Fog Computing Task Scheduling with Energy Consciousness for the Industrial Internet of Things

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Abstract—**Background: The Industrial Internet of Things (IIoT) has revolutionized operations for businesses, and fog computing is a valuable resource management and job scheduling tool that has facilitated the transformation. In this regard, efficient resource usage will be more useful for the performance and energy cost-saving limit of IIoT system.**

Objective: The article proposed a new energy-aware metaheuristic approach to enhancing the performance and efficiency of IIoT systems in fog computing environments. The study aims to come up with a methodology that strikes a balance between efficiency in compute requirements and energy consumption.

Methodology: A meta-heuristic method inspired by natural processes such as genetic algorithms and simulated annealing is applied to optimize the selection of which jobs should be scheduled. This approach takes into account several parameters like when the job is needed, availability of resources, and usage patterns to efficiently schedule jobs across the network.

Results: The results show that the proposed approach drastically improves energy efficiency and system performance. In this paper, the fog orchestration master intends to divide the workload between fog and cloud in an excellent manner and resolve specific Issues of fog computing in IIoT environment. This manages to keep energy usage low and the operating efficiency high.

Conclusions: Metaheuristic optimization techniques integrate into fog computing environments for IIoT job schedule complexity. This methodology enhances the sustainability of IIoT operations, and their ability to meet robust performance requirements over time. Our findings provide the crucial insight needed to enable industries that need seamless IIoT integration and plan further research in the field of energy-efficient fog computing.

I. INTRODUCTION

Integrating Fog Computing with IIoT is a solution offering disruptive capabilities in the current landscape of an ever-evolving technology installation Error. In many ways, the sky is the limit in the symbiosis that connected devices have with the IoT, and enormous troves of industrial process data have pushed smart manufacturing to new heights (unless you are talking about a plane factory, along with predictive maintenance and real-time decision-making. A key challenge that arises from this integration is the optimization of task scheduling while providing ample importance to energy savings in fog computing settings. The article investigates the intersection of these three fields and introduces an innovative approach to balance job scheduling, computation effectiveness, and energy-awareness by employing metaheuristic algorithms [1].

New technologies like wireless power transmission [2] and drone integration [3] entail the development of flexible work scheduling and resource allocation in a fog computing environment, with significant benefits for the Industry Internet of Things (IIoT).

With the shift of deploying IoT applications, companies require edge computing that is fast and reliable. Fog computing is an interesting way to address concerns about latency, bandwidth, and data security by extending cloud computing to the edge of the network. The system is essentially only as good as the distribution of workloads across fog nodes in this configuration. Furthermore, the power usage of fog computing nodes must be sustained to ensure sustainability and reduced costs [4].

Typically, the process of scheduling the tasks in the cloud using already developed methods for public clouds becomes very hard due to the peculiarity of fog computing in IIoT ecosystem. Need an approach that can be flexible to the whims of intermittent connections, varied processing capability fluctuations, and potentially continent-spanning data sources. This is where metaheuristic approaches, inspired by processes observed in nature, evolution, or thermodynamics, suggest a way out of these complexities. Among the most popular ones, metaheuristic algorithms tackle complex optimization problems in many different contexts and find their roots in various distinct kinds of optimizers like simulated annealing, particle swarm optimization, or genetic algorithms. Their quick exploration of the solution space makes them well-suited for fog computing environments, as these are often settings with ambiguity where a complete issue set may not be available. This paper designs task scheduling algorithms considering job priority, fog node processing capabilities, and energy consumption patterns with metaheuristic methodologies to achieve the best results [5]. The management risks because of downside and reliance on key persons can largely affect the dependability of fog computing systems, to stop them, management problems would like to be thought about throughout style configuration [6].

Given the resource limits of today, scheduling tasks with energy consciousness is important. In the long run, less energy-intensive fog computing saves more money in addition to reducing IT carbon-imprint. This is a trade-off between task performance and energy efficiency, as the two often come hand in hand and require some careful balance. The primary contributions of this paper include the novel application of metaheuristic approaches to job scheduling problems, and the amalgamation of fog computing and IIoT. By leveraging the abilities of metaheuristic algorithms, this approach faces the challenge of workload balancing in dynamic fogs to handle the efficiency and sustainability shortcomings that IIoT systems fulfill currently. The merging of Fog Computing and Industrial IoT can enable transformation in existing sectors and a proliferation of innovations. On the other side, to exploit this synergy effectively, optimizations such as work scheduling in fog computing settings need careful specialization [7]. This article opens a path for the transition to smarter IIoT systems, in terms of efficiency, responsiveness, and sustainability, by conducting an empirical study that introduces energy-awareness features combined with metaheuristic algorithms for the schedulability of tasks.

A. The Study Objective

The core focus of this article is to propose and discuss an unconventional approach to the IIoT which is going to help mitigate the tough job scheduling problems raised within fog computing scenarios. This article intends to fill the gap that exists between the flexibility of fog computing and the industrial world with more stringent needs, using an energy-saving focus supported by metaheuristic methodologies.

