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Blockchain-Powered Incentive System for JIT Arrival Operations and Decarbonization in Maritime Shipping

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Abstract: Efficiency and sustainability are undisputedly the most critical objectives for modern ports. Current exercises for port services still lack performance profiling for arriving vessels regarding their arrival punctuality and compliance with port resource schedule for Just-in-time (JIT) service, as well as their efforts contributing towards less emission through reduced turnaround time within port. As a result, a performance-based incentive is missing. Bringing in the incentive component may facilitate the objectives of achieving both port efficiency and sustainability. Blockchain technology, owning to its intrinsic features like immutability, traceability, governance and provenance, and in-built tokens (for most public chain platforms), allow for the establishment of system solutions to record key performance indicators (KPIs) and distribute incentives to good performers. This paper is the first to propose a blockchain-based system to incentivize JIT and green operations in ports. The platform system design and operating mechanisms are elaborated in detail, and a prototype system has been implemented based on the Solana blockchain to demonstrate the core features. The current system's potential is substantial, considering the industry's increasing awareness about its environmental footprint. Continuous developments can be facilitated by connecting to market-based measures such as carbon pricing and emission trading in the maritime sector.

Keywords: container shipping; JIT arrival; blockchain; decarbonization; port optimization; sustainability

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1. Introduction

Just-in-time (JIT) and decarbonization of shipping activities are two essential aspects for next-generation seaports to achieve efficiency and sustainability in port operations [1]. Maritime port authorities worldwide are promoting and working towards introducing JIT practices, which involve providing vessels with a notice of their scheduled terminal berthing time slot in advance. JIT arrival aims to provide a reliable operational arrangement of scheduled services in advance so that unnecessary waiting time can be utilized for lower sailing speed (i.e., slow-steaming), saving fuel, reducing emissions, and constrained port resources (e.g., anchorage zone, port traffic density).

The JIT procedure includes a series of processes, from tracking, communication, and decision-making to the final execution. The vessel operators must undertake these actions together with pilotage, towage, ship chandlers, bunkering, and other port service providers to effectively manage the vessel's arrival to be JIT. However, while the long-term mutual benefits of JIT have been quantified in previous studies [2], a pragmatic view of maritime businesses suggests that not all stakeholders are able or immediately motivated to adhere to the JIT operational principle in every port call [3]. This reality suggests a gap in transparency and recognition in the JIT operation to motivate involved stakeholders in short-term and port call-by-port calls to quantify the contributions and ensure seamless JIT coordinative optimization.

Decarbonization refers to reducing carbon emissions with different measures, such as transitioning to cleaner energy sources, electrification, and vessel retrofitting [4]. Decarbonization has become a critical objective for the maritime industry due to the sector's determination to contribute towards controlling global greenhouse gas emissions. Next-generation seaports need to prioritize decarbonization to align with the global climate goals, improve air quality, especially for coastal cities, promote sustainability, and meet regulatory requirements. In various aspects, JIT and decarbonization are complementary. For instance, optimizing port operations and reducing dwell time through effective JIT can lead to lower fuel consumption and emissions. Similarly, embracing decarbonization measures like JIT aligns with the benefits of port operations by enhancing overall operation performance and releasing pressure on port resources.

Implementing sustainable port initiatives and JIT necessitates a system that can automatically recognize contributions and effective actions by recording key performance indicators (KPIs) and cooperative behaviors and assessing their impact. To encourage and recognize collaborative efforts, the incorporation of a blockchain-based incentive component will be important in supporting the JIT consortium. The blockchain-based subsystem will enable the recording of maritime players' performance, ensuring their compliance with JIT recommendations, and provide incentives for promoting cooperative actions using crypto-secured tokens. Blockchain technology, owing to its properties of immutability, traceability, transparency, and provenance [5], has great potential to fill such a gap in the innovative development of the next-gen port systems. Though there are some practical examples of blockchain applications in the port system and maritime supply chain management, blockchain technology has yet to be commonly used in port management [6–8].

An identified central challenge is to develop a system that can reliably and transparently account for collaborative effort. We see that these features are highly compatible with blockchain's intrinsic nature. In this paper, we propose a use case of blockchain technologies to promote and incentivize JIT and decarbonization efforts in seaports. The use case leverages the immutability and transparency of blockchain to record the KPIs in terms of JIT and emission profile from vessel fleets, and, from there, to provide incentive rewards to good performers. In this solution, blockchain provides a decentralized and transparent ledger to store the KPIs related to JIT and emissions. For example, relevant data, such as vessel arrival times, operation durations, and emissions, are securely recorded on the blockchain after being resourced, assessed, and validated, eliminating the possibility of tampering. With the high-level trustworthiness of the information of JIT and emission performance, smart contracts are implementable to provide insights into the performance and extent of contributions from individual stakeholders, especially shipping companies and their fleets. These data help identify those who demonstrate excellent adherence to JIT practices and curbing emissions, allowing them to be recognized as "good performers" in overall operation efficiency and decarbonization efforts. The generation, distribution, and usage (e.g., redeem, transfer, decay) of incentive instruments can then be realized as a reciprocation for the efforts. In this way, the incentive instrument is both a quantification of contributions and a transferable, liquid form of value. The incentive instruments are called "recognition tokens" (RT) in this paper and include JIT RT (JRT) and Green RT (GRT). They are distributed and accounted for using a public blockchain infrastructure. The separation of the incentive instruments is to differentiate two distinct aspects of operation efficiency and decarbonization, respectively. The proposed blockchain solution enables consensus on performance metrics and the establishment of a rewarding mechanism that would be essential for the success of port efficiency and sustainability by promoting and rewarding JIT and decarbonization practices.

The remainder of the paper is arranged as follows. Section 2 reviews related literature to concretely locate the targeted knowledge gaps. The fundamental principles of the system are described in Section 3. Sections 4 and 5 elaborate on the design and operation of a prototype on the Solana public blockchain before the conclusion in Section 6.

2. Literature Review

This section reviews the literature to signify the criticality of an incentivizing mechanism to support JIT operation and decarbonization. Existing blockchain applications in the maritime logistics industry were also investigated to identify the novelty of our application.

2.1. Blockchain in Decarbonization Efforts

Decarbonization is undoubtedly among the most focused research topics in separate sectors and throughout the supply chain [9,10]. In the energy management domain, the study of WEF [11] mentioned the following applications: peer-to-peer energy trading, crowd sale for renewable energy investment, optimized distributed grid management, renewable energy certificates, carbon offsetting, and sustainability accounting. For example, through transparency in smart grids and P2P energy trading, smart energy management could be enabled to reduce energy wastage [12]. The decarbonization contributions of blockchain mentioned in previous studies include privacy, security, and transparency concerning the current centralized design of energy distribution systems based on smart contract usage and its immutability [12,13]. Blockchains could power platforms that facilitate a free market of exchanging credits involving multiple parties, such as generators, suppliers, traders, end-users, and prosumers [12]. In such settings, blockchain-based systems aim for a free market where the supply chain of energy can be monitored, and combinatory efforts to facilitate clean power can be collectively executed (e.g., distributed ledger of energy credit accounts). Concurrently, there have also been concerns about the energy consumption of the blockchains themselves.

For example, Bitcoin energy consumption has been criticized in studies as enormous and attached to an inequivalent contribution to society [14,15].

Nevertheless, many blockchains have evolved from Proof-of-Work to other mechanisms like Proof-of-Stake, substantially reducing their carbon footprint while maintaining a high level of security and decentralization (e.g., Ethereum, Solana, Cardano) [12]. These latest-generation blockchains are highly programmable, promising use cases beyond financial instruments to improve their cost-to-benefit ratio [16,17]. Blockchain technical solutions, such as inter-chain bridging protocols, roll-up, sidechain, and subchain, ensure the capacity to accommodate the aggregated demands from different applications [16,18].

