IoT Enabled Smart Logistics Using Smart Contracts

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***Abstract*—Advancements in sensors and devices have enabled Internet of Things (IoT) adoption in various sectors, especially in domains looking to automate and increase their real-time decision making capabilities to improve efficiencies. Supply chain management in logistics is a perfect fit for adoption of IoT, since it involves shipment of assets being moved, tracked and housed by a number of machines, vehicles and people each day. Smart Contracts are terms and conditions parties can specify that assure trust in the enforceability of the contract and provide visibility at every step of a supply chain. IoT devices can write to a smart contract as a product moves from the factory floor to the store shelves, providing real-time visibility of an enterprises entire supply chain. This paper proposes a smart logistics solution encapsulating smart contracts, logistics planner and condition monitoring of the assets in the Supply Chain Management area. A prototype of the solution is implemented which demonstrates accountability, traceability and liability for asset handling across the supply chain by various parties involved in a logistics scenario.**

Keywords—Blockchain, smart contracts, IoT, AI planner, edge analytics, machine learning

I. Introduction

Supply Chain Management (SCM) process involves various activities to transport goods from point of origin to the point of consumption. The process involves design, planning, execution, control and monitoring of the Supply Chain (SC) activities. The various parties involved across the supply chain work in silos as they have their own Enterprise Resource Planning (ERP) or manual systems to carry out their functions. In addition each element of the SCM follows different processes bridged by paper based contracts or disparate digital systems with little or no standards.

A typical process carried out with respect to logistics in a supply chain involves a paper contract between the purchaser and supplier detailing information like quantity of goods, environment conditions, deadline and penalty involved in case of violation. The supplier then prepares a contract with the distribution network and the purchaser is left to track and verify the shipment based on the contractual obligations signed with the other parties with limited or no feedback. There may also be a need for re-planning due to unexpected route conditions or spoilage of goods in transit. Dynamic adaptability to mitigate such situations is an important requirement for the logistics process. If there is a violation of terms and conditions the concerned parties need to negotiate amongst themselves and come to a settlement. This may lead to losses for one or both parties involved due to lack of transparency and traceability. Options exist to check the conditions in real-time however the information is accessible for the party involved in the specific stage of the logistics process and not for all. There is no unified way of monitoring the entire process from a single viewpoint leading to lack of transparency. Suppliers and purchasers do not have visibility on the state of their assets until they reach the destination.

The first three industrial revolutions came as a result of the introduction of mechanization, electricity and IT. Nowadays, the introduction of IoT and Services into the industrial environment has triggered the fourth industrial revolution with the vision of everything connected with everything else [2]. Meanwhile the blockchain technology is disrupting various verticals with its digitalized, decentralized and public ledger features. The state of art Logistic 4.0 [11] uses Cyber-Physical Systems (CPS) monitors to control the physical processes, usually with feedback loops where physical processes affect computations and vice versa. CPS can identify or sense and locate the item, and send the data to a computer which collects and analyzes the relevant information. These systems communicate with other systems or with humans using the internet as a means of communication, so that data can be shared in real time and coordinate the relevant processes [3]. The demand for high-individualized products and services is continually increasing. Therefore, supply chain processes (inbound logistics and outbound logistics) have to adapt to this changing environment, since due to the increasing complexity, it cannot be handled with ordinary planning and control practices [4].

Smart Logistics architecture explained in this paper provides a holistic way of managing the logistics involved in a supply chain with the help of IoT technologies, blockchain based Smart Contracts, Machine Learning and Big data.