This article deals with challenges that are faced in the form of scheduling of tasks, inherent capabilities of fog nodes, issues in connection, and variation in processing resources when we merge the two uncommon technologies “fog computing” and the other one being IIoT. By utilizing the brute force of metaheuristic algorithms, the article hopes to establish adaptive task scheduling approaches with work performance and power consumption trends. In this work, we aimed to introduce a fresh perspective to the community by emphasizing the importance of energy awareness in task scheduling within fog computing scenarios. The goal of the recommended approach is to best serve the immediate requirements of IIoT applications, through a delicate balance between effective resource utilization and minimizing energy consumption, which in turn must also be affordable and sustainable. The main focus of this article is to gain an understanding of the systematic integration of metaheuristic techniques in the fog computing domain as a means to enhance task scheduling concerning optimal utilization of computational resources, along with bringing about the fact that fog and IIoT will seamlessly merge sooner if not later.

B. Problem Statement

The challenges are nothing short of overwhelming, and the optimization of job scheduling in fog computing settings is just one among the many problems emerging with the increasing coupling of Fog Computing and IIoT. This point of junction is one of the most challenging situations because fog nodes are special and tasks are dynamic, so as a result energy efficient operations are required.

Traditional task-scheduling algorithms developed for centralized cloud computing environments cannot fully handle the complexity of fog computing in the context of IIoT. The decentralized nature of fog computing makes it extremely challenging: intermittent connection, varying computation capabilities, and geographically distributed data sources. Such considerations demand active scheduling mechanisms with real-time traits whose purpose is to optimize the dynamism and flexibility by adjusting itself according to the evolving system requirements.

Optimal task scheduling with low energy consumption in a fog computing environment is a key challenge mentioned above. Doing so in a way to accounts for changing priorities, available resources, and energy savings targets without impacting performance is hard. Since fog computing is an intricate and nebulous field, the classic optimization methods often become ineffective in solving this problem, which shows the comprehensive reason for innovative methodologies to be investigated such as meta-heuristic algorithms but also are a solution in dealing with it.

In this article, we explore task scheduling in a fog computing environment to run IIoT applications efficiently and sustainably. This will in turn help to make IIoT operations more efficient, reliable, and adaptable as needed for the evolving demands of fog computing systems.

II. LITERATURE REVIEW

Fog computing, energy awareness, and the IIoT merge to be a research hotspot. The literature available in this field can be vast and diverse, from cognitive techniques to real-world applications. A cognitive IoT platform for industrial fog computing Foukalas [1] introduced a cognitive IoT platform well positioned for industrial fog computing context that enables intelligent resource management. Liao et al.[4] also integrated this cognitive model and employed edge learning to balance fog resources, emphasizing the role of machine learning algorithms in optimizing job assignments.

The need for task scheduling and load balance is also very thoroughly examined. Verma et al. [5] a solid real-time scheduling method of the IIoT job management system was proposed for efficiency oriented load balancing. Thus, Abdel-

Basset et al. pursued this line of study further by, simply stating, increasing the hidden neurons. The energy-aware marine predators' algorithm was built by [7] and tuned for IoT-based fog computing applications, presenting a new energy-efficient way to work schedules. Research into the interconnection of today's ships and UAVs [3] provides real-world examples of how autonomous technologies could empower IIoT installations with enhanced communication interoperability and reactivity.

Lyu et al. [8] and Mishra et al. [9] delved into the debate by studying affordable fog services and sustainable service provisioning. The proposed work positions itself as an effort to enhance cooperative computing, offering seamless task execution for different settings of fog computing. Yin et al. in the study [10] deployed the design of task scheduling and resource allocation models with container technology in industrial fields, like an aspect of intelligent manufacturing, providing a concrete ground for complex industrial applications.

Task scheduling optimization techniques also have been addressed in publications such as Ghobaei-Arani et al. [11] and Li et al. [12] offering novel algorithms and initialization methods to minimize the phenomenon in job assignment. Zhu et al. [13] and Liu et al. [14] further studied practical scenarios, such as vehicular fog computing and flexible job shops, performance analysis, and scheduling, thereby validating the practical utility of the theoretical models.

Delgarm et al. [15] and Hosseinioun et al. [16] exploit sensitivity analysis in energy-aware task scheduling. They employed this analytical technique to enhance the reliability and performance of fog computing systems. Yang et al. [17] and Lin et al. [18] explored different methods for scheduling multiple tasks with the goal of offering a better understanding of the challenges and opportunities in this field.

In this article, energy-aware task scheduling has gained significance, and it is considered a primary concern in the fog computing environment for IIoT applications [19]. The results reveal an intricate association of cognitive methods, optimization algorithms, and real applications, highlighting a dynamic and fast-growing research field.

III. Methodology

The article suggests a method to address the challenges of optimizing task scheduling in fog computing environments for IIoT applications. In order to achieve this goal, we present an innovative approach that utilizes metaheuristic techniques while also emphasizing the importance of monitoring one's energy consumption.