In maritime logistics, the decarbonization efforts focused on the system's carbon footprint, i.e., logistics system energy usage and direct vehicle emission. The low-carbon shipping measures in this sector could be categorized into two groups: technical and operational [19–21]. The *technical measures* concentrate on physical modifications of the ships and their components (e.g., air lubrication, hull-form designs, engine efficiency and derating, and heat recovery) to reduce the fuel consumption rate of individual vessels [22–24]. The *operational measures* achieve decarbonization through better fleet management (e.g., cargo consolidation, reducing speed, optimized route design, and trim optimization) [25–28]. At the macro level, regulation is being implemented to enforce greener shipping systematically [29]. While the potential has been well-proven in previous studies, carbon accounting for the industry still contains important gaps. A core of these efforts is to maintain a secured record of emissions from ships so that a system of responsibility accounting can operate fairly and effectively (e.g., the EU Emissions Trading System will soon include maritime shipping) [29–31]. An incentive and acknowledgment instrument for decarbonization efforts is needed to encourage collaborative decarbonization activities, such as Just-in-Time ship-port coordination [31,32]. Similar to the energy sector, this is a gap in the maritime industry to which blockchain can possibly contribute.

2.2. Port-Ship Coordination and Just-in-Time Arrival of Ships

Regarding scalability and applicability, it has been pointed out that technical measures are individual-based and costly. At the same time, operational counterparts are feasible for many ships/fleets once the technology is mature with substantially lower cost [28,33]. Among operational measures, JIT arrival is a well-known and straightforward concept (Figure 1) that relies on the speed reduction of the ship and port's operational reliability to achieve lower fuel consumption and emissions. In JIT arrival, port/terminal operators can provide a reliable prediction or scheduled time slots for incoming ships based on the operating schedules. By receiving the requested time of arrival (RTA), ships can reduce their arrival speed, saving fuel and thus decreasing emissions [34,35]. The slowed traffic also means lower vessel density in port, which translates to reduced coastal pollution and a safer navigational environment.

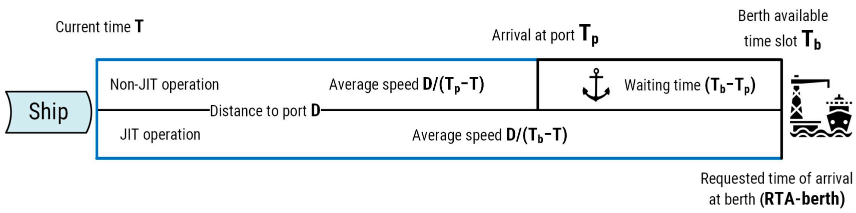

Figure 1. Just-in-Time ship arrival concept.

In the bulk and tanker sectors, the assumption of the ship's arrival committing to "the obligation to proceed with utmost despatch" is reserved through the concept of "virtual arrival", in which ship's Notice of Readiness is sent and accepted as if ships do not adjust their speed following RTA [36,37]. GloMEEP [3] suggested that the container sector is more suitable for JIT operation considering its (1) higher emission contribution and density, (2) higher level of digitalization and predictability, (3) lower contractual barrier, higher speed, more powerful engines, and shorter port-to-port distance (larger abatement potential), and (4) a more concentrated market (faster adoption).

Its emission abatement and fuel-saving potential have been proven significant in different scenarios. The recent study of MarineTraffic [2] using recorded AIS data of 5050 vessels in 2019 indicated that the abatement effects are 14.16%, 5.90%, and 4.23% for JIT speed adjustment made from Pilot Boarding Place, 24-h prior, and 12-h prior to Pilot Boarding Place, respectively. There are existing solutions that allow and support port/terminal operators to implement JIT, such as information exchange platforms (e.g., PortXchange, digitalPORT@SG) and fuel consumption estimation/prediction models [28,38,39]. Leading port operators and port authorities have also implemented software and hardware infrastructure to facilitate JIT arrival, such as Port of Antwerp, Port of Rotterdam, and Singapore Port [40]. A key to JIT arrival implementation is to mandate or encourage multi-party participation, focusing on accurate, updated, and secured timestamps of important events from ships, ports, and terminals in a digitalized and dynamic environment [3]. Since JIT is a collaborative effort, the system should be able to record contributions, allowing for quantification of JIT arrival performance and creating a level playing field. These requirements suggest the potential of a peer-to-peer system, in which not only the distributed ledger can be secured and trusted, but also the incentive instruments (e.g., tokens) can be circulated.

2.3. Blockchain Applications in Maritime Logistics

In maritime logistics, blockchain has been associated with various potentials, such as secured digitalization of transport documents and transparency standardization and promotion [41–43]. Blockchain-based solutions were expected to tackle over-centralization, fragmentations, inefficiencies, and obscurities by creating multilateral interfaces for data pooling and tracing, facilitating a digital chain of parties along the carriage [8,10,41]. By aggregating traceable information to extract better quality data, big data and machine learning can be deployed for optimization, prediction, and risk management [10,42]. Some of the examples include cloud-based blockchain and machine learning in logistics operational management and various aspects of sustainability [44], and maritime transport reliability and safety based on blockchain and edge computing [45]. Tsiulin et al. [46] categorized blockchain-based applications in shipping into document workflow management, financial processes, and device connectivity. They concluded that while having clear interlinkages, none of the reviewed projects have full coverage. Pu and Lam [47], Ahmad et al. [48], Irannezhad and Faroqi [49], and Lu et al. [50] provided conceptual frameworks to apply blockchain's fortes into maritime logistics operations and port services applications. However, empirical studies in this field indicated that collaboration of related stakeholders, suitable use cases, technology maturity, and supportive policies would be critical for blockchain to successfully apply [6,51]. Being co-developed by Maersk and IBM, TradeLens has been used as an example of pioneering blockchain applications in container shipping [9,52–54]. However, its discontinuation from the end of 2023′s first quarter has been seen as a significant setback for the technology. Even though Maersk and IBM are both powerhouses in their sectors, they cannot rally enough support from the industry to the project. This highlights the challenges in achieving mass blockchain adoption in maritime logistics, emphasizing the need for clear benefits, industry-wide collaboration, and addressing existing sectoral barriers to spur a domino effect of adoption [6].

2.4. Key Innovations and Contributions

The literature review depicted the contrast between the potential of blockchain in maritime operations and management, and the limited cases of successful application. A critical barrier to be addressed is a suitable use case where the characteristics of blockchain fit its implementation. On the other hand, JIT arrival is among the most recommended operational low-carbon shipping measures. Applying JIT arrival would benefit from a secured and multilateral platform to record immutable related data, facilitating a level playing field to recognize and encourage collaborative efforts in materializing JIT.

In this paper, we propose the design of a novel application of blockchain technology for the case of Just-in-Time (JIT) performance, focusing on incentivizing effective traffic flow management, port resource utilization, and collaborative decarbonization efforts. The system is designed to integrate both on-chain and off-chain storage and computation to deliver essential services for the blockchain-based incentive solution. The solution has no restrictions regarding blockchain types. In our design, blockchain functions include the following.

1. *Immutable and tamper-free storage* for critical data records (i.e., JIT and emission performance) that brings in transparency and immutability.
2. *Incentive distributor* of built-in tokens for recognition of collaborative efforts.
3. *Backbone digitalized network* linking with other services, such as port operation optimization, carbon accounting, and emission trading platform.

The originality and innovation of this work are summarized as follows:

1. To the best of our knowledge, this is the first implementation of blockchain in promoting and incentivizing JIT for decarbonization efforts [55,56].
2. The details on technological design approaches and architecture paradigms associated with port operation practices are elaborated with rationale.
3. Incentive rewarding models for JIT and decarbonization are proposed.
4. A working prototype system is implemented on Solana blockchain, demonstrating the system's feasibility and key features.

3. Fundamental Concepts and Infrastructure Elements

This section discusses the conceptual framework, technical foundation, and infrastructure design of the blockchain-based incentive system solutions, including the scope and contents that could be extended based on the proposed solution. This section first presents the concepts in JIT arrival and the bases for quantifying collaboration efforts in

JIT operations benefiting ship and port management under the form of RTs (Section 3.1). The potential usage scenarios of RTs to promote Just-in-Time (JIT) operation and reduce emissions will be discussed in Section 3.2, before the system design and blockchain architecture is shown in Section 3.3. It is noteworthy that the focus of this work is largely on conceptual designs and implementation of the blockchain-based system at the level of proof-of-concept (POC) prototype. Therefore, modularized approaches have been utilized to ensure the cohesion and flexibility of blocks so that components of modules can be easily replaced and upgraded if needed.

