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공학박사 학위논문

**Internet of Things-Enabled  
Dynamic Performance  
Measurement for Real-Time Supply  
Chain Management**

**- Toward Smarter Supply Chain -**

2018년 2월

서울대학교 대학원  
산업공학과  
**Abdallah Dweekat**

# **Internet of Things- Enabled Dynamic Performance Measurement for Real-Time Supply Chain Management**

**- Toward Smarter Supply Chain -**

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이 논문을 공학박사 학위논문으로 제출함  
2018 년 02 월

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# Abstract

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Supply chain performance measurement has become one of the most important and critical management strategies in the pursuit of perfection and in strengthening the competitive edges of supply chains to face the challenges in today's global markets. To constantly cope with the resulting rapid changes and adopt new process designs while reviving supply chain initiatives and keeping them alive, an effective real-time performance-based IT system should be developed. And there are many researches on supply chain performance measurement system based on the real-time information system.

This thesis proposes a standard framework of a digitalized smart real-time performance-based system. The framework represents a new type of smart real-time monitoring and controlling performance-based IT mechanism for the next-generation of supply chain management practices with dynamic and intelligent aspects concerning strategic performance targets. The idea of this mechanism has been derived from the main concepts of traditional supply chain workflow and performance measurement systems; where the time-based flow is greatly emphasized and considered as the most critical success factor.

The proposed mechanism is called Dynamic Supply Chain Performance Mapping (DSCPM), a computerized event-driven performance-based IT system that runs in real-time according to supply

chain management principles that cover all supply chain aspects through a diversity of powerful practices to effectively capture violations, and enable timely decision-making to reduce wastes and maximize value.

The DSCPM is proposed to contain different types of engines of which the most important one is the “Performance Practices and Applications Engine” (PPAE) due to its involvement with several modules to guarantee the comprehensiveness of the real-time monitoring system. Each of these modules is specified to control a specific supply chain application that is equipped with suitable real-time monitoring and controlling rules called “Real-Time Performance Control Rules” (RT-PCRs), which are expressed using “Complex Event Processing” (CEP) method. The RT-PCRs enable DSCPM to detect any interruptions or violation smartly and accordingly trigger real-time decision-making warnings or re-(actions) to control the performance and achieve a smart real-time working environment.

The contributions of this dissertation are as follows: (1) building a conceptual framework to digitalize the supply chain, based on their strategic performance targets, deploying IoT technologies to convert its resources to smart-objects and therefore enable a dynamic and real-time supply chain performance measurement and management. (2) Demonstrating the feasibility of the DSCPM concerning performance targets by developing some practices and tool modules that are supplied with RT-PCRs (e.g., Real-time Demand Lead-time Analysis, Real-time Smart Decision-making Analysis (RT-SDA), Real-time Supply Chain Cost Tracking System (RT-SCCT), etc.). (3) Verifying the effectiveness of RT-PCRs in RT-SDA and RT-SCCT modules by building simulation models using AnyLogic simulation software.

**Keywords:** Internet of Things (IoT), Complex Event Processing (CEP), Supply Chain Performance Measurement (SCPM), SCOR model, ISA-95.

**Student Number: 2014-31502**

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# List of Acronyms

- **ABC**            Activity-Based Costing
- **AHP**            Analytical Hierarchy Process
- **ASO**            Automated Store Ordering System
- **AVSM**           Actual Value Stream Map
- **BP**              Business Process
- **CEP**            Complex Event Processing
- **CTP**            Cost-Time Profile
- **DEA**            Data Envelopment Analysis
- **DLT**            Demand Lead Time
- **DSCPM**        Dynamic Supply Chain Performance Mapping
- **DSCPM-DB**    DSCPM-Database
- **DSO**            Dynamic Smart-Objects
- **EEE**            Event Extraction Engine
- **EPC**            Electronic Product Code
- **ERP**            Enterprise Resource Planning
- **EVA**            Economic Value Added
- **FGs**            Finished Products
- **GUI**            Graphical User Interface
- **HDR**            High Demand Retailer
- **IO**              Inspection Operators
- **IoT**            Internet of Things
- **IT**              Information Technology
- **JIT**            Just In Time
- **KPI**            Key Performance Indicator
- **LDR**            Low Demand Retailer