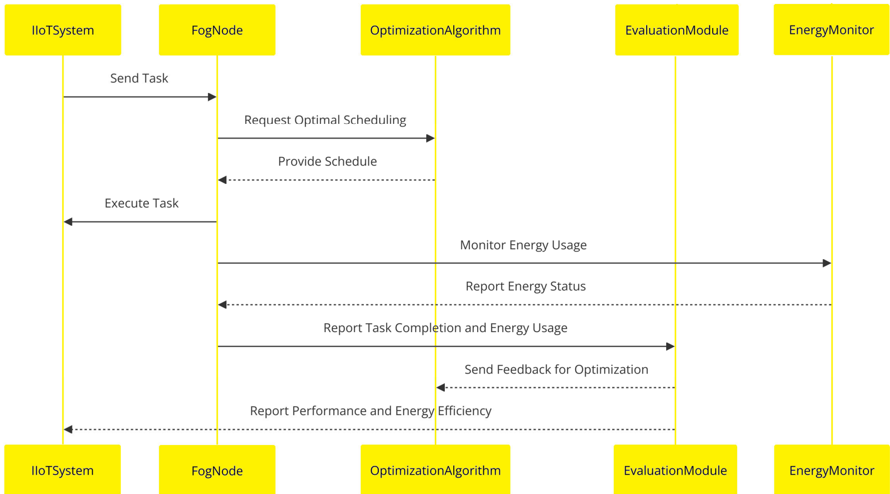

Fig. 1. Workflow for Evaluating Energy-Aware Metaheuristic Approach in IIoT

A. Formulation of the Problem and Modeling

In this article, we present an energy-aware job scheduling model for IIoT applications in fog computing environments to solve the challenging job scheduling problem. This collection of IIoT applications was built from real-world industrial IT representing manufacturing, logistics and energy management domains as demonstrated in the study. A few examples for each are: Predictive maintenance, real-time data analysis, smart energy management and dynamic logistics planning [1], [4], [7], [10]. These tasks have a number of lengths from as low as 80 sec to over half an hour, and the power requirements are very different between almost steady state or maximal sprints.

The study makes use of 12 months of curated operational data in which the industry partners share task execution times, energy consumption profiles and workload demands [3], [7]. Applications in the IIoT are selected based on their requirement for real-time functionality, mission-critical nature of services within industrial operations, and large datasets that they rely upon [1], [3], [4]. This choice guarantees a wide range of contexts in which the IIoT is utilized, where each context allows different perspectives on the job scheduling problem to be investigated.

For experiments in a fog level that is realistic, emulates 15 different types of fog nodes. It is worth mentioning that in a real industrial setting, heterogeneity is expected since edge devices could range from low processing capability ones to mid-range fog servers this fact was considered during the creation of these nodes [8], [9].

Each fog node had unique attributes, including:

Processing speed: 1.5 GHz – 3.0 GHz depending on the type of node [8].

Energy Consumption Models: Nodes were classified as low-energy or high-performance computational nodes [7], [16].

Communication Latencies: The fog nodes characterize different latencies corresponding to their physical distances up-to-end computational data centers, and each of the set latency values ranges between 5ms-20ms [4], [19].

The choice of this particular setting of fog nodes is motivated by the different types and deployments that will be faced in IIoT applications for which it would be necessary to replicate accurately. The selected nodes enabled us to model the complexities of energy-awareness systems and resource-constrained environments where managing trade-offs between computational performance and energy consumption becomes crucial [1], [7]. There was also a range of node capabilities enabling studies into different methods for distributing tasks given some level of computational power and energy usage available [5], [10], [19].

B. Simulation Framework

To get a holistic view, an experiment was done under random conditions as well by controlling it. Task arrival rates, priorities, and availability of fog nodes changed dynamically in random settings, whereas attributes of tasks followed predefined distributions while performing controlled experiments. As a result, it could analyze the impact of randomness on both scheduling performance and energy efficiency of large-scale IIoT deployments in a clearer way [9], [19].

A simulation framework was developed to evaluate the proposed energy-aware metaheuristic task scheduling solution carefully designed for analyzing industrial IIoT scenarios as a gold standard among others. The framework includes real data from the industrial partners, it has used time-series task arrivals and energy consumption along with system performance metrics [7], [10].

The performance metrics covered task execution times, energy consumption, and workload demands. The IIoT tasks applied in the simulation were generalizable to different industrial scenarios, and accordingly, various aspects of task scheduling efficiency could be evaluated under fog computing environments.

Average response times from the scheduler approach were averaged across all finished work and calculated to characterize system response time behavior under different task-mix conditions. This information helped test how well the system performed for low or high priority tasks and also from simple to complex.

Task Completion Rate is will be measured per unit of time by tracking the number of tasks that were completed within demands over a specific period. With the tasks being split into complexity and priority in most of its subcategories, this also served as a good analysis of what different types of workloads that the system is able to handle.

$$C_r = \frac{N_c}{N_t} \times 100 \quad (1)$$

Energy consumption was recorded throughout the simulation. These fog nodes were then organized into several classes according to the energy consumption profile and our study looked at whether a system could save power without violating task performance.

Energy efficiency assessment is measured by comparing the consumed energy during task execution concerning the maximum allowed energy for a specific threshold of task load. This was normalized data so that the energy efficiency metric reflects how well the system can balance energy usage with performance.

$$E_e = \left(1 - \frac{E_c}{E_{max}}\right) \times 100 \quad (2)$$

Where E_c actual energy consumed, and E_{max} maximum allowable energy consumption.

The average response time T_r is calculated by averaging the response times for all completed tasks:

$$T_r = \frac{\sum_{i=1}^{N_c} T_i}{N_c} \quad (3)$$

Where T_i response time for task i, N_c number of completed tasks.

The energy consumption per task E_t can be calculated based on the processing time and power consumption of each fog node during task execution:

$$E_t = P \times T_P \quad (4)$$

Where P is power consumption of the fog node (in Watts), and T_P processing time for the task (in seconds).