3.1. JIT Framework and Coordination Plan

The principal participants in the JIT framework include shipping companies and port-related parties (e.g., port authority/operators/port service providers). Their market standing and JIT arrival's benefits and contribution, together with decarbonization efforts, are summarized in Table 1. In this setting, the port's digital platform is critical in gathering and distributing information regarding the scheduled service time slots to individual ships. Examples of such platforms include PortXchange (formerly known as Pronto) for the Port of Rotterdam and digitalPORT@SG for the Singapore port.

Table 1. The participants and their roles, benefits, and contribution in port systems.

	Shipping Companies	**Port Operator**
Service market position	- Port and terminal service user	- Port and terminal service provider - Port authority/Data exchange platform owner
JIT and decarbonization benefits and motivations	- Lower fuel cost - Reputational recognition as more efficient and greener	- Lower port density—port congestion reduction - Better port safety situation - Better port service and management - Assure global and regional goals for emission reduction and meet legislative requirements
JIT contributions	- Operationally ready for JIT arrival - Follow JIT requests to implement slow-steaming	- Berthing slot prediction and assurance - Supportive services assurance
Decarbonization contributions	- Less fuel consumption—Less emission - Reduction of emissions in coastal areas	- Drive sustainable port development - Reduce the impact of ship emissions on coastal and urban area - Reduce overall emissions while providing a better level of port service

The JIT operation starts with monitoring arriving vessels, and the JIT feasibility can be assessed by comparing the current ETA of individual ships (e.g., AIS data or berth application) with the predicted/scheduled berth time slot. Since the terminal operations are dynamic, a horizon should be decided to ensure the certainty of the assigned Requested Time of Arrival (RTA), concerning the fact that JIT failure could occur if the ships have to increase speed to meet RTA. Once the JIT potential is confirmed, the ship operator will receive the RTA and an estimation of recognition and other benefits. Based on the operation plan and intentions upon arrival, the ship will return their decision of JIT commitment, indicating their updated ETA. After the ship's arrival, evaluation can be conducted to calculate the dedication of the port and ship in the JIT effort. The flow of information to and from each of these parties is described in Figure 2.

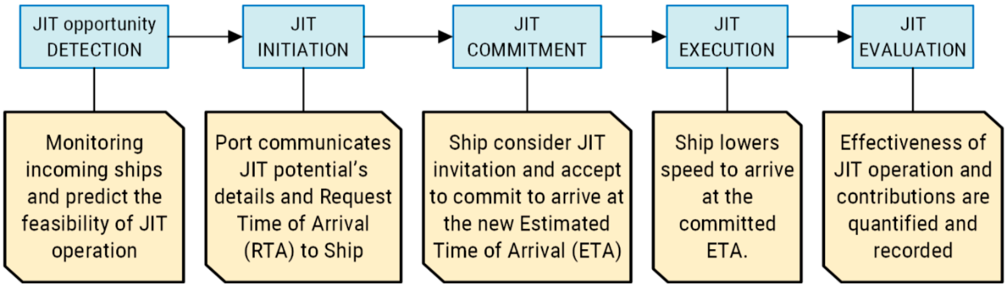

Figure 2. The flow of information of Just-in-Time processes.

To recognize and promote JIT practices, this paper proposes the concepts of recognition tokens (RTs), including JIT RT (JRT) and Green RT (GRT). They are distributed and accounted for using a public blockchain infrastructure. The separation of the incentive instruments is to differentiate two distinct aspects of operation efficiency and decarbonization, respectively. At the conceptual level, the calculations of JRT should be based on comparing the two states of "JIT" and "non-JIT" to capture the effort to achieve JIT operation. Regarding the operational aspect, the JRT reward (R_{JRT}) for individual ships is determined by two principal factors: the extent of schedule adjustment efforts (Adjustment, denoted by A) and impact on port operation (Impact, denoted by I) (Equation (1)). Adjustment could be measured through the difference between the original Estimated Time of Arrival (ETA) (t_{ETA}) and the new ETA (t'_{ETA}) resulting from speed reduction after receiving a JIT request, denoted as Δt (Equation (2)). To quantify the ship's impacts on port operation (I), a summation can be used to aggregate the ship's impacts (I) on n different port resources (e.g., as berthing, piloting, tugging, supplying, and bunkering) (Equation (3)). Depending on the perspectives and strategies of port authority in encouraging JIT, different methods of calculation can be applied for each resource I_k, as well as the importance of such resources to port expressed as an impact weight factor w_k.

$$R_{JRT} = C_{JRT} \cdot f(I, A) \tag{1}$$

$$A = \Delta t = t'_{ETA} - t_{ETA} \tag{2}$$

$$I = \sum_{k=1}^{n} (w_k \cdot I_k) \mid \sum_{k=1}^{n} w_k = 1 \tag{3}$$

For example, the impact of the ship on cargo handling facilities (I_c) can be quantified based on berth stay time T_{berth} and berth length occupied, which could be estimated from ship length (L), which has been widely implemented in berth allocation optimization studies [57] (Equation (4)). The spatial-temporal occupation (I_o) of the ship in the port's water can be quantified based on the ship's two-dimensional size from ship length (L) and ship width (W) and total time spent (T_{stay}) in port (Equation (5)). For tugging and pilotage services, it could be the total capacity hours that is required for the ship in that particular port call (e.g., man hour and tugboat power capacity hour).

$$I_c = t_b \cdot L \tag{4}$$

$$I_o = (W \cdot L) \cdot T_{stay} \tag{5}$$

The factor C_{JRT} is reserved for conversion factor(s) from the quantification of weighted effort to the total amount of reward token. JIT requires alignment between port service providers and arriving ships (i.e., shipping companies). The reward split between shipping companies and port service providers is negotiable (e.g., Port:Ship of 5:95).

$$R_{GRT} = \begin{cases} 0 & E \leq E' \\ (E - E')\cdot C_{GRT} & E > E' \end{cases} \quad (6)$$

Regarding the GRT reward (R_{GRT}), the baseline emission quota (denoted by E) as a reference for comparison and incentive reward calculation can be determined according to the port development plan and long-term strategies on emission reduction, for instance, the "Maritime Singapore Decarbonization Blueprint" released by Maritime and Port Authority of Singapore (MPA). An annual quota on cumulative carbon emission can be allocated to the shipping companies; accordingly, the emission amount of a shipping company's actual committed annual emission (denoted by E') less than the annual quota is applied to derive the GRT reward, as expressed in Equation (6), where the factor C_{GRT} is denoted as a factor coefficient to convert emission reduction to nominating value holders (e.g., cryptographic tokens).

The aforementioned JRT and GRT reward functions are based on simple models for an intuitive derivation from the JIT performance and efforts on emission reduction. It can be observed that no penalty has yet been introduced for consideration. Such incentive-rewarding models can be replaced by more realistic models and adapted to any specific requirements demanded by individual ports.

The fund sources for monetary incentive reward can be driven by the port authority, since both JIT and decarbonization will benefit the port operation efficiency and sustainability, which eventually support enhancing the port competitiveness, throughput, quality of service, and regional air quality, and contributing to the overall revenue increase of port businesses. In addition to the monetary incentive, non-monetary incentives can also be developed based on the historical KPIs recorded for individual shipping companies, such as regarding their punctuality and compliance to port side arrangement and scheduling. Thus, by ranking their performance, port resources and services can be prioritized and optimized.

3.2. Crypto-Economic Considerations

Fundamental principles: The proposed system, while straightforward in initial ideas and prototyping, will need careful considerations before deployment. The following fundamental principles are recommended based on previous studies and the current application context. ***First***, it is recognized that token systems are complicated and would require comprehensive testing to understand the behaviors of involved parties, and the supply and demand of RTs to be allocated. While a consortium blockchain could ensure the commitment of participants, it requires extensive resources to maintain network security and it is vulnerable to scenarios of withdrawal, which have been observed as critical in the case of TradeLens [6]. A public blockchain would be potentially suitable in this case, as its security and decentralization have already been protected and battle-tested in protecting a large amount-value of transactions for an extended period of time, alleviating developers and users the efforts of building system from scratch [58]. ***Second***, the utility of tokens is a key motivation for industry parties to adopt this solution. As recommended by industry experts, a recommendation has been to start with simple implementations before expanding the use cases and new mechanisms [6]. ***Third***, the system is designed to have an iterative and transparent design to be examined by all potential participants. System sustainability is a critical factors, suggesting that the blockchains that are in a transitional period or suffer from network congestion (e.g., Ethereum) might not be an ideal choice [58]. The backbone blockchain should be adequate regarding transaction throughput, settling latency, and operational fee to ensure low inertia for participants [59]. A well-supported and developer-friendly ecosystem is also important to reduce technical inertia and improve network effects. However, iterative development should not change the purpose-driven design of the token, which is to quantify the contribution of fleet to the port operation and decarbonization journey, which aligns with the net-zero GHG emissions roadmap of the industry. For example, token holders can participate in voting in different technical and operational aspects of the system. ***Fourth***, it is critical to tie the supply and demand of the RTs to the dynamicity of the operational situation to avoid inflation. This would require algorithms to incorporate mechanisms such as elastic supply or token decay/burning to ensure the system's capability to reinforce the slow-steaming and emission reduction behaviors of participants while taking into consideration the port situation.