- **LO** Logistic Operators
- **NVA** Non-Value Added
- **NVAT** Non-Value Added Time
- **PPAE** Performance Practices and Applications Engine
- **PPAs** Performance Practices and Applications
- **PMS** Performance Measurement System
- **PO** Production Operators
- **RCE** Rule Construction Elements
- **RFID** Radio Frequency Identification System
- **RIE** Rule Input Elements
- **RM**s Raw Materials
- **ROI** Return on Investment
- **RTBE** Remaining Time Before Expiration
- **RT-CEP** Real-time Complex Event Processing
- **RT-CTP** Real-time Cost-time Profile
- **RT-SCCT** Real-time Supply Chain Costs Tracking Module
- **RT-PCR** Real-Time Performance Control Rules
- **RT-RE** Real-Time Rules-Engine
- **RT-REB** Real-Time Rules Expression Builder
- **RT-SDA** Real-time Smart Decision-making Analysis
- **RT-VE** Real-time Visualization Engine
- **SC** Supply Chain
- **SCM** Supply Chain Management
- **SKU** Stock Keeping Unit
- **SCOR** Supply Chain Operations Reference Model
- **SCPM** Supply Chain Performance Measurement System

- **SO** Smart-Objects
- **SSO** Static Smart-Objects
- **TUI** Touch User Interface
- **VA** Value Added Activity
- **VSM** Value Stream Mapping
- **VVSM** Virtual Value Stream Map
- **WF** Workflow
- **WMS** Workflow Management System
- **WIP** Working-In-Process or (Work-In-Progress)
- **WMS** Warehouse Management System
- **WSN** Wireless Sensor Networks

# Chapter 1. Introduction

## 1.1 Overview

Supply Chain Management (SCM) has received a substantial amount of attention from academics and practitioners in the past few years [1]. Mentzer et al. [2] define supply chain management as the “systematic, strategic coordination of the traditional business functions and the tactics across these business functions within a supply chain, to improve the long-term performance of the individual companies and the supply chain as a whole.” Supply Chains (SCs) are involved in the entire product lifecycle, from material procurement to manufacturing to distribution, customer service and eventually the recycling and disposal of the product [3]. As the focus has shifted, during the recent years, from manufacturing management level (internal business processes) to the enterprise management level of SCs and to fulfill their objectives, organizations must keep their SC under control and manage processes that often extend beyond their boundaries [4]. Many performance measurement models and approaches have been developed, i.e., Balanced Scorecard (BSC), Supply Chain Operations Reference (SCOR) model, etc. All of these models tried to provide means to pick the right metrics based on business objectives and clear definition of purpose and scope to focus on suitable data collection and calculation methods [5]. There are different purposes for developing a Performance Measurement System (PMS) in SCs: such as to identify success, identify whether customer needs are met, understand business processes, enhance decision-making process, etc. [6]. Consequently, an organization’s PMS has a significant role in managing businesses and SCs. Kaplan and Norton [7] state: “No measures, no improvement.” It is vital to measure the right thing at the right time to allow timely

decisions to be taken, and consideration of the SC as a whole is very significant when designing a supply chain performance measurement system (SCPMS)[8].

However, today's global markets drive enterprises and supply chains to create more complex operations and manufacturing systems to respond to the fluctuating demand, changing customer expectations and globalized competition, trends of online shopping, individualized customer demand, and logistic challenges like same day delivery or multi-channel strategies. These systems characterized by high dynamic behavior, uncertainty, and high variability (i.e., mass-customized products with different routings, material and resource requirements, due dates, priorities, specifications, quantities, wide variety of components, smaller-lot sizes, etc.) [9]. Consequently, such complex and dynamic environment brings many obstacles for designing, implementation, using, and reviewing an efficient SCPMS [8]. Some of these obstacles related to identifying a balanced set of metrics that can satisfy the integration and collaboration between SC players and their internal processes. Others are technical and related to data collection, dispersed IT infrastructure, poor communication, and poor visibility. And other problems related to the data structure and data integrity caused by data size and diverse sources [10]. Therefore, it has become increasingly difficult to address or represent such environments with simple and traditional PMSs [11]. These obstacles lead to incomplete, inaccurate, misleading, as well as untimely information collection and results, which then severely affect the performance-based applications and decision-making process as a whole especially when it comes to the interaction with rapid changes in the environments regarding products and processes, that because information becomes outdated over time. Accordingly, traditional PMS is insufficient to represent an



accurate picture of real-time situations, leading to an ineffective decision-making and therefore inefficient SCM practices. Thus, to solve these problems, the efficiency of SCPMS needs to be improved for better practicing, where new methods and technologies can be utilized.