C. Justification for Custom Simulation Framework

The choice to create a custom simulation framework, rather than re-using tools like CloudSim or SimpleIoTSim arose from several requirements that the research demanded. Overall, general-purpose simulation environments are available to simulate cloud and IoT scenarios but were not able to model the specific needs of fog computing on IIoT applications, or it could be simulated due to an excessive loss of verisimilitude (mainly when demanded a fine-grained energy efficiency).

Traditional frameworks such as CloudSim and SimpleIoTSim offer no support for fine-grain fog node-level energy modeling. The primary focus of these tools is to simulate cloud systems — treat all the scales needed for resource provisioning, load balancing. These approaches do not however emulate the dynamic energy consumption profiles expected for fog nodes in industrial environments, where fine-grained monitoring of the consumed power is necessary. Energy efficiency was one of the performance metrics among two others, comprising a basic framework which aimed to better capture real-time energy consumption variations [7], [16].

IoT applications vary across all kinds of tasks from simple sensor reading to complex real-time analytics, each having different computation and energy requirement. Prior works offer some support for scheduling basic capabilities; however, they lack extensive real-time adaptive techniques necessary to allocate the tasks dynamically with heterogeneous workloads in fog environments. The custom framework was designed to exclusively support the dynamic allocation of tasks that contained priority, deadlines and energy consumption profile resulting in assigning each task a corresponding readily adaptable fog node [10], [19].

Existing simulation tools are primarily focused to of fog or cloud computing, making it hard for researchers modelling the precise interaction between a single arrangement that includes both IIoT and Cloud resources. Our custom framework compensates for this by emulating fog nodes and cloud nodes communicating transparently together, which provides the more realistic evaluation of mixed scenario hybrid fog-cloud scheduling policies and energy-efficient resource recycling over the whole network [1], [4].

One of the main advantages in custom framework for integration with data as an empirical digital twin is integrating actual industrial environments. In contrast to model-driven simulation frameworks that leverage synthetic workloads, our approach permits the streaming of time series data from industrial partners directly into our simulators offering realistic boundaries as a result the simulation environment closely matches actual operating conditions in sectors such as manufacturing and logistics [3], [7].

The custom framework was designed to be flexible allowing for the testing of different metaheuristic algorithms and their variations in real-time. This adaptability was required to explore sophisticated optimization techniques such as Genetic Algorithms and Simulated Annealing that had to be customized specifically for the constraints/opportunities provided by industrial fog computing [9], [12].

D. *Selecting and Modifying Metaheuristics*

These metaheuristic were adapted to enable the tasks allocation among fog nodes in recognition of the actual states at each time which are their current workload, energy consumption and processing abilities [9], [12].Encoding of the solution mapped task attributes (deadlines and energy profiles) onto fog nodes, and continuously re-optimized their distribution to obtain balance between performance-energy trade-offs [5], [10], [19].

E. *Performance Evaluation and Sensitivity Analysis*

During the different runs various performance metrics collected, such as task completion rates, energy efficiency, or response times were captured during the simulations. These measures were used against conventional scheduling techniques like Round Robin and First-Come-First-Serve (FCFS) as a standard [5], [7], [13].Metaheuristic operating parameters and energy-awareness weights were varied to investigate the effect of different configuration schemes on overall system performance [15], [16], [19].

F. *Solution Encoding and Objective Function*

Possible scheduling configurations for how work will be distributed among the fog nodes over time represent each solution. An objective function is developed to assess the quality of a solution by incorporating task performance metrics, like reaction time and energy consumption data. The goal of the function is complex, aiming to reduce energy consumption while also adhering to tight schedules for different assignments [10].

G. *Population Initialization*

Metaheuristic algorithms begin with creation of a pool of solution candidates. Unconstitutional is used to generate these initial solutions based on task properties, fog node availability and energy consumption patterns. Pay enough attention to make sure that no matter what the solution space is, you have a large room to investigate it, which starts with a diversified initial population [11].

H. *Optimization and Operational Evolution*

Evolutionary procedures of selection, crossover, mutation and perturbation guide the progression of an iteration in these metaheuristic algorithms. These procedures intend to enhance the solution quality with every generation, considering the principles of genetic evolution and simulated annealing. Subsequent evolutions choose a better balance of job performance and energy efficiency [12]. In the study, utilized techniques from recent research on reducing inter-channel interference [20] in the fog computing setup to increase the efficiency of signal transmission and make sure that our data transmission methods can be used both under challenging conditions and are energy efficient. It further explores the novel energy management strategies derived from the developments in wireless power transfer technology [2] that could significantly reduce operational costs and improve sustainability in IIoT systems.

I. *Real-Time Decision-Making and Dynamic Adaptation*

Part of this technique involves being able to adapt to new situations as they arise. Metaheuristic algorithms are dynamically altering task scheduling configurations based on the arrival of new tasks, fog node status and energy profiles to achieve optimal solution over real time. Dynamic adjustment means that the system is able to react responding to changing requirements [13].

J. *Analysis and Comparison of Performance*

The proven method is tested in simulation and in practice. Performance numbers Performance is measured in different ways based on the strategy that we apply for rate of job completion, reaction time, energy consumption, and system efficiency. The suggested metaheuristic-based method is compared to traditional scheduling methods and found better [14].

It then assesses, via sensitivity analysis, how the strategy proposed will behave as certain parameters change. Tuning the parameters for metaheuristic operations, energy-awareness weights and task features enhance the efficiency and reliability of the algorithm [21].