Potential utilities: The first and foremost usage of RTs is recording and recognizing collaboration efforts in JIT operations. The accumulated JRT and GRT can be used as a credit for the contribution of both the ships and the port in JIT operation. However, leveraging the security and immutability of these tokens being distributed and accounted for in a public ledger, an ecosystem can be established using JRT and GRT as trading instruments and storing value, which are materializable in "monetary" forms. For example, JRT could be integrated into the port service system, redeemable for related services, such as anchorage zone fee, pilotage fee, or even a fine if ships failed to arrive at the committed ETA. If the port cannot provide direct berthing or the waiting time as agreed upon, the port should partly pay the ship's anchorage fee. GRT could be redeemed when paying for environment-related services and procedures, such as garbage collection, emission tax rebates, and cold ironing. Another potential in using GRT is connecting it with an Emission Trading Scheme (ETS), expanding the token's liquidity. "Non-monetary" forms of redemption can also be considered. For instance, prioritizing the port services to those shipping companies that consistently meet or exceed JIT targets while maintaining low emission levels according to their historical performance recorded on the blockchain. These integrations can be easily integrated based on the transparency and verifiability of transactions of crypto-secured tokens managed by the ledger and transaction-handling smart contracts.

With the above discussions, the authors recognize and fully respect the complexity of a full-fledged crypto-economic frameworks. However, in its most basic form, this solution serves as a transparent and immutable ledger, recording RTs accounts as testaments to participation of early-adopters in JIT operation, encouraging parties to participate while waiting for features to be developed and implemented and barriers to be lifted progressively, such as liquidity features (e.g., unlock transferability) and administration features (e.g., declare and examination of RT accounts). This will also reduce the regulatory concerns, which has been mentioned extensively in the literature [7,60]. Potential research directions to fill these knowledge gaps will be discussed in Section 5.

3.3. System Design and Architecture of the Blockchain-Based Incentive Solution

The proposed JIT supporting system relies on blockchain technology to record the JIT and emission KPIs of stakeholders and accordingly incentivize those contributing towards port efficiency and sustainability. It is worth mentioning that those KPIs are business-sensitive and should be tamper-free and securely stored to ensure that recorded KPIs cannot be modified or manipulated without authorization. This is critical considering the purpose and operating mechanisms of JIT arrival. In this regard, blockchain's immutability and transparency serve as the backbone to support this requirement.

Specifically, to bring in the blockchain as the underlying base technology to support the addressed use scenario in terms of promoting the sustainable and efficient port operation is considered from the perspective of either "essential in design" or "easier to implement" to fulfil the application requirements. First, the whole system and its incentive mechanism only work if the key performance indicators (KPIs) of vessel/fleet are recorded in an "immutable", "tamper-free", and "trustworthy" way, which is guaranteed by the intrinsic properties of blockchain. If using any existing centralized solutions, KPIs can be potentially modified by personnel, such staffs who manage or control the servers and database, to maximize the benefit to or in favor of one of parties in a collusion situation (to help a specific shipping company gain more benefit like tax reduction from the port incentivizing plan or policy). Since incentives are derived from the performance of vessels (complying with port operation scheduling for efficiency and emission control), and are tied to rewards and interest, the KPIs must be securely stored for transparency, provenance, and resistance against any malicious modification. This is the primary reason that the blockchain must be taken into consideration. Second, blockchain technology, over the past several years, has experienced rapid development and has become matured in aspects like allowing high transaction throughput (such as Solana, selected in our solution); meanwhile, the built-in token and coins solutions and fund transfer are naturally supported by almost all blockchain platforms. This is an essential feature in our use scenarios for token mint, incentive calculation, and incentive distribution through coin transfer, etc. All these blockchain intrinsic properties make it easy to implement our application tailored features. The overall schematic architecture of the proposed blockchain-based incentive solution for port management is illustrated in Figure 3.

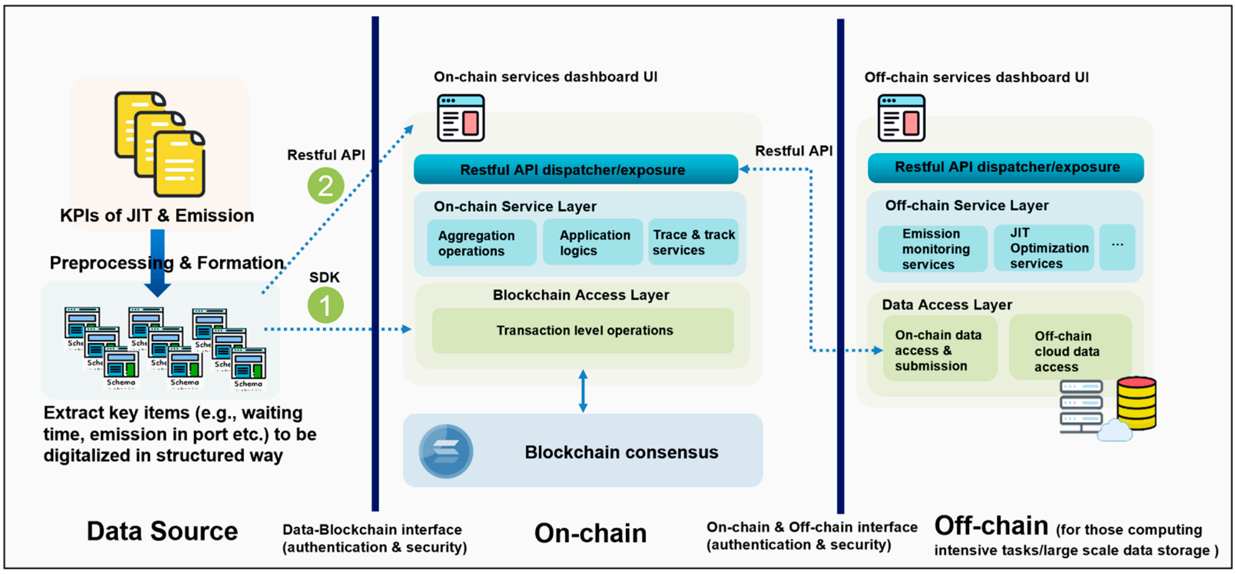

Figure 3. System architecture design of the proposed blockchain-based incentive solution.

The KPIs regarding JIT and emissions are derived according to vessels' operations in ports, which have been elaborated in Section 3.1. The KPIs are uploaded and stored onto blockchain through the Representational State Transfer (REST) API, developed using the Software Development Kit (SDK). The idea of on-chain and off-chain integration, which has been proposed in previous studies, is adopted from the study of Xiao et al. [61] in order to enable large-scale or privacy-preserving off-chain data storage as well as resource-intensive and nondeterministic computation-based services. Those off-chain data include the raw vessel traffic and operation data, while off-chain computation is various decision support models and services, such as ETA prediction, port situation monitoring, and operation optimization. The off-chain computation services could also be the creation of situation awareness and insights, and other decision-making engines like optimization of port operations, port stay prediction, and coordinative optimization. On-chain and off-chain integration could be flexibly achieved through any standard networking/data retrieval interface techniques like REST, EDI messaging, or Remote Procedure Call (RPC). Figure 4 illustrates the essence of on-chain/off-chain integration and the core design concept in an abstract form for generality.