In this context, there has been growing interest in the use of Internet of Things (IoT) technologies in SC to digitalize its information and improve its overall performance. As a real-time activity data capturing system, IoT plays a vital role in providing companies with immediate, accurate, and detailed information regarding the current situation [12]. With this technology, any object on the operational-level (we call it from now on, execution-level) could be turned into a “smart-object” and thus, becomes identifiable in real-time to the existing information system. However, IoT adoption did not yet spread as rapidly as initially expected, due to many reasons. One reason is that companies have not fully realized or understood the potentials of this technology and how to utilize it in practice [13]. To this day, few methodologies describe clear steps on how to utilize the captured real-time operations data to bring more benefits and to obtain a Return on Investment (ROI) [14]. Besides that, the integration of IoT through the current Information Technology (IT) systems remains a big challenge [9] providing further evidence that IoT technologies have not yet reached its mature point for companies to adopt this technology [15]. In this context, [16, 17] have indicated that an integration of IoT within the area of SCM may bring revolutionary improvement for conventional performance measurement practices and push SCs into leadership positions within their industries. Furthermore, the recent advancement in using IT systems and wireless technologies may facilitate the integration between IoT (e.g., RFID, WSN, etc.) and SCPM to develop a real-time or near real-time

intelligent performance monitoring and measurement systems [18].

For rapid IoT maturity and success, this research addresses the integration of real-time data capturing technologies, IoT, with business processes workflow concepts (i.e., according to SCOR model) to develop a computerized real-time performance-oriented IT system, known as “Dynamic Supply Chain Performance Mapping” (DSCPM). It is built around the idea that, IoT can track the status of any smart-object on the execution-level in the form of value streams and automatically map the value stream of the individual products with all relevant information. Thus, DSCPM can keep up with the highly dynamic behavior of the operations and manufacturing systems by:

*First*, bridging the time-gaps between physical events (i.e., flows of products and the generated corresponding interaction events between smart-objects on the execution-level).

*Second*, bridging the information-gaps in the associated information flow between the operational and higher management levels.

In other words, that is to enhance, support, reinforce, and sustain the efficient SCM initiatives and applications by keeping them alive, enabling real-time monitoring, and tracking environment in the long-term.

## **1.2 Problem Statement and Motivation**

The complexity in today’s SCs and its operations and manufacturing systems are driven by rapid changes in global markets based on customer requirements makes performance measurement and decision-making process more difficult and therefore leads to risky and uncertain SCM practices [4]. Shorter product life cycle leads to continuous changes regarding supplying, manufacturing, distribution and after-sales processes [19], causing performance-based application

in such environment to become inefficient and ineffective, and therefore die over time due to inflexibility and lack of continuous care and supervision.

Another challenge of traditional PMS, in such environments, is that it has been designed to cover a limited scope of processes and data related to one single firm of the SC [11]. Today's global markets require measuring the performance of a large spectrum of external and internal tasks (e.g., logistics, inventory management and warehousing, demand forecasting, and supplier and customer relationship management), and managing it through a set of practices at the extended SC level [20]. Additionally, due to dynamic global competition and ever-changing technologies, enterprise decision makers are no longer content with locally scheduled analytics reports. Their needs have changed, and they must be able to execute dynamic ad-hoc queries utilizing a local and global real-time operational performance data, delivered to the right people at the right time, and with a justified control over the data used for analysis and reporting [21]. Decisions made on out-of-date, wrongly intentioned, or poor quality data can do more harm than good [22]. Decision makers also want flexible and easily adjustable performance-based practices and applications, which can stay alive for a long time by accommodating the rapid changes in the environment and technologies being used. Therefore, it is a matter of SCPMSs and its applications to survive in such a complex and dynamic environment without the support of real-time based dynamic mechanism.

During the last few years, to address these new challenges, there has been an increase in studies conducted by SC and performance measurement researchers who tried to add new ideas and develop new frameworks to extend traditional PMS abilities to adapt to the new

situation of SCs. For instance, [23] has put a preliminary conceptual framework “Measuring the Unmeasurable” for selecting the relevant measures and measurement approach depending on the strategic context and operational distribution of players in the SC competitiveness. [24-28] have developed frameworks and models for supply chains performance measurement using different approaches (e.g., BSC, SCOR, etc.). While [29, 30] have developed architectures for dynamic and automated SCPMS by utilizing IT and Data warehouse technologies to integrate supply chains business processes and functions and enable business intelligence applications.