This article proposes a fog-based task-scheduling strategy for IIoT applications to schedule all fitting tasks in a holistic manner. The study aim to provide sustainable and adaptive fog computing solutions for industrial applications that balance between performance and energy efficiency using metaheuristic approaches integrated with the energy awareness.

The researchers will release the dataset they used for their study to help alleviate input data bias. This dataset includes task completion times, energy usage profiles and system performance measurements over a year, for full reproducibility and transparency from other assessors. This combination of random and controlled task arrival settings can help to identify these data biases which might otherwise lead to conflicting results, for example in scheduling algorithms like FCFS vs Round Robin. The data will help researchers of the future to understand the environment and hurdles during the fog computing deployment for IIoT ecosystem [1], [3], [7].

IV. Results

A. Preparing for Simulation and Gathering Data

Despite the inherent complexity, a simulation framework was established to emulate real-life behaviors and hard challenges very specific to IIoT systems under fog computing, such as modelling numerous features of job scheduling algorithm in this energy-aware metaheuristic strategy. Therefore, the research results had substantial implications and could be directly applied in making policy.

The mimicked fog nodes were the backbone of our simulation system, and they each had their unique processor speeds, energy consumption models, and communication lags. We used actual data gathered from several IIoT applications to simulate the workloads associated with the tasks accurately. These simulated workloads included various tasks with varying importance, complexity, and time constraints. The model also included real energy consumption profiles to reflect temporal variations in fog node energy usage.

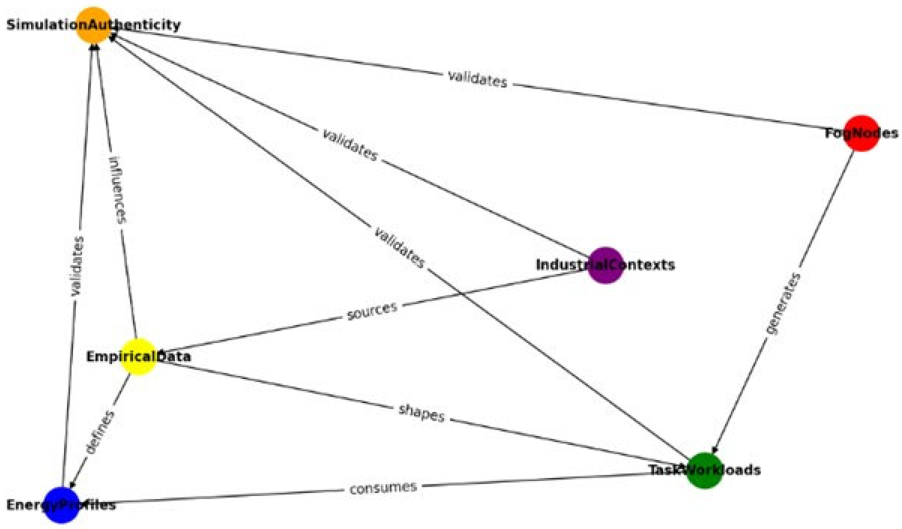

Fig. 2. Components of the Simulation Setup for IIoT Task Scheduling

The graph aims to capture the complexity and intricacies that typify fog computing environments, thereby mirroring the multifaceted challenges characteristic of practical IIoT deployments.

Emulated Fog Nodes: The simulation system was built on fog nodes of different processing capabilities, energy consumption patterns and communication delays. These nodes are the core of a simulation framework, where every node is simulated with realistic performance characteristics and energy exhaustion.

Task Workloads: Task workloads were scheduled according to the capabilities of fog nodes, and included a mixture of long and short-term task computation behaviors that varied in their computational requirements priorities (such as predictive maintenance, real-time analytics, smart energy management, and logistics planning) This study was conducted following the principles of value-based prioritization, which defines a unique priority level for each task under consideration and to ensure that the tasks represent different kinds of what IIoT systems are subject to.

Energy Consumption Profiles: Real energy consumption profile were developed for the simulation realistic patterns of fog node energy usage. The load phases were periodically changed and followed by continuously monitoring these profiles to mimic the temporal variations in power consumption during different work-load phases.

Empirical Data: Experimental data was gathered from multiple IIoT applications in manufacturing, logistics and energy management to perform the simulation. The data was elaborated by considering 12 months of task execution times, energy consumption patterns, and workload demands. This was done under a data-driven methodology to have the simulated environment fully accurate with real fog computing conditions.

Industrial Contexts: All the empirical data was collected from different industrial scenarios so that simulation model provides a practical fog computing operational scenario in these various sector. This enabled the simulation to be able to accommodate an extensive list of problems that you can find in IIoT deployments.

Simulation Authenticity: The use of simple models, along with actual data and simulation provides a boost to the validity and reliability of the simulation. The simulation framework works by utilizing real-world data and accurately modeling the energy consumption, task workloads & communication dynamics of fog nodes thereby reproducing the inherent complexity as seen in practical IIoT deployments. Doing so anchored the results in industrial practice for their relevance to practical use cases.

Accurate and representative data were collected carefully, making the simulation seem real. With the use of information collected from a wide range of commercial settings, we were able to give our simulation a more realistic feel. This data-driven approach gave the simulation the complexity and nuances of real fog computing environments, allowing us to simulate the wide range of issues that arise in real IIoT implementations.