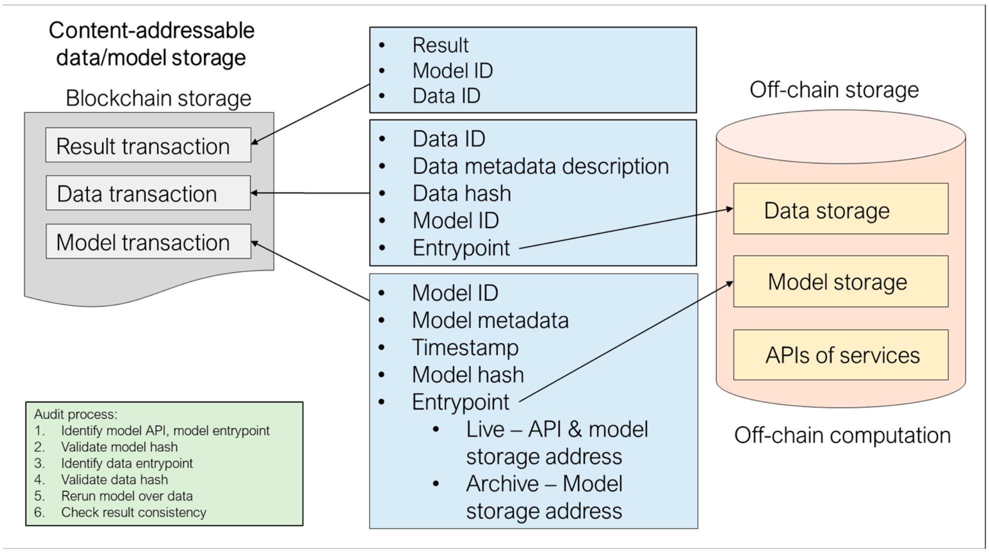

Figure 4. On-chain/off-chain data integration design.

In Figure 4, off-chain computation allows better flexibility to deal with data unsuitable to put on chain (e.g., due to privacy concerns, or large-scale data volume or model complexity). With on-chain/off-chain integration design, although data/model can be stored/executed off-chain, it can still preserve the provenance of data integrity and off-chain modeling and computation trustworthiness without compromising the traceability, verification, and provenance of the lifecycle of processes. In Figure 4, data transaction records the information of input data with its identity, metadata, and hash/checksum; the model transaction persists the model identity, its metadata, and hash/checksum, while the result transaction links both the data and the model that has been executed to create the result and generate the insights. In our use case, the raw data regarding the fuel consumption, such as daily diesel tanker sounding records and the relevant business data like the detailed information on cargos, can be put off-chain for computing to generate necessary input for on-chain based emission (or its reduction) estimation, etc. This method maintains privacy by allowing the off-chain computation to be hosted using on-promise servers or cloud services solely controlled by the operating company who own the business data, and only the cryptographic hash or checksum of their data and model as "digital fingerprint" are required to be put on-chain for potential provenance in case that any audit process is triggered and requires replicating the computing results for comparison with the on-chain recorded checksums.

Such design allows blockchain-based regulation of off-chain storage and computation, i.e., content-addressable data/model storage. For audit and investigation purposes, it allows initializing a model re-execution to replicate the modeling results for consistency verification using the identical input data and model assured by hash fingerprint recorded on-chain, as shown in the inset of Figure 4. On-chain and off-chain integration also introduces feasibility in real-world implementation for better query/retrieval. The lightweight data and computation are implemented on-chain and protected by the consensus mechanism, while large-scale data and heavy-overhead computing tasks are deployed and run off-chain. This design can flexibly access the dedicated high-performance server or cloud resources that can be cross-verified, regulated, and audited by the respective on-chain storage. It is worth mentioning that the "model" could be any form of traditional statistical algorithm or machine learning model. This "plug-in" mode enhances the flexibility of the proposed solution to allow continuous development of other modeling components (e.g., ETA prediction of incoming ships and port situation prediction based on AIS data, fuel consumption prediction, etc.).

Regarding on-chain storage and computational services, the main service components include: (i) recording vessel performance profiling in a trustworthy, reliable, and transparent manner; (ii) the crypto token (i.e., JRT, GRT, and any additional RTs) transfer to distribute the monetary incentive to shipping companies; and (iii) recording all the necessary data to facilitate on-chain/off-chain integration linking with other technologies, such as port operation optimization, ETA prediction, port stay prediction, and emission estimation.

The details on system features, the platform roles they serve, and the corresponding on-chain/off-chain data storage and computational services are provided in Table 2. Systems features to be linked with the operations of the platform end users will be elaborated in Section 4. The user interface allows shipping company users to register vessels and retrieve vessel fleets and the related JIT and emission performance. Port users can retrieve the shipping companies that visit the port, obtain the rank of shipping companies regarding their JIT and emission performance, view the derived JRT and GRT incentives, and endorse them.

Table 2. Roles of parties and their involved on/off-chain data storage and computation.

Platform Role/End User	Operational Functions	On-Chain/Off-Chain Data Storage and Computation
Shipping Companies	- Retrieval of fleet of all ships and see their performance (KPIs) - Add ship	- JIT-related performance indicators (on-chain storage) - Emission-related performance indicators (on-chain storage) - Raw traffic and operation data (off-chain storage) - Service scheduling and intelligent decision support features (off-chain computation) - Ship information like ship name, MMSI, IMO, and shipping company (on-chain storage)
Port	- Retrieval of how many registered shipping companies and their shipping - Retrieval of ship performance by shipping company and ranking the ship companies and history transactions - Calculate the reward and transfer incentive	- Shipping companies' information (on-chain storage) - Performance ranking (on-chain computation) - Rewarding transactions (on-chain storage) - Reward calculation (on-chain computation) - Token transfer (on-chain computation)

To address the urgency of decarbonization, our proposed solution necessitates specific design considerations for the base blockchain platform and its technical specifications. Solana was selected as the base blockchain platform for the solution implementation in this work primarily based on four reasons. First, the base blockchain network should be efficient to satisfy the target use case requirements, considering the arrival rate of vessels and transaction submission rate of the relevant KPIs and other on-chain computational logic, while keeping its financial and ecological cost sustainable and scalable. Solana is characterized by high Transaction Per Second (TPS), low transaction latency (i.e., time until a submitted transaction is included in blocks), and minimal transaction fees (i.e., token spends for transactions to be validated in blocks). Second, Solana has the native token liquefiable on mainstream crypto tokens trading platforms while still allowing for the definition and minting of novel tokens, such as the JRT and GRT in our context. Third, while consortium blockchain platforms like Hyperledger Fabric might appear as potential candidates, they inherently require the formation of a consortium and the selection of partners to host nodes and co-manage the blockchain network. Contrarily, Solana operates as a public blockchain, providing a more decentralized approach by relying on public nodes and network. Solana's architecture combines Proof of Stake with Proof of History, thereby ensuring the security of the network through a decentralized system of validators. This decentralized consensus mechanism is especially pertinent given our emphasis on decarbonization, ensuring energy efficiency. Fourth, the existing ecosystem and interoperability standards within Solana promote developer-friendly practices and encourage adherence to industry-wide benchmarks. This facilitates the cross-platform compatibility of vital components like token design, smart contract format, and security standards (e.g., ERC-20 and ERC-721 tokens on Ethereum). It is also noteworthy that we do not rule out the possibility of other public blockchains to be comprehensively considered using a multi-criteria decision-making model for the full-scale application.

4. Proof-of-Concept (POC) Prototype System Implementation

This section provides details of the solution implementation, design, and development of on-chain storage (i.e., Solana accounts), computation or smart contract (i.e., Solana programs), and system deployment. Notably, the incentive models implemented in this work are mainly for demonstrative purposes. The system's rigorous and more realistic versions would require more investigation on the economic properties, such as the quantity of tokens to be initially supplied/issued and the decision on the amount rewarded to eligible individuals under the fund limit to maximize the incentive to the whole system. While relevant to the current research, those considerations are out of this work's scope and deserve dedicated studies. However, incentive models can be easily incorporated into the proposed solution by implementing the corresponding smart contracts that deal with the reward calculation based on the inputs like JIT and decarbonization KPIs of the players and the total reward fund limit.