II. Challenges

The Food and Agriculture Organization (FAO) of the United Nations published an article [5] that states that one third of the food is spoiled before it reaches the end customer. Lack of crucial flow of information amongst the parties involved creates a supply and demand issue. A contract may not cover all the aspects or scenarios that are likely to happen in the logistics process leading to ambiguities and loss of resources and capital. Improper planning leads to non-harmonization between channel partners resulting in loss of goods, time and capital. All these issues demand a need for an integrated approach to solve the logistics problem in supply chain management. In general, most experts ascribe a high importance to data and analytics to the logistics sector [6]. This brings in vast opportunities to improve performance and customer satisfaction. Some of the fundamental challenges in the logistics area are:

- *Transparency:* This is needed for the overall optimization of SCM and effective use of resources across the entire supply chain. Transparency is in direct relation to trust which is of paramount importance in this sector. Many experts [7] therefore propose the use of Blockchain to provide this much-needed trust.
- *Traceability*: This is needed in order to track the movement of products across the supply chain. In particular, in the area of food logistics, governments are increasingly legislating for adopting traceability systems to minimize food wastage [8]. Traceability also becomes critical for consumers to know the facts of the product origin and production methods of food items.
- *Accountability and Liability*: This is defined rendering necessary explanation to the buyer with regard to the storage, transportation, insurance, customs, inspection, supervision, packaging, value-added procedures, stock management, order management and similar services provided by the third party logistics provider. Logistics accountability is comparable to answerability; buyer expects service at its best quality for the price paid. Logistics accountability will also have a positive influence on trust [9].

The challenges discussed above can be addressed by employing a robust combination of blockchain based smart contracts, logistics planner and condition monitoring of the assets. Due to lack of space, the details of these technologies, along with how they can address logistics related challenges, are listed in Table I.

III. Smart Logistics Solution

Our proposed Smart Logistics solution implements the end-to-end tasks starting from performance based supplier recommendation, contract negotiation, logistics planning to contract controlled asset monitoring and contract fulfillment. We have built a holistic solution that combines the power of the following building blocks which are standalone and reusable micro services, see Fig. 1.

A. Brief Overview

A High Level Architecture with the core modules of the Smart Logistics solution is depicted in Fig. 2.

1) Smart Contract: In 1996, Nick Szabo described a smart contract as a set of promises, specified in digital form, including protocols within which the parties perform on these promises. [1]. The main objective of the smart contract module is to digitize the paper based or manual procedure of putting down the terms and conditions of a purchase contract. The module identifies and recommends suitable supplier(s) for the purchaser and enables the negotiation of pricing and contract terms with the supplier. Once the contract terms are accepted by both supplier(s) and the purchaser, a purchase order is created. Quality and the delivery time are considered as the key obligation terms in the contract which is provided as an input to the Condition Monitoring (CM) module. The smart contract module helps to automate the entire smart contract life-cycle using a blockchain based substrate encompassing contract negotiation, partner selection, contract finalization, contract enactment, contract monitoring, conflict/issue resolution during contract enactment.

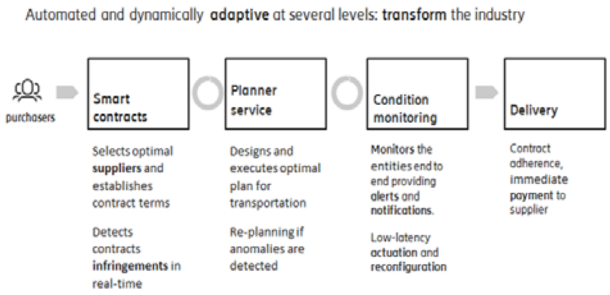

Fig. 1. The typical flow of events in the Smart Logistics Solution

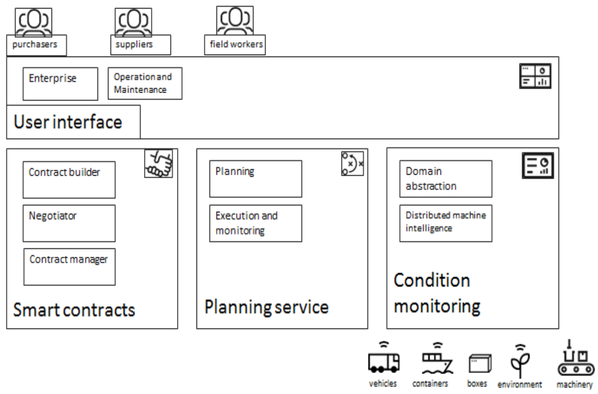

Fig. 2. The high level architecture of the Smart Logistics Solution

2) Logistics Planner: A single work order may be fulfilled by more than one supplier. Each supplier may be located in a different location and can be fulfilling different quantities. We assume a scenario where distributor network consists of a warehouse and several trucks that are used to move goods from supplier warehouse to the purchasers delivery point. The logistics planner takes care of designing the optimal plan for transporting the goods. The planner is also invoked when there are events (unforeseen) that jeopardize the plan, i.e., the steps in the plan cannot be executed as intended, e.g., a truck breaking down and not able to ship the products. This means that some parts of the plan are affected and consequently the terms agreed to in the contract may also be violated. It is important to be able to detect this early and initiate a re-plan where necessary and alert dependent parties where important.

3) Condition Monitoring: Constant monitoring of the assets is required for successful contract fulfillment. This component provides the functionality to collect all the data from the sensors, controls and reconfigure the system that is managing the assets. The distributed framework provides for a possibility to distribute the intelligence acquired from the data to appropriate location: namely edge (with sensors, gateways like the trucks), fog (small clouds/servers deployed on factories or warehouses) and cloud as big data centers with unlimited capabilities. This framework harnesses the power of edge analytics where latency is a stringent requirement for maintaining assets integrity. Decisions are carried out based on the existing conditions via a distributed machine intelligence framework which tries to overcome the limitations of network bandwidth and resource constrained devices.

TABLE I. EXISTING CHALLENGES AND POSSIBLE SOLUTIONS

Component	Challenges	How can it help
Smart Contracts	Complex and Cumbersome documents Multiple parties Interactions Accountability and liability	Digitises Bills of Lading (Contracts). Connects members of the supply chain to a decentralized network and allows them a direct exchange of documents. Manages ownership of documents on the blockchain to eliminate disputes, forgeries and unnecessary risks. Records the terms of a trade. Automatically executes the flow of money based upon signals resulting from the flow of goods thereby reducing processing costs. Simplification of complex multi-party systems delivery. Connects banks, lenders, buyers, and suppliers to streamline and automate settlement, reduce fraud risk and costs. Use of an IoT sensor as an arbitrator in the event of dispute, e.g., payment of a penalty to the defaulting party. Arbitration appeal from IoT device to selected panel of arbiters. Decision executed on the smart contract. Enhanced tracing and verification to reduce risk of fraud and theft. Data provenance and reliability. [10]
IoT and Condition Monitoring	Transparency Need for integrity Control Need for planning optimization of available resources	Asset/inventory management and remote monitoring Predictive maintenance, operational health monitoring and outage management Quality assurance and smart testing Increased operational efficiency and productivity Increased customer control with easy availability of realtime co-related information Data management and analytics
AI Planning	Ensuring a viable plan exists prior to committing to a contract Unforeseen events may jeopardize a contract or a plan	Create initial plans that are optimized and meet the specifications of a contract Decide the impact of an unforeseen event on a plan and compute its impact on some aspects of the contract. Compute alternative plans as extensions to current plans in the presence of some events that invalidate an existing plan

B. *Functional Architecture*

The functional architecture of our solution, which documents the interactions among its components, is depicted in Fig. 3. Implementation Details and key features: (Table II provides more details of these implementation details and their practical realization.)

Smart Contract System (SCS): The SCS (see Fig. 4) provides a recommended list of suppliers for a particular item that needs to be procured (e.g. 1000 liters of Cream). Once the list of suppliers has been selected, SCS sends notifications to the corresponding suppliers and starts the negotiation process between the purchaser and the supplier regarding terms and conditions. After completing the negotiation process a smart contract is established and a purchase order is created. The SCS also periodically receives updates from the planner and condition monitoring modules that provide information about the current status of the purchase order fulfillment. These updates are used by the SCS to verify if the contract terms are followed as per the agreement. In case of any violations, SCS triggers the appropriate action defined in the contract, e.g., penalty or even cancellation of the purchase order.