However, these new approaches still have limited abilities to tackle the comprehensive view and the dynamic behavior and complexity of SCs and its operations systems. Thus, it is required to employ the new technologies (e.g., IoT) for collecting the information necessary to drive improvements and efficiencies at each process not only inside a single player of the supply chain but also through the overall supply chain [16]. On the other hand, the lack of an efficient digital SC transformation and sustainability frameworks for real-time monitoring and controlling further intensifies today’s SCM challenges, which leads to more failure in such dynamic environments [31].

With the recent advancement of IT systems and wireless technologies, there has been growing interest in the supply chain field to IoT technologies to digitalize the operation information and automate its processes [31]. In the context of these technologies applications, several researches such as [9] have been conducted concerning RFID and WSNs integration and adoption in logistics, supply chains, manufacturing and other fields. These papers explore several benefits; they have proven that RFID and WSNs can help enterprises to increase the exchange of information to promote process

efficiency and save costs. Thus, the SC can achieve real-time monitoring of Raw Materials (RMs), Work-In-Process (WIP), Finished Products (FGs), transportation, stocks, deliveries, sales, as well as monitoring activities such as putting items back on the shelf and returning goods. However, RFID and WSNs will not significantly benefit enterprises and SCs if they simply use it for sensing locally and tracking the location of products and do not use it beyond this point.

To overcome the above mentioned SC challenges, few studies have investigated the possibility of combining IoT with SCPM approach. Therefore, this research will use IoT to build a computerized real-time performance-based system for intelligent SCM implementation for the next-generation of SCs. This research is driven by the fact that while several researchers have widely investigated IoT technologies adoption in supply chains, logistics, and other manufacturing and operations areas in different industries, almost no study has systematically investigated how to integrate IoT with SCPM.

### **1.3 Research Objectives**

This research addresses a two-dimensional problem: Firstly, the challenges and limitations of current SCPMS, where traditional systems have become inefficient and difficult to accommodate the new environment characteristics (i.e., complexity, dynamicity, etc.). Secondly, the adoption of IoT in SC performance measurement to enable PPAs remains questionable and doubtful, as companies are still quite hesitant to adopt it in their manufacturing and operations systems.

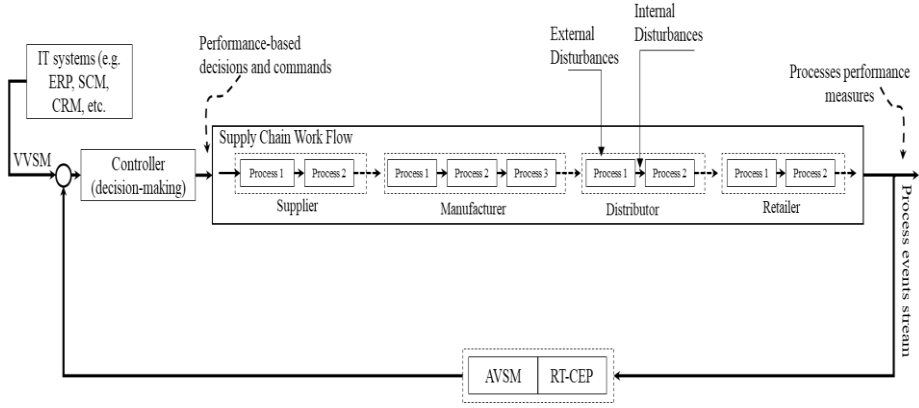
The main objective of this thesis is to structure a solid basis for a standard framework of a digitalized smart real-time performance-based system that can overcome today's SC operations challenges and describe the best practice of IoT technology in SCM. This framework

presents the integration of real-time execution data captured via IoT with performance-based initiatives to achieve an intelligent, comprehensive, integrated, and holistic real-time performance-based SC manufacturing and operations system. This system is supposed to work automatically according to SCM concepts and tools that working in conjunction with each other to effectively reduce wastes and maximize value. Accordingly, the expected outputs of this research can be illustrated as below:

1. Develop a conceptual framework for performance-based digital SC transformation, using IoT technologies and SCOR model.
2. Introduce a framework of performance-based IT mechanism, for smart real-time monitoring and controlling of the next-generation of SCM systems.
3. Prove the superiority of the framework by demonstrating its applicability in a dairy supply chain using AnyLogic simulation software.