In order to demonstrate the viability of our solution design elaborated in Section 3, we have implemented a POC prototype (hereby called the "POC" for short). The whole system has been coded using Anchor 0.24.2 framework for Solana 1.10.26 backend smart contract and blockchain state programming and Svelte framework for the front end. Anchor was chosen due to the presence of existing packages for actions such as deserializing accounts. As a framework for development on Solana's Sealevel (the engine that processes transactions on Solana), we found this to be the state-of-the-art software for development. The system was coded using *Rust 1.64.0* programming language on *Windows Subsystem for Linux (WSL) 20.04.* A high-level flowchart of the prototype operation is illustrated in Figure 5.

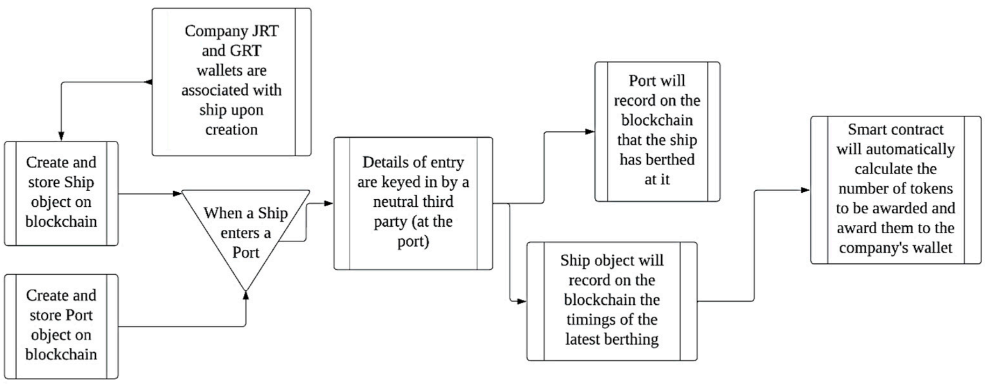

Figure 5. The key features of the platform and processing workflow.

In the following sections, the term "user" refers to any entities that use the program. These entities could range from shipping companies registering their ships to port operators who wish to inspect the ships berthed at port. "Program" refers to any smart contract or connected logical group of smart contracts for specific purposes. The term "provider" refers to the central authority managing the system. This authority would be the one minting the JRT and GRT and awarding them to shipping companies that comply with JIT practices. Its wallet would also be referred to as the "central wallet".

4.1. The Relevant Entities

The main entities engaged in the system are ships and ports (Table 3). Here, ships are mainly considered as sea-going merchant ships like container vessels belonging to a shipping company, which a unique identifier in the system will represent. These attributes are required for the smart contract to calculate the number of tokens to award each ship for their contribution to align with port JIT recommendations (i.e., assigned time slot of berth availability). Every ship will be created on the ship creation page, and all the information on that ship will be stored on the blockchain.

Table 3. The key attributes of ship and port entities.

Entity	Attribute	Description
Ship	Company_id	Unique company identifier
	Ship_id	Unique ship identifier (MMSI/IMO)
	berth_time	Actual berthing time of the ships
	intial_berth_time	The timing ship was going to berth before the slow speeding request
	expected_berth_time	The timing of the ship was requested to berth
	emission	The amount of greenhouse gasses emitted by the ship
	wallet_id	Unique wallet ID (unique to each company) to be used in transactions of GRTs
	Slowspeed_reward	The amount of GRTs awarded to the ship
Port	port_id	Unique port identifier
	ship_count	An integer showing the number of ships currently berthed at the port
	wallet_id	Unique wallet ID (unique to each port)
	ships_berthed	A vector containing the MMSIs of the ships currently berthed at port

The decentralized recording of these pieces of information, especially the KPIs' related attributes and identities, ensures a layer of security against information tampering and transparency and reliability to the transactions of crypto tokens. A similar system is implemented for ports (i.e., attributes and verifiable unique identifiers). However, the only information stored in this structure is a vector of the names of the ships currently berthed at the port. This vector is set to be mutable only by the smart contract program. Possessing a unique keypair for every entity that owns a wallet ensures that the information regarding the ships is reliable, preventing any entity without access to the program's keypair from changing the committed records.

4.2. Transaction Security and Wallet Ownership

Every port and shipping company that wishes to participate in JIT and transact tokens must possess a wallet for every transactable token, thus having separate unique keypairs for protection. Two main tokens are created with separate wallets for each of them, namely JRT and GRT wallets. For convenience, the actionable front end can integrate both tokens with two main wallets in the same User Interface (UI). The authority that allocates ownership of the wallets will be the Solana Program Library (SPL) Token Program, which is the sole authority that can enforce token ownership and transfers. This program is a set of immutable smart contracts that possess a public key, which is the sole authority required to sign any form of token transaction. It should be noted that the Solana cryptocurrency (SOL), though needed for transaction fees, is separate from JRT and GRT. Only the smart contracts of the POC have jurisdiction to perform JRT and GRT transactions.

The immutability of the on-chain data, Solana ledger, and on-chain/off-chain integration (Figure 4) serves as the fundamental layer of the POC security for transactions. Transparency is ensured through the publicity of the Solana ledger, which is readable through Solana Explorer. Fraudulent minting of the tokens is prevented by the sole authority of the SPL in minting and distributing JRT and GRT tokens. Smart contracts were developed for the POC, from adding ship and port entities to the awarding of tokens for the adjustment of arrival time or slow speeding to meet JIT, and they are all implemented as account structures (Figure 6).

```
use anchor_lang::prelude::*;

#[account]
pub struct Ship(
      pub company_id: String,
      pub ship_id: String,
      pub berth_time: i64,
      pub initial_berth_time: i64,
      pub expected_berth_time: i64,
      pub leave_time: i64,
      pub ship_etl: i64,
      pub punctuality: i64,
      pub emission: i64,
      pub wallet_id: i64,
      pub slowspeed_reward: Pubkey,
      pub total_reward: i64
)
```

Figure 6. Example of an account structure implementation on Solana with Rust.

This concept is implemented to allow simplicity in development, where every entity can be created with a base structure known as an account. Every account is protected by its private key (similar to a digital signature), encrypted using the SHA-256 algorithm, and can be referred to by other accounts via its public key (similar to an address for transactions). Every created smart contract is required to have an attribute "system_program", which is essentially the Solana core program, containing helper functions that can be called to carry out specific tasks (e.g., adding ships to the blockchain, specifying attributes to call on later for other functions/features, etc.).

Following that, the entities are initialized as accounts with mutable attributes, with the payer being the wallet whose identification is indicated by the user in the front end user form. Considering the memory available on the blockchain, the number of ships that can be stored in each port is limited to 100 in this POC, but this can be altered accordingly as long as the user allocates more space or splits accounts to release the space limit set by Solana programs and accounts.

4.3. Remote Procedure Calls and Functions

The front end features functions defined by Solana to fetch an existing account by its public key. This is performed via Remote Procedure Calls (RPC). The RPC form allows us to request a service from the Solana network without having to understand its exact network details (e.g., retrieving ships and ports currently registered on the blockchain). After the entities of involved parties are created, information on every object created (ports and ships with information, as in Table 3) can be retrieved from the blockchain by port operators and shipping companies. Solana SDK provides the methods and will be called with each valid form submission on the front end.

The first step for any port operator or shipping company wishing to use the POC would be to initialize the test validator. This is conducted by running the *solana-test-validator* command in the WSL terminal. The test validator creates a ledger, which records transactions' history, allowing Solana to utilize the proof-of-history method to validate transactions. The program would then create JRT and GRT via the *createMint()* function, ready for awarding ships JRT and GRT for contributing to JIT efforts. This is performed with the *providerWalletATACreator()* function.

Subsequently, when the shipping company registers ships, the *createUserAndAssociatedWallet()* function will be used, creating and returning both the ship account and the associated token account. When a ship is berthed, and if it is deemed eligible for rewards from JIT contribution, the RPC command *initExchange()* will be called to transfer the relevant tokens from the provider's associated token account to the ship's associated token account, for both JRT and GRT (Figure 7).