Key features:

- Cloud-based system modeling and development to facilitate smart contract implementation
- The eContractAgent module focusses on user account management, service management and smart contract management.
- Once the contract is signed by all the parties, the system deploys the smart contract in the contract runtime environment implemented on Ethereum Virtual Machine (EVM) to deploy, execute and monitor the smart contract state machine.
- Distributed smart contract monitoring infrastructure in the IoT cloud.
- Dynamic machine learning based approach for efficient selection of a smart contract based on transaction history from past smart contracts.
- Dynamic enforcement of smart contract terms and conditions based on real-time data from distributed sources
- Securing business transactions via techniques such as distributed ledger and blockchain technologies

Logistics Planner: The Logistics Planner (LP) (see Fig. 5) is responsible for designing and executing the optimal plan to fulfill smart contract.

Key features:

- Planning: LP uses a standard AI planner that can plan with timing considerations. The open source, domain agnostic, OPTIC planner [18] using PDDL (Planning Domain Definition Language) domain specification is used as an input. However this can be replaced by planner that take advantage of domain knowledge, without needing to change other parts of the system.
- DN - Execution: The execution consists of a bunch of trucks which move around containers. The controller hands off plans to individual trucks (agents) and

monitors and reports on their progress. The executor simulates the movement of the trucks like a Distribution Network (DN) which interacts with the controller. The data from the containers of the truck is monitored by the Condition Monitoring module.

- The planner-executor system is controlled via a REST API interface to a component called the Logistics Planner (LP) controller. This provides a management interface to start and stop the components as well as initiate and monitor the progress of their execution via HTTP interfaces.
- These components are loosely integrated (see Fig. 5), re-targetable to any other use cases and in many cases directly reusable.

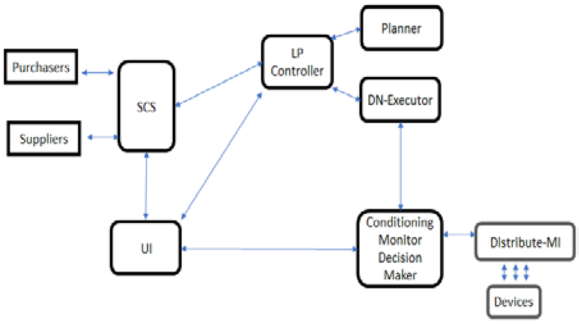

Fig 3. Functional architecture: interaction between the components

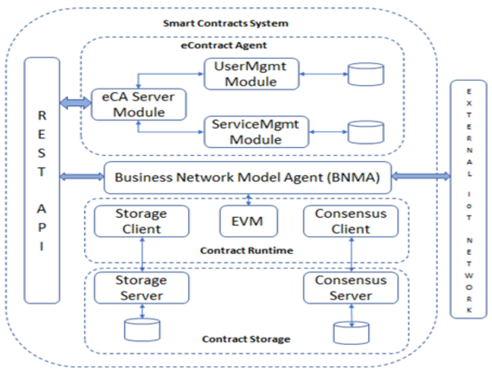

Fig. 4. The internal architecture of the Smart Contract System.

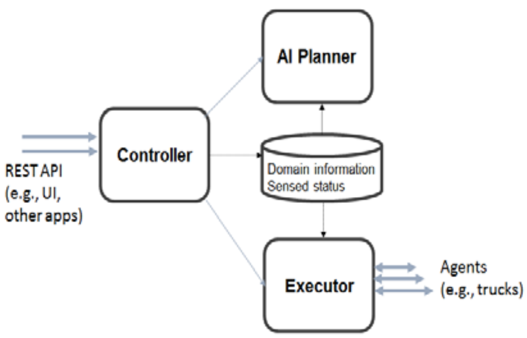

Fig. 6. Internal architecture of the logistics planner

Condition monitoring using Distributed Machine Intelligence framework: The goal of this component (see Fig. 6) is to provide a reusable component that can be used to gather sensor data and process it for analytical and actuation purposes. The component provides the possibility to deploy the intelligence and processing of data at multiple levels and locations. It allows the data to be processed close to its generation despite limitations such as computation, memory, storage. For example, the functionality can be deployed at edge devices, capillary gateways, fog nodes or cloud datacenters. Aspects such as how is the asset being handled, by whom, when and which highlight accountability and liability is the key target of this module. Other applications include:

- Prediction of individual best before end (BBE) dates of items/goods based on contextual information. (Predictive analysis)
- Decision for expediting delivery of goods thereby reducing waste can be taken based on the sensor readings.
- Analytics can be employed for calculating optimal transportation routes based on the sensor readings in-order to meet contract terms on time.

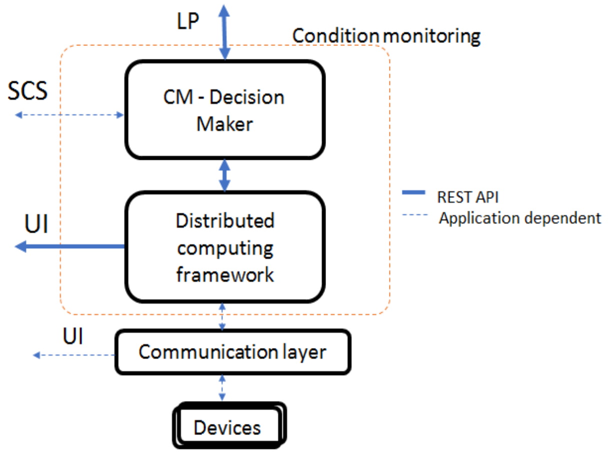

Fig. 6. Condition monitoring module interfaces

Key features:

- The condition monitoring module interacts with both the LP and SCS through the CM-Decision Maker (DM)
- The module facilitates a distributed application environment developed using an actor based toolkit, akka.io [14].
- A HTTP API is defined to interact with the system. The CM-DM component provides a simplify API, specific for the Smart Logistics.
- A cluster manager provides the control of all the locations deployed (cloud, fog, edge, capillary gateways,) and orchestrates the deployment of the functionality. It provides a fault-tolerant and resilient system.
- Multiple workers are deployed on remote locations, and are used to deploy the distributed processors depending on the needs of the application
- Communication components: means of interaction between the devices and the processors.
- Local databases on locations are used to provide local persistency of the data.

TABLE II. SUMMARY OF THE DIFFERENT REUSABLE COMPONENTS USED IN THE SOLUTION

Component	Technology stack	Applications in this solution
Smart contracts	Cumulus – Ethereum Virtual Machine	Learning based supplier selection Binding users into contracts
Logistics planner	For PDDL – OPTIC Domain inputs for Logistics	Optimization of plans and schedules
Condition monitoring	Akka Python (packages: pandas, numpy, scikit-learn) TensorFlow [17]	Condition monitoring Asset management (Predictive analytics, anomalies detection, forecasting, online training etc.) Data management Low-latency control

IV. PROTOTYPE AND RESULTS

Prototype of the proposed architecture that integrates the core building blocks of the Smart Logistics Solution is discussed. Consider the following use case to demonstrate the capability of this solution. A purchaser needs to procure 1000 liters of Cream from supplier(s). The condition of the asset (cream) in the contract expects utmost quality to be maintained. The ideal temperature is required to be around 2 - 4°C and minimal vibrations by the truck to ensure the cream quality. Penalties are set in the smart contract when there is a breach in maintaining the temperature and an allowable threshold of vibrations is crossed. These are the conditions which the condition monitoring module needs to report to the SCS and LP. The following sequence diagram helps in depicting the flow of information across the different components involved to fulfill the contract set by the purchaser.

The purchaser places a procurement request with the smart contract system (SCS) to place his purchase order (PO). The SCS will recommend a set of suppliers along with their ratings who can fulfill the PO. The SCS negotiates with the suppliers and a contract is established with the PO being acknowledged. The SCS interfaces with Logistics Planner (LP) for planning and execution of the PO. The LP creates the plan and executes on the Distribution Network (DN) which is a set of trucks and warehouses. Based on the agreed plan, execution begins where the assets (in this case the Cream cartons) are being transported to reach the destination. Meanwhile the asset is being monitored using sensors such as temperature and vibration so as to maintain the quality agreed in the smart contract. At any change in the temperature or the vibration, an anomaly is sent to the LP and SCS from the Condition Monitoring (CM) through the Decision maker (DM) which monitors the truck containers. Similarly, in cases when there are some issues with respect to route conditions or deterioration of the assets, the LP steps in to re-plan the trip to optimize the resource utilization.

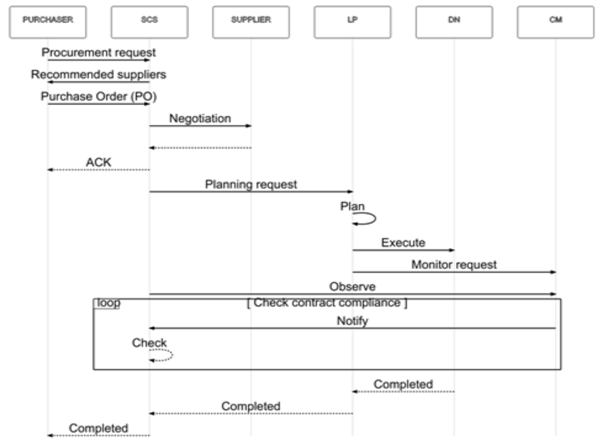

Fig. 7. An example sequence of events depicting a successful logistics process of the Smart Logistics Solution.

Based on the computation through the trip the SCS expedites payments to the suppliers and also updates the rating of the suppliers based on fulfillment or violation counts agreed in the contract. This ensures accountability and trust based on the facts and data.

V. RELATED WORK

Toll Global Logistics deployed a RFID-based pallet identification system to more efficiently track good and shipments at its Singapore facility [12]. The company estimates that this system will save more than 600 person-days per year.

Transportation of dangerous goods is another potential area for improvement. At present, the technology lacks monitoring of dangerous goods' condition inside the container in transit which can act as a early warning and hazardous situation prevention system. The application of low-power sensor networks inside containers, as well as automatic positioning in the cargo hold, can effectively protect the security of maritime container logistics chain [16]. Perishable goods, that are also temperature-sensitive products, are a fundamental source of revenue for the cold chain logistics enterprises; their management, however, constitutes a severe challenge for cold chain logistics enterprises [15].

Track and trace is the most common form of IoT in the supply chain and a number of firms are seeing real rewards from getting ahead with this technology. Decathlon a sports retailer that owns 850 stores in 22 countries is a prime example of this. [13]. There are lots of solutions out there which focus only on optimizing using IoT technology or Smart Contracts based on the needs but we provide a solution that integrates all the aspects encompassing an end to end solution for any logistics use case.

VI. CONCLUSIONS

This paper provides the implementation and key features of the core components of the proposed Smart Logistics solution. Its key value propositions are the following: incorporation of technologies such as smart contracts, distributed machine intelligence and IoT-based condition monitoring to provide improved trust, traceability and accountability; and an end-to-end solution spanning contract negotiation and monitoring, optimal planning and asset condition monitoring. Future work will focus on scaling up our solution for larger and more complex logistics scenarios.

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