The initial step of this study is developing a systematic method to transform SC to a digital SC according to its strategic fit and using IoT technologies. Then, Based on the concepts of traditional business processes and workflow, where the time-based flow is greatly emphasized and considered as the most critical success factor of performance detecting, the next step starts with building a digitalized workflow-based framework that integrates IoT technologies with SCM initiatives. The proposed framework is named as Dynamic Supply Chain Performance Mapping (DSCPM). DSCPM is proposed to be used at an intermediate operational level, where the administration level (i.e., ERP) and the execution-level will be combined to achieve an integrated real-time digital SC.

This study will also illustrate how DSCPM, as a performance-based IT system, can intelligently monitor and control operational issues on the execution-level. Thus, the DSCPM is proposed to contain several real-time performance-based operational modules concerning PPAs (e.g., costing tools, waste monitoring, continuous improvement, etc.). Each module is equipped with suitable algorithms or mathematical models which are translated into what is known as Real-Time Performance Control Rules (RT-PCRs) that are based on the Complex Event Processing (CEP) mechanism. The study provides a systematic explanation on how IoT captured real-time data can be effectively utilized to support the functionality of PPA-modules that continuously provide supervision on the practicing of PPAs as well as to systematically detect unwanted incidents and unforeseen disruptions that have occurred and smartly generate the appropriate real-time decision-making support or re-(actions). In this regard, a dedicated module has been developed to automatically detect the causes of performance violation along the SC value stream in term of time. Figure 1.1 below summarizes the function of DSCPM in SC environments as an enabler to achieve a real-time closed-loop performance-based SC operations system. AVSM stands for Actual Value Stream Map that represents the current situation on the execution-level, whereas VVSM stands for Virtual Value Stream Map that represents the ideal or the planned situation on the execution-level.



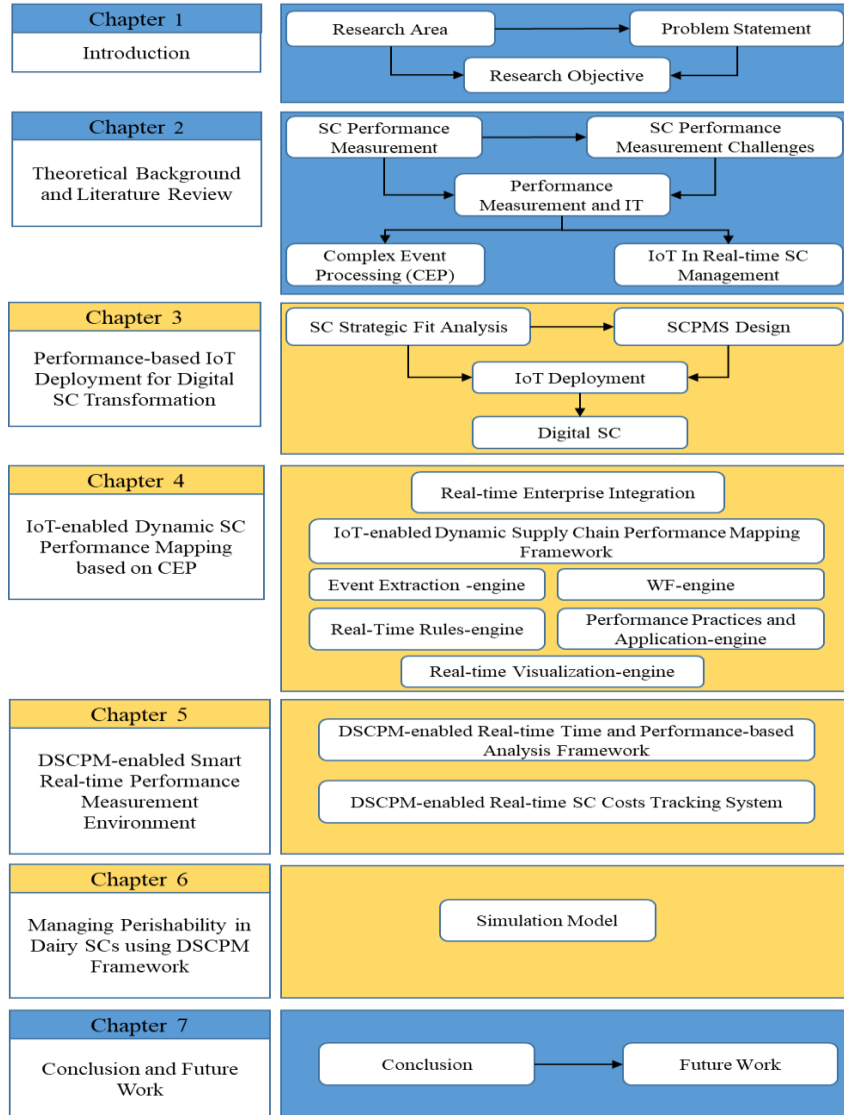
**Figure 1.1: Overview of Real-time Intelligent Performance-based Monitoring and Controlling System.**