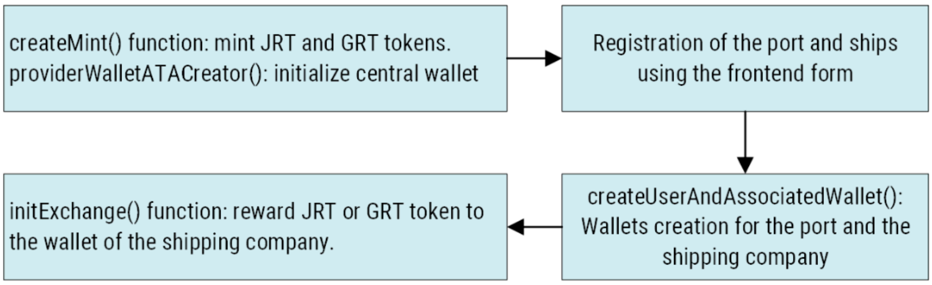

Figure 7. Functions being called along the JIT operation.

In Solana, gas fees are transaction fees that will be distributed to *validators* to compensate for the resources they have allocated to keep validating and securing the Solana public blockchain. Each shipping company would need only one main wallet to log into the POC platform, which will store SOL for handling gas fees incurred during transactions and is different from dedicated wallets for JRT and GRT (explained in Sections 4.2 and 4.3). In the current version of the POC, the transactions of JRT and GRT tokens can only be performed by the smart contracts written, called *program-derived smart contracts*. However, additional features and functions, such as peer-transfer of tokens, can be developed in future updates. Finally, the working mechanism of the POC's initial version is illustrated in Figure 8.

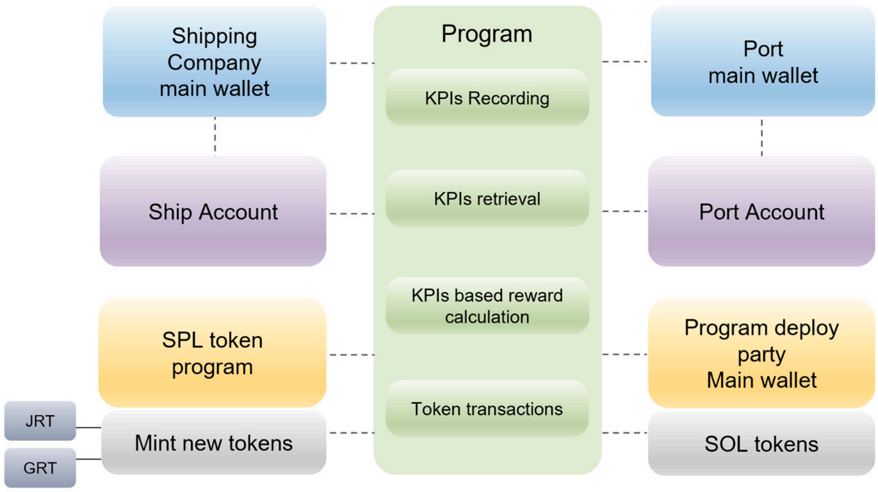

Figure 8. Implementation and organization of POC based on Solana blockchain.

4.4. Software Testing and the Implemented User Interface (UI)

For testing the POC, the described process was put into action through a simulated environment on JavaScript. Limit testing was conducted to confirm the limit of 100 ships (i.e., vanilla Rust implementation of vectors). In actual system implementation, this limitation is adjustable by the central management authority based on the expected maximum number of ships that will berth at the port for an amount of time that the central management authority can set. Every implemented function was tested, from account and wallet registrations, token reward, to information retrieval functions to display all the ships currently berthed. The entire program was functionally tested with the help of the framework *Mocha 10.1.0*. The test dependencies include *@project-serum/anchor 0.25.0*, *npm-run-all 4.1.2*, *@solana/web3.js 1.78.4*, *@svelte-on-solana/wallet-adapter-anchor 1.0.16-alpha.0*, and *number-to-bn 1.7.0*.

The UI implemented with the POC system is relatively simple and straightforward (Figure 9). It should be ensured that the central wallet always contains enough SOL to carry out token transactions (as gas fees). The wallet can be topped up with the *solana airdrop n* command, where n is the number of SOL tokens to be airdropped into the wallet.

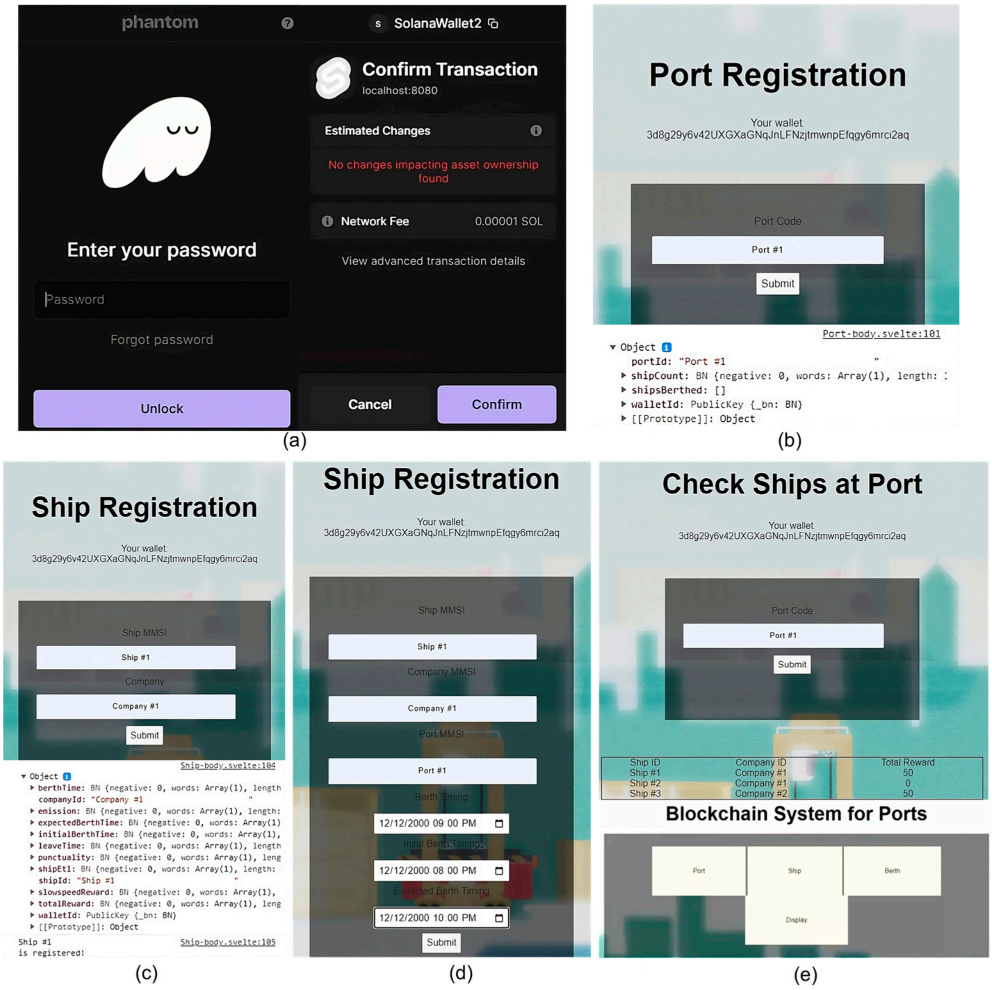

Figure 9. UI implementation of the POC system, including (**a**) Phantom Wallet browser extension login, (**b**) port's registration, (**c**) ship's registration, (**d**) berthing timestamps, and (**e**) aggregated operational information.

Logging in using Phantom Wallet: Once the user (ports or shipping companies) uses the Phantom Wallet browser extension to log in, the public key of their main wallet will be shown (Figure 9a).

Registration: To register a new port, a system operator simply has to enter the name of the port (Figure 9b). For ships, the shipping company can submit information on the ship via the "Submit a Ship (Shipping Companies)" option. The shipping company would have to enter the ship's unique identifier and the company the ship belongs to. Submitting will register the ship as an account on the blockchain (Figure 9c).

Reward transactions: For a ship's arrival, the amount of JRTs and GRTs the ships are eligible to receive will be calculated and sent from the central wallets to the shipping company's wallets (Figure 9d). These timestamps would then be stored in the ship's account on the blockchain.

Information retrieval: Historical records of ships' and ports' JIT performance is retrievable for future reference. Their information is protected by Solana blockchain's layers of security. Additionally, operational information, such as the ships that are currently berthed at the port, is also derivable from the blockchain for administrative purposes (e.g., details of ships currently berthed and their total token rewarded). (Figure 9e). It should be noted that the current POC is only to demonstrate that the concept of an incentive system to support JIT on the blockchain is feasible and scalable, which can be developed further. The bottom diagram of Figure 9e illustrates the entry portals accessing all the functional features, as shown in Figure 9.

5. Decarbonization Potential and Challenges for Continuous Developments

Even though the integration of the blockchain-based incentives and other components in the JIT support system is still ongoing, a preliminary experiment has been conducted to examine the potential of JIT arrival to Singapore port, which reflected the meaningfulness of the RTs in adjusting the speed behavior of ships arriving port (Section 5.1). Section 5.2 summarizes the challenges that will require additional research effort to address.

5.1. Decarbonization Potential Experiment

Apart from the developed POC detailed in this paper, the experiment includes other modules. *The first module* provides ETA predictions for ships coming to Singapore port (ETA prediction). *The second module* outputs predict whether the ship could be directly berthed if it arrives at different potential ETAs, corresponding to a different speed band (Direct berthing prediction). *The third module* estimates the fuel consumption of the ship for both main and auxiliary engines, corresponding to ship specifications, voyage specifications, and navigational conditions (Fuel consumption prediction). The experiment setup is shown in Figure 10a, together with a preliminary UI as in Figure 10b. The experiment was conducted assuming that ships will follow slow-steaming recommendations based on the provided estimation of fuel saving, together with the distributed RTs. The monitoring period for each vessel starts from the first time the predicted ETA returns 3-day ETA. The results indicated that the total fuel consumption of all ships berthed in Singapore port would be reduced by 11.83%, measured on 17 container vessels in one month of May 2020. This result aligned with the previous study by MarineTraffic [2] of 5050 vessels in 2019, which indicated that the abatement effects are 14.16%, 5.90%, and 4.23% for JIT speed adjustment made from Pilot Boarding Place, 24-h prior, and 12-h prior to Pilot Boarding Place, respectively.

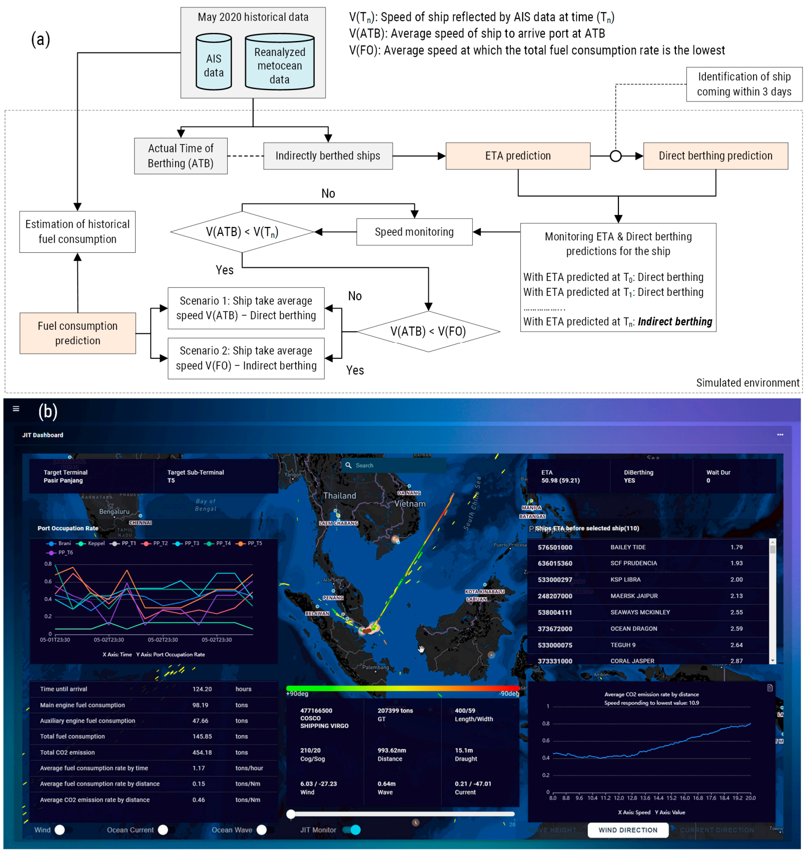

Figure 10. JIT simulated experiment design (**a**) and UI (**b**).

5.2. Challenges for Continuous Improvements

From a crypto-economics perspective, there are multiple aspects that require extensive investigation and analysis to drive the proposed solution out of the POC state. First, monetary policy for the RTs is essential if more advanced features are to be applied, such as token trading, being used as payment instruments, or liquidity to carbon trading systems (e.g., EU Emissions Trading System—ETS) [29]. Technically, blockchain-based tokens can be linked to carbon credits in digital trading platforms to improve the ETS's overall liquidity, facilitating the tracking and trading of emissions allowances [62,63]. However, the exact mechanism and legal framework surrounding such an implementation would depend on the specifics of the ETS and related regulations. Second, some key specifications regarding the supply of RTs have not been detailed. Token deflationary strategies are necessary to maintain RTs' scarcity (e.g., lifecycle of tokens, token burning, token flow planning) [16,42]. Third, research into the adoptability of the solution is required to ensure its potential network effects, as well as taking feedback from the possible involved parties. A roadmap to develop the solution in parallel with a growing number of users or integrations will be beneficial for this purpose. Finally, research should be conducted to ensure the solution's regulatory compliance. For example, tokens might be categorized differently (e.g., utility vs. security) depending on their design and use case. It is critical that the stakeholders are communicated with clearly regarding the local and international regulations' implication [6].

From a technical perspective, several issues were encountered during the implementation and optimization of the blockchain-based POC. There are tests that were unable to be carried out. Storage limit testing, for example, might demand a more efficient approach to how the entities (ships and ports) are stored. Another test is whether transaction speeds would eventually be up to par with the demands of the industry. However, TPS has not been seen in any applications built on Solana as a technical constraint (i.e., the network has only utilized a fraction of its TPS capability). Regarding data structure implementation, while the current application has been built and passed the functionality tests, there might be issues that could only be detected in later pilots and trials, which calls for a more systematic manner of continuous development and testing.

6. Conclusions

This paper has presented an innovative use case for blockchain technology as a solution to incentivize the adoption of Just-in-Time (JIT) performance and decarbonization efforts in maritime port operations. The study has revealed that the application of blockchain technology could help improve efficiency, transparency, and sustainability for port operations.

The proposed system takes advantage of the blockchain's intrinsic properties, such as immutability, traceability, and provenance, to create a decentralized and tamper-free storage for critical data records related to JIT and emissions. The blockchain not only enables an efficient and reliable recording of sensitive KPIs but also serves as an incentive distributor rewarding collaborative efforts in achieving optimized operation schedules and reduced emissions. Furthermore, it can act as a backbone digitalized network, linking with other digitized services, thus promoting a more integrated, efficient, and sustainable maritime ecosystem. By building a prototype system on the Solana blockchain, we demonstrated the system's capability to record, track, and incentivize performances in terms of JIT operations and emission reduction. This pioneering application of blockchain technology bridges the gap between the potential of blockchain in maritime operations and its practical implementation and contributes to the wider adoption of low-carbon shipping measures. Furthermore, it can act as a backbone digitalized network, linking with other digitized services (e.g., EU Emission Trading Scheme), thus promoting a more integrated, efficient, and sustainable maritime ecosystem. This aligns with IMO and EU's current system of accounting for carbon emissions by vessels.

Nevertheless, for the broader adoption of the proposed system, additional research is needed to address potential regulatory and security issues and ensure interoperability with existing systems. Firstly, the tokenomics—the economic feasibility surrounding the usage of the token–represents a crucial aspect that merits dedicated research. Future studies could delve into aspects such as token lifecycle management and token decay, which could encourage more active token usage or trading within the maritime ecosystem. This area of research is necessary to ensure the long-term viability and efficiency of the blockchain-based incentive system. Secondly, although the JIT principal parties can be simplified to include only the ship and port, successful JIT operation often requires the collaboration of other parties, thereby increasing the complexity of the system. For instance, depending on the specific ports, the involvement of port authorities or individual port service providers can play a significant role in the JIT operation's success. Future research could explore integrating these additional stakeholders into the blockchain-based system without compromising its efficacy or the transparency of the incentive distribution.

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