An IoT-Enabled Framework for Dynamic Supply Chain Performance Management

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Abstract—**This paper presents a framework of smart real-time performance monitoring and controlling of next-generation supply chains. It is based on enabling a set of Internet-of-Things (IoT) functions across the supply chain for dynamic and intelligent information processing and performance management. This is realized through the utilization of IoT technology in conjunction with workflow modeling to address the dynamic aspects of supply chain in a real-time environment. The proposed mechanism is referred to as Dynamic Supply Chain Performance Management (DSCPM) which is a computerized event-driven system that runs in real-time, monitors a set of selected supply chain performance measures, and effectively enables real-time decision-making. DSCPM functionality is based on the concepts of Complex Event Processing (CEP) to manage the massive event-instances across the supply chain and to convert them into beneficial information. Adopting DSCPM is expected to facilitate real-time corrective actions that reduce wastes and costs and maximize value across the supply chain.**

Keywords—Internet of Things, performance management, SCOR model, supply chain management.

I. Introduction

A supply chain is often viewed as a network of material flow from sources to end-users (forward flow) and from end-users to sources (backward flow or reverse logistics). To facilitate and coordinate the material flow amongst various supply chain entities and stakeholders, the network integrates money and information flow [1]. Such topology is no longer limited to the supply chains of manufacturing firms. Service supply chains (e.g., hospitality, healthcare, finance, education, etc.) can be also viewed and analyzed in a similar manner.

Supply chain performance management is an essential function in effective supply chain management [2, 3]. This is typically approached through periodic data collection and monitoring of Key Performance Indicators (KPIs). The most popular model for implementing performance-measurement initiatives in supply chains is the Supply Chain Operations Reference (SCOR) model [4]. The model utilizes specific KPIs at the different interfaces of the supply chain to assess performance and plan operations.

However, with the dynamic changes in market demand, supplies delivery, and process availability, supply chains will typically exhibit several kinds of operational problems and, consequently, generate wastes and losses due to delay in information processing, taking corrective actions, and decision-making. As discussed in [5], today's supply chains and its manufacturing systems are characterized by its high dynamicity, uncertainty, and high variability (i.e. mass-customization, due dates, priorities, quantities, variety of components, small lot sizes, etc.). This comes along with the quick changes in supply chain technology. Therefore, it has become more difficult to represent, monitor, and control these circumstances using simple, off-line, and static performance measurement systems [13].

In general, modern computers and IT developments have made it easy to computerize manufacturing and work flow information. However, as discussed in [6], since over a decade, the available systems and application are still cannot provide the required flexibility to tackle the rapidly changing business process. Therefore, there is a necessity for a new performance measurement system that is able to automatically monitor the work flow and continuously monitor the performance. This particularly important given the high complexity, uncertainty, variability and dynamical behavior of today's supply chains environments.

Given such context, there has been growing interest in using IoT in supply chains to capture and monitor its information and improve its performance. As a real-time activity data capturing system, IoT plays an important role in providing companies with instant, accurate, and detailed information regarding its current situation [7]. With this technology, any object on the operational-level (i.e., execution-level) of the supply chain could be turned into a "smart-object" that is able to emit real-time data and thus, could be seen, tracked, and managed in real-time with the integrated information system.

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To this end, this paper presents a framework that integrates IoT as a real-time data capturing technology with business process modeling concepts (based on the SCOR model) to develop a computerized real-time DSCPM system. DSCPM is an event-driven system that uses CEP to tackle the huge amount of triggered events data at the supply chain execution-level, process IoT data, and support performance-based practices and decision making at the higher management levels. The framework also allows performance management specialist to create Real Time-Performance Control Rules (RT-PCRs) for monitoring and enabling decision making during run time or in the near real execution time. The reminder of this paper is organized as follows: section 2 provides a brief of the use of IoT technology within the supply chain context, section 3 describe the framework details, and section 4 presents the framework validation requirements and expected results.

II. IOT FOR REAL-TIME PERFORMANCE MANAGEMENT

One of the main challenges facing a supply chains performance management systems in today's dynamic environment is the inability to capture sudden changes that occur across supply chains in real-time and, consequently, the inability to make quick timely decisions. This is mainly caused due to the time and information gaps (i.e., asynchrony) amongst the three levels of an enterprise's management system (i.e., horizontal time gaps between the products flow and the associated events on the execution level and the associated vertical gaps in the information flow at the operational level and the highest planning level). These gaps are shown in Figure 1.

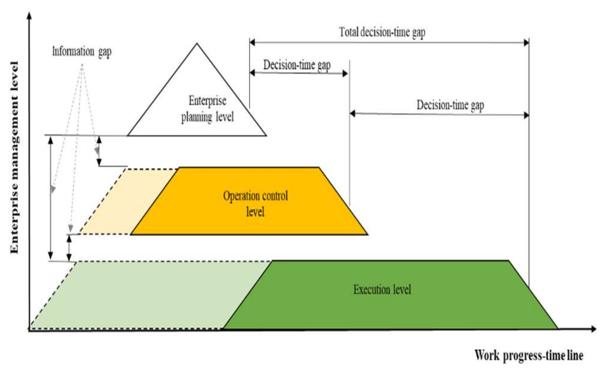

Fig. 1: Time and information gaps within enterprise management levels

As shown in Figure 1, bridging these gaps is very crucial for efficient and effective decision-making process. For instance, it is highly important that the taken decisions can tackle the actual state at the execution-level. In this context, being unable to monitor the current performance, the enterprises has to be increasingly agile to rapidly respond to dynamic supply chain changes and challenges. Bullwhip effect in supply chains can be also related to information delay and distortion. Therefore, it is important to bridge the time and information gaps within different enterprise levels using a real-time performance management systems. IoT technology provides such capability.

Radio Frequency Identification (RFID) and Wireless Sensory (WSNs) are the main IoT technologies used in supply chain applications [8]. However, such technologies are not well known and used as rapidly as initially expected, due to many reasons [9]. Companies might have not fully realized or recognize the potentials of this technology and how to utilize it in practice. In addition, the integration of IoT through the existing IT systems (i.e., ERP) still remains a big challenge. To this day, few methodologies have described clear descriptions on how to utilize the captured real-time operations data to bring more benefits and facilitate decision making across the supply chain. This provides more evidence that IoT technologies has not yet reached its mature point for companies to adopt this technology in their supply chains [10,11,13].

Several researchers have highlighted that an integration of IoT within the SCM framework may bring revolutionary improvement for conventional performance measurement and management practices. Examples include live decision-making and on-time corrective actions, reduced bullwhip effect, increased logistics transparency, more effective warehouse and inventory management, and so on. This can potentially improve the competitiveness of IoT-enabled supply chains within their business fields. In addition, the latest developments in using IT and wireless technologies can facilitate the integration between IoT hardware (e.g. GPS, RFID, WSNs, laser scanners, etc.) and supply chain management in order to develop a real-time or near real-time intelligent performance management systems [12,13].

The envisaged DSCPM is proposed to bridge these gaps and lead to a real-time integration both horizontally and vertically using SCOR model and its performance metrics hierarchy principles. The vertical integration of information and knowledge between the execution-level and top management is required to bridge the horizontal time-gap (i.e., between resources integration). This can be achieved by using smart-objects at the execution enterprise level. Figure 2 depicts the proposed integration framework.

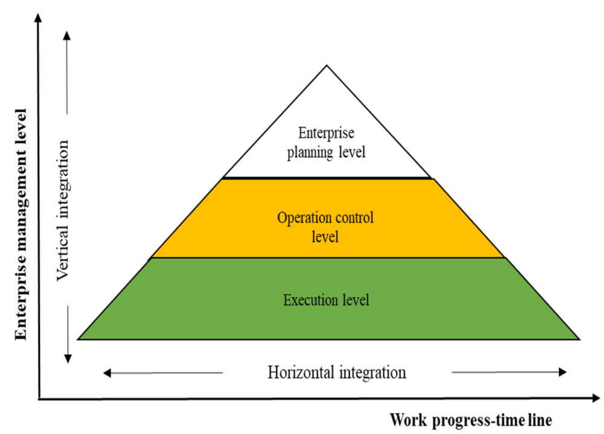

Fig. 2: The IoT integration of enterprise management levels

III. THE PROPOSED FRAMEWORK

After deploying IoT technologies across the supply chain to transform the execution-level into a smart environment, the event driven performance-based system, DSCPM, is integrated within the IT infrastructure. DSCPM functions as a short-term performance monitoring system that is situated between the real-time event processing layer and the top layer of long-term planning. Figure 3 shows the integration of the DSCPM real-time performance-based system with the enterprise planning systems (e.g. ERP, SCM, etc.).

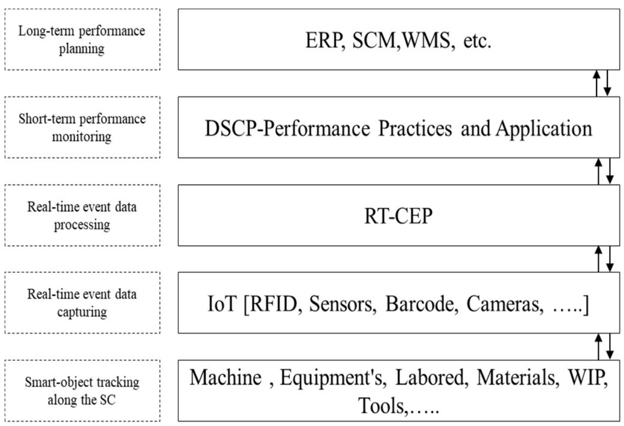

Fig. 3: DSCPM integration within the enterprise IT system

As shown in Figure 3, the CEP method is integrated within the enterprise IT infrastructure to support the functionality of DSCPM. The RT-CEP layer is the interface between IoT-technology of event data capturing (RFID, Sensors, Barcode, etc.) at the execution-level and the DSCPM level (i.e., RT-CEP can be assumed as an IoT middleware). The OPC/OPC-UA standards can be used to establish the communication between the IoT middleware software and IoT-data readers as well as other execution-level systems (e.g. PLC, HMI, sensors, etc.) which can be utilized with the IoT. Enormous amount of generated events can be pre-processed at the RT-CEP layer and forwarded to the DSCPM layer to dynamically reflect events on the supply chain performance measures (i.e., DSCPM has different engines for different functions) and transfer them to the highest level of the enterprise's IT system

A. The DSCPM Structure

The DSCPM structure represents the core of the proposed framework that handle the integration of IoT data-capturing system with the supply chain business processes, according to the SCOR model, in order to develop a performance-based smart supply chain management. DSCPM works as a digitalized event-driven IT system that involved different smart performance-based management and control modules to manage, enhance, and continuously sustain the targeted performance across the supply chain environment. To this end, DSCPM manages the massive event-instances processed by CEP and converts them into beneficial information to facilitate real-time corrective actions and decisions that avoid wastes, prevent problems, and add value. An overview of the DSCPM components is depicted in Figure 4. As shown in Figure 4, the DSCPM framework is consists of six engines:

First: Event Extractor Engine (EEE), it is a real-time performance-based data collection and transformation engine. It reflects and integrates the current state of the smart-objects at the execution-level within the enterprise environment. Therefore, EEE serves as a linkage between the physical world (i.e. resources on the execution-lev) and the virtual world (i.e. IT system).

Second: Actual Work Flow Engine (AWF-Engine), it is the DSCPM-interface with the execution-level. It translates the smart-objects related data into flow in terms of time and location, (i.e. Work Flow (WF) format).

Third: Virtual Work Flow-Engine (VWF-Engine), it is the DSCPM-interface with the enterprise levels. It translates the performance-based data that has been developed at the higher enterprise's levels into the context of event-instances (i.e. WF format). For example, before starting customers' orders execution or releasing the products for production, each order or product should have a VWF that represents its targeted performance-based data.

Fourth: Real-time Rules Engine (RT-RE), in this engine, the Real-Time Rules Expression Builder (RT-REB) module gives the performance management manager the ability to express or construct the suitable rules for other DSCPM-Engines with the assistance of the "Rule Construction Elements" (RCE) module. For example, rules for the EEE to extract the required events or to create Real Time Performance Control Rules (RT-PCRs) for the Performance Practices and Applications-Engine (PPAE) to control working processes based on performance targets, or to supply the AWF and VWF-Engines with the required rules to execute their functions.