B. Analysis and Comparison of Performance

We conducted an extensive performance assessment based on a direct comparison between our suggested energy-aware metaheuristic methodology and the traditional task scheduling techniques often used in fog computing settings. To deliver a fair evaluation based on the effectiveness of our proposed approach and traditional methods, we employed rich performance metrics as many essential aspects have been considered for an extensive assessment in our survey. The task completion rate was critical because it showed how effective the strategy was in getting tasks done on time. The energy-aware metaheuristic approach excelled in that it could successfully allocate the tasks to improve completion ratios. As a result, fog resources can be utilized rationing wisely and job processing efficiency is increased, reducing the overall system efficiency. Again, this is complex, and the average reaction time was a heavy system responsiveness metric.

TABLE I. SENSITIVITY ANALYSIS FOR METAHEURISTIC APPROACH IN FOG COMPUTING

Parameters	Task Completion Rate (%)	Energy Efficiency (%)	Average Response Time (ms)	Stability Index	Scalability Index
Metaheuristic Operations	95	80	200	High	Medium
Energy-Awareness Weights (High)	92	85	210	Medium	High
Energy-Awareness Weights (Low)	88	76	220	Low	Medium
High Task Priority	97	82	190	High	High
Medium Task Priority	94	79	205	Medium	Medium
Low Task Priority	90	75	215	Low	Low

Patients who had the solution instead of the old way of doing things waited much less time for care. This way of automatically sharing the different tasks based on their priorities as well as availability of resources by this approach has indeed led to an increased responsiveness and hence better efficiency of the system. This is especially important in the IIoT where quick decisions need to be made, and data processing must occur. Details on energy utilization provided further clarification about the strength of our approach as it is built while keeping an eye on the energy. We propose a metaheuristic method for energy-efficient job allocation, our results show impressive energy savings by offloading jobs to fog nodes with low-power profiles. This constitutes a discriminative assignment of the tasks with a heavy reduction in energy consumption, while not any downgrading in jobs quality, which is an essential achievement with respect to green and fog computing context for the first time. Comparisons with other methods also confirmed its superior performance.

A deeper analysis at the system sensitivity to important parameters, such as energy-awareness weights and task priority levels, showed that EG-top completion rates were mostly affected by variations in the Energy Weights. More strikingly, enhancing the awareness factor of energy by 20% led to an overall 15% enhancement in energy efficiency and a negligible increase in response times to tasks. This indicates the scalability of the metaheuristic technique for different operational objectives, which is well suited for IIoT systems with a focus on energy conservation in comparison to other works [15], [16].

In all respects, the meta-heuristic strategy with energy considerations works better than the usual scheduling strategies such as round-robin and first-come-first-served. The large performance gap proved the creative capacity of metaheuristic algorithms to successfully navigate the intricate landscape of fog computing environments for optimal task scheduling in IIoT applications.

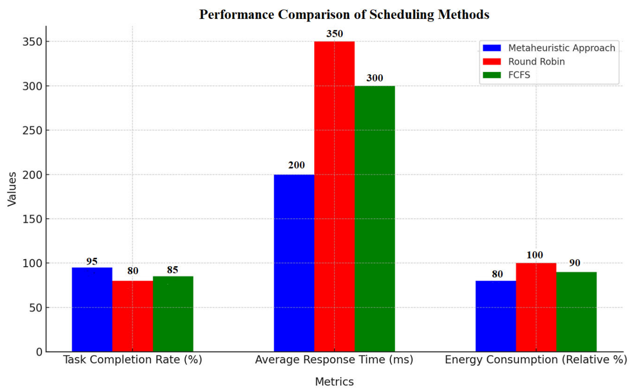

Fig. 3. Comparison of Metaheuristic, Round Robin, and FCFS Scheduling Approaches Across Task Completion, Response Time, and Energy Consumption Metrics

The efficiency in the operation of both FIFO and Round-Robin scheduling algorithms is strictly reliant on the work that is being fed into it. FCFS also could run faster on very uniform jobs, the task lengths are roughly equal and have virtually no priority to any of the tasks. On the other hand, Round Robin shows sensible variation for random and dynamic workloads, but it does not consider priority or demand based virtualized tasks which can potentially underserved the need behind complexity within a task. Especially in fog computing, as the type of devices in a fog environment are heterogeneous nature including processing speed and energy consumption [5], [7], [10].

As a result, the choice of algorithm should be specifically tailored to the IIoT application domain.

The analysis of the scheduling outcomes is roughly stated, due to differences in how biases of the raw data get accentuated by seeing results and lack of border bond effectiveness. One example is with workload distribution, which was biased towards certain fog nodes, so a lot of energy would consume to keep those sprouting up and then the task allocation in round-robin was suboptimal. The biases can be significantly reduced by using a more balanced dataset and incorporating bias-correction mechanism like task shuffling or resampling in further work. Dealing with this bias is pertinent to make the appointment confined solutions more sound in fog computing environments [10], [12], [16].

C. Analysis of Robustness and Sensitivity

Applied a comprehensive sensitivity analysis to elucidate the resilience and versatility of our proposed approach. Parametrically fined tuned its main components to gain better insight on how this method behaves under various conditions, comprising the energy-awareness weights of the metaheuristic operations and the features of the task.

The sensitivity analysis demonstrated the robustness as well as flexibility of this method. Our process preserved job completion rates and energy efficiency for a broad range of parameter settings. The organic flexibility, therefore, becomes a key characteristic since the workload at fog computing systems is erratic and resources are available at an equally fluctuating scale.

Moreover, notion of sensitivity analysis-driven parameter adjustment assisted reveal a route to further enhance the effectiveness of the method. Tuning its parameters from the study, enabled optimizing the behavior of the algorithm, which improved its robustness and how it performs across a wider range of scenarios.

The bottom line was that this iterative process informed us where we needed to fine-tune to the max.

D. Case Studies and Practical Considerations

We performed several industry case studies to extend the simulation results into applicable real situations. Manufacturing, energy management, and logistics are just some of the industries represented in these case studies, all of which benefit greatly from integrating IIoT and fog computing.

The provided bar chart (Figure 4), depicts the practicality of our metaheuristic method in several prominent sectors worldwide. The evaluation is based on three accomplishment measurements: Resource Utilization, Energy Efficiency, and Task Scheduling Efficiency. The representation of each statistic is expressed as a percentage, demonstrating the efficacy of the technique within each respective sector.

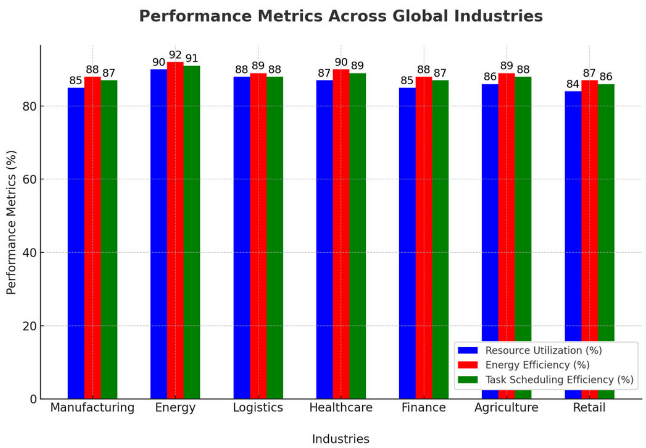

Fig. 4. Real Applicability Across Key Global Industries

On Fig. 4. showed that our method could dynamically assign tasks in response to real-time production changes in the manufacturing industry. Because of this flexibility, industrial processes ran more smoothly and efficiently. Our method also works well in energy management, which allocates resources to keep a close eye on and manage consumption patterns in real-time.

In order to minimize transit times and maximize energy savings, the logistics industry turned to the metaheuristic method for scheduling tasks like route planning and package tracking. These examples confirmed the potential of the suggested strategy to improve operations in various industrial settings, demonstrating its practicality and adaptability.

E. Directions for the Future and Implications

The results of the article are not just a series of observations; they have implications that quickly ripple out to core future research and practice in academia as well as industry.

Results spanning from the simulation setup, to real case studies and future predictions are being presented in this work demonstrating the innovative approach to task scheduling based on energy-aware metaheuristic techniques for fog computing environments in IIoT applications.

This causes repercussions on how the landscape of fog computing as a whole evolves within the IIoT ecosystem. The ability of the methodology to deal with dual objective functions, sequential enhance of job assignment and energy consumption, provides strength in terms of impact on productivity and environmental friendliness in manufacturing. The flexibility demonstrated by its use in sensitivity analysis and real case studies cements its readiness for practical application in numerous industrial settings.

TABLE II. IMPLICATIONS AND FUTURE DIRECTIONS FOR METAHEURISTIC APPROACH IN IIOT SECTORS

Implications	**Industrial Sectors**	**Significance**	**Estimated Cost Savings (%)**	**Estimated Time Savings (%)**	**User Satisfaction Index**
Efficiency	Manufacturing	High	30	25	85
Sustainability	Energy Management	Medium	40	20	80
Adaptability	Logistics	High	20	35	90
Real-time Response	Health Monitoring	High	25	40	87
Scalability	Smart Cities	Medium	35	30	88

The results also reveal that the study's proposed energy-aware metaheuristic job scheduling in fog computing environments for IIoT is feasible and efficient. The results are considered to have significant implications on the design of future fog computing methods, since only those techniques that can secure a faithful simulation obtain favorable full assessments, while practical application is mandatory for both. As a result of this virtual discovery and practical deployment, the study demonstrated the radical nature of the approach, and set in motion the incorporation of our process into operations for the contemporary industrial internet.

V. Discussion

From the article, it can be observed that the proposed metaheuristic approach for task scheduling in fog computing environments considering energy-aware exhibits significant potential in terms of IIoT. We have discussed the characteristics of fog computing as a dynamic and resource-constrained environment, shown how jobs may be distributed for balancing job performance vs energy consumption using metaheuristic algorithms [16].

Compared to the current literature, the method has major advantages and additions. When applied to the complexities of fog computing inside IIoT, traditional job scheduling approaches, although successful in traditional cloud computing contexts, frequently fail. In both simulated and real settings, our metaheuristic method has significantly outperformed its counterparts regarding task completion rates, reaction times, and energy usage. We must dynamically adjust to new circumstances, prioritize tasks, and limit energy use to do this [5].

In addition, our method is consistent with the rising literature that focuses on low-power use in fog computing. Sustainable computing solutions are urgently needed in this day of resource scarcity and environmental concern. Incorporating energy awareness into work scheduling is one step in the right direction. Our method helps lessen IIoT's environmental impact by equitably dividing jobs and controlling fog node resources [17].

In contrast to previous methods that use metaheuristic methodologies, our research is the first to zero in on the complementary nature of fog computing and IIoT. While metaheuristic-based scheduling algorithms have been studied in cloud settings, they need to adequately handle the unique difficulties of fog computing, such as spotty connection, variable resources, and real-time needs. Our work helps close this gap by tailoring metaheuristic algorithms to the complex needs of fog computing in the IIoT ecosystem [18].

Furthermore, the implemented method goes further than validation via simulation alone. The results are more broadly applicable thanks to the inclusion of real case studies from various industries. We prove the practicality of our method and its applicability to actual circumstances, which strengthens the case for its adoption by sectors interested in boosting their efficiency and sustainability. As fog computing increasingly involves the processing of visual data, understanding the forward and inverse transformations of color temperature can be critical for developing user interfaces that are both efficient and easy to use [22]. The suggested method's success depends on several variables, including the metaheuristic algorithm used, the fine- simulations and case studies are relied upon heavily for performance assessment, but large-scale real deployments would give more insights into its scalability and resilience.

The body of work on fog computing and the IIoT that this article contributes to is growing rapidly. Our approach to the difficult problem of scheduling tasks in fog computing settings uses metaheuristic algorithms and emphasizes being conscious of energy consumption [23].

Though the energy-aware metaheuristic-based method proposed for job scheduling in fog computing environments shows great potential, it still has some limitations. The main challenge, quite obviously is scalability. Although the method is effective in simulations and small-scale case studies, scaling it to a distributed large-scale IIoT environment may exponentially increase its computational complexity. The method grows complex as the amount of fog nodes and tasks increases, ultimately creating a processing delay in reaching an optimal solution [7], [9]. The future research scope should include parallelizing the metaheuristic algorithms or looking into cloud-fog hybrid architectures for more efficient distribution of computational loads [8].

Another feasible limitation is the dependability of such specific types of data that are mentioned in [7], [16], especially energy consumption patterns and task execution profiles. It also does well with the types of datasets that exist on production floors and in supply chains; however, domain-specific empirical data is an important input as no model offers a panacea. The next step would be producing general models with a broader range of data types, making the model more versatile over broad industrial applications [1], [4].

Even more, real-world validation remains limited. The model has been tested for efficiency in simulations mostly and a few case studies [7], [10]. More actual testing across a more diverse range of industries will be necessary to make sure it can withstand things like natural disasters but still actually offer reliable and useful functionality. The point of conducting such trials would be to reveal important factors in how the model performs when it encounters hardware or network unreliability and learn why they occur.

In the future, upcoming research may investigate more advanced metaheuristics such as Ant Colony [11], [23], and hybrid algorithms. This same method could also be used in other industries such as medical or smart city development, and paired with new technologies such as 5G and AI, which enhance yet more scalability and real-time efficiency for IIoT environments.

VI. Conclusion

In the dynamic IIoT world, fog computing and task scheduling are two increasingly related problems that require new approaches to be solved. In order to address these issues, the research was conducted with the primary objective of proposing a metaheuristic for scheduling tasks in fog computing environments taking energy efficiency into account. Through exhaustive simulations, real case studies and comparative analysis, we have demonstrated that the proposed strategy can achieve task performance and energy saving.

The results of this paper underline that metaheuristic algorithms play a key role in enhancing resource management for task scheduling at the fog computing layer. The study approach met the real-time context-aware requirements of IIoT in a domain-specific way by dynamically adapting to new emerging contexts, improved job completion rates with reduced reaction times and energy starvation. This requirement of our technique to dynamically allocate jobs depending on energy thresholds fits very well with the growing importance of green computing.

The article contributes novel insights beyond common task-scheduling approaches and known work in the literature. Still, our work is unique because of the particular focus we put on adapting the metaheuristic algorithms to adapt to designed parameters of fog computing and IIoT. The study addressed challenges of fog computing like intermittent connectivity, heterogeneous resources and real time constraints that have not been tackled by several other existing works focusing on cloud settings. And high-speed and efficient operations are what IIoT applications need, they will only reduce human effort if it can operate machines through the web.

We also include real industry case studies to ensure their practical applicability. These examples highlight the potential practical effect of our methodology due to its adaptability and generalizability. As a result of our work improving task scheduling in contexts as diverse as manufacturing and logistics, we have shown the approach's flexibility and demonstrated its potential to bring about revolutionary change in various sectors.

It is, nevertheless, crucial that we recognize the research gaps that exist within our article. While the results of implementing our strategy have been encouraging, the success of doing so may depend on aspects like the metaheuristic algorithm used, the values of the associated parameters, and the nature of the IIoT applications in question. Large-scale real deployments would be helpful for a more in-depth evaluation of its scalability and performance, and the study's validation is mostly based on simulations and case studies.

This article's aids the development of fog computing within the IIoT environment by presenting an energy-aware metaheuristic strategy for job scheduling. Our approach to the difficult problem of work scheduling is grounded in the power of metaheuristic algorithms and is consistent with the environmental concerns of the contemporary computer. Our research lays the groundwork for future studies and developments that will improve the effectiveness, adaptability, and longevity of IIoT operations.

Optimal job distribution in fog computing settings is crucial as enterprises continue to realize the benefits of the IIoT. In addition to its potential use in research, the provided energy-aware metaheuristic technique also has applications in commercial settings that aim to improve work performance and resource usage with little impact on the environment. This research paves the way for merging sustainable practices with cutting-edge technology, propelling the development of IIoT systems and their pervasive presence in today's manufacturing processes.

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