As a result, this thesis aims to fill the gap of knowledge regarding the use of IoT technology in SC management and performance measurement and tries to remove the ongoing doubts and ambiguity about IoT adoption in SC performance measurement and management field. It shows that more IoT benefits can be harvested through performance measurement and IoT integration, which can provide an alternative solution for SC practitioners instead of a traditional PMS. This will convince companies and SCs to adopt IoT in their systems and consequently achieve a short-term ROI as well as contribute to solving today's SC challenges.



## 1.4 Thesis Outline

To achieve the research objectives, Figure 1.2 shows the research methodology and thesis outline.



**Figure 1.2: The Research Methodology of This Dissertation.**

# **Chapter 2. Background and Literature Review**

## **2.1 Introduction**

The supply chain performance measurement system is “a set of metrics used to quantify the efficiency and effectiveness of supply chain processes and relationships, spanning multiple organizational functions and multiple firms and enabling SC orchestration” [11]. The implementation of performance measurement has shown significant impacts on various industries. Numerous studies have tried to develop performance measurement systems and applications to tackle the challenges of today’s SC manufacturing and operations systems to avoid waste and achieve perfection. However, despite the advancement of using real-time IT systems, not much attention has been given yet to combine supply chain performance measurement with IoT to enable a digital and smart environment as well as to achieve planned and strategic targets [36].

In this context, today’s SCM challenges demand a revolutionary improvement to keep performance measurement and its application effective and prevent them from becoming obsolete. In other words, a real-time IoT system can be employed to improve the quality of information (i.e., accuracy and timeliness) and consequently facilitate the adoption of digital and smarter environment, solutions, and practices.

In the context of real-time visibility, IoT technology can be considered as the major enabler to support a performance-oriented IT system with real-time execution data. To enhance its functionality, IoT supported by different data capturing systems (e.g., RFID, sensors,

digital cameras, data-entry systems, etc.) can reach about 100% execution-level visibility [19].

IoT technologies is an emerging technology in SC due to its ability to record products, materials, equipment, and personal information at an item-level in a way that is fully automatic, instantaneous, and touch-free [37]. For instance, RFID could be used to achieve a smart environment through a better and effective usage of real-time execution data to support performance monitoring and SCM practices, leading to the violation and waste detection and elimination and overall improvement in competitive strategy. Subsequently, the efficiency and effectiveness of operations can constantly be improved, leading to higher levels of customer service and lower costs [19].

## **2.2 Supply Chain Performance Measurement**

### **2.2.1 Literature Review about SC Performance Measurement**

Traditionally, performance measurement is defined as the process of quantifying the effectiveness and efficiency of actions [38]. In other words, measuring performance means transforming the complex reality of performance into a sequence of limited samples that can be communicated and reported under similar circumstances [39]. In modern business management, performance measurement assumes a far more significant role than quantification and accounting. It is concerned with measuring the efficiency and effectiveness of processes and activities, aggregating and standardizing information, and setting appropriate targets [38]. Sink and Tuttle [40] claimed that “you can’t manage what you can’t measure.” Performance measurement can provide important feedback information to enable managers to monitor performance, reveal progress, enhance motivation, and communication,

diagnose problems and make decisions. According to Kueng et al. [41], performance measurement system should perform four main functions:

- Track the performance of an organization.
- Support company internal and external communication regarding performance.
- Help managers by supporting both tactical and strategic decision-making.
- Capture knowledge in a company, and facilitate organizational learning.

The performance measurement literature usually assumes that a PMS is a system adopted within a single firm boundary [11]. It can span different processes and functions, involve different organizational units and use different types of metrics. Normally it serves the purpose of monitoring and reporting tasks that are in the firm's management interest. Instead, when considering processes and relationships involving multiple SC actors, we inevitably fall outside the sphere of influence of a single firm. Here, the focus shifted to SCM context and start talking about SCPMS where performance measurement can facilitate inter-understanding and integration among SC members. It also provides insