising approach to addressing urban safety challenges, contributing to the development of

smarter and safer cities.

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