Fifth: Performance Practices and Applications-Engine (PPAE) is supposed to work as the core of DSCPM. It enables a smart real-time re-(action) mechanism without the need for human intervention (i.e., because humans unable to monitor all work-related information and make immediate decisions). The RT-RE is set to supply this engine with different RT-PCRs, which utilize the event-instances in AWF, DSCPM-database (DSCPM-dB), as well as VWFs-data for smart real-time monitoring and controlling of the supply chain workflow. This takes place using specific performance targets and the performance practices and applications (PPAs) can be improved based on the details of daily or weekly runs. Thus, this engine bridges the gap between the targeted performance-based environment represented by VWF and the physical situation represented by AWF which enables continuous development and smart supply chain management.

Sixth: Real-time Visualization Engine (RT-VE), it displays the AWF of each order/product for the local TUI of workers, supervisors, middle management, or top management. The RT-VE is equipped with rules to invoke and process the current execution data from AWF, performance-based control data (i.e. reactions), and targeted performance values from VWF to display them in WF-format.

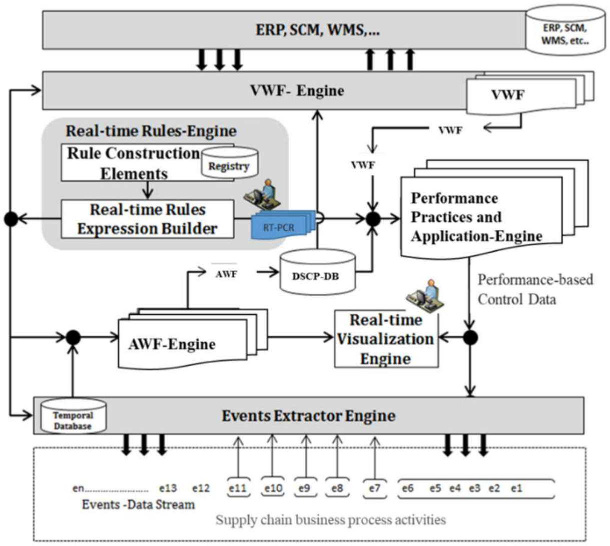

Fig. 4: An overview of the DSCPM framework

B. The DSCPM Functionality

Within the context of DSCPM, RT-PCRs can be created and saved on a certain module in PPAE and can be then used during the execution run to generate a quick re-(action) towards the performance violation or unexpected incidents and disturbances that typically cause waste and losses. Moreover, a certain RT-PCR could be set to serve as a control algorithm of a specific management policy. Other RT-PCRs could be used to study the behavior of the supply chain resource using specific patterns to predict or detect the interruptions and errors in advance and, accordingly, generate real-time re-(action) that can reduce potential wastes in term of material, time, motion, utilization, etc. Additionally, these rules could also be set to detect the opportunities for further continues improvements. The working mechanism and the interaction between the DSCPM-Engines are illustrated in Figure 5

IV. FRAMEWORK VALIDATION

To validate the functionality of the proposed framework, we need to implement it physically to an existing supply chain or, alternatively, integrate it into a supply chain simulation model. A supply chain of dairy products company will be targeted for both validation approaches. The data will be collected from various stages of the supply chain (procurement, processing, packaging, inventory control, and distribution). KPIs will be collected from various stages of the supply chain and integrated into the DSCPM system. Simulation will be used first as a validation platform and physical implementation can then follow. The application will be supported by a feasibility study including cost-benefit analyses. The limited expiration dates of dairy products and their sensitivity to demand variation and warehousing conditions can demonstrate the value of adopting the DSCPM system in terms of reducing losses and wastes. In both scenarios, we need to prove two functionalities:

- How to achieve the vertical integration (i.e. bridging information gap) by integrating the supply chain business process' real-time workflow and its performance vertically from the operational level to the enterprise level. To do that, we need to decide on the KPIs to be monitored across the supply chain and then analyze the supply chain scenarios using all levels of the SCOR model (i.e., the CEP will show how the lower level activities can be aggregated and processed to provide performance measures to the upper level business processes). Examples KPIs can be measures of performance such as % milk expired, % delivered on-time, order lead time, cost of losses and waste, and so on. The full details will be presented in a coming publication.
- How to achieve the horizontal integration (i.e. bridging decision-time gap) by controlling the interactions within different smart-objects at the execution-level to support a specific PPAT or, for example, to invoke a certain inventory management policy. To assess the value of horizontal integration, the study will develop certain scenarios that show how more efficient and automated (real-time) corrective actions and decisions can be taken to reduce or totally avoid wastes and losses.

Furthermore, and to demonstrate how IoT-based DSCPM system can support smart supply chain performance management, a number of modules can be integrated into the framework using the CEP method. Examples of these modules include lead time analysis, real-time costing, real-time waste detection, and lean practices (VSM, JIT, 5S, SMED, TPM, etc.).

A. Expected results

The DSCPM system will be first tested using a simulation model of dairy products supply chain with a focus on milk processing, storage, and distribution. Expected results include a comparison between the current supply chain performance and after integrating the IoT-based real-time performance monitoring capability. Two main attributes of supply chain performance will be monitored; costs or revenues and flexibility (responsiveness). Specific KPIs will be set to quantify the performance such as milk expiration percentage, fill rate, service level, etc. The simulation results will demonstrate the role and effects of IoT functionality on the dynamic adjustment of the overall products perishability management. Results can be also used for deep learning and dynamic set up of supply chain parameters for effective inventory control, warehousing, transportation, production scheduling, and distribution.

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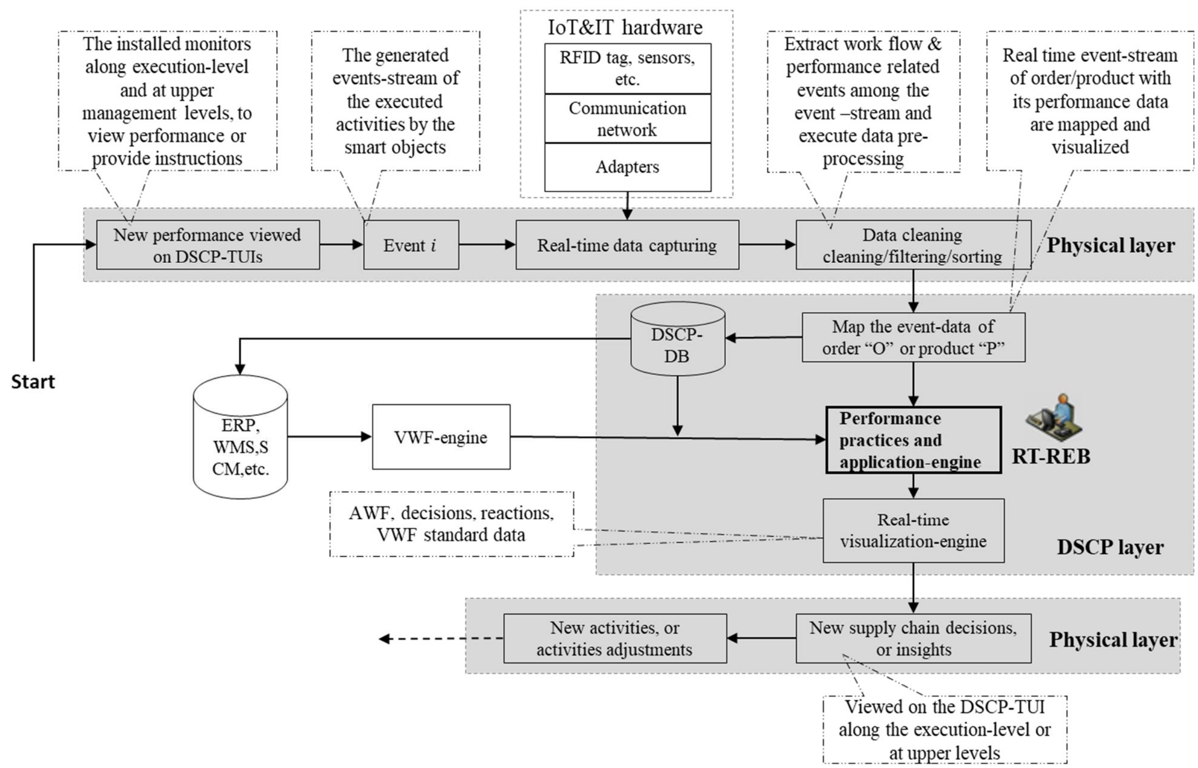

Fig. 5: The DSCPM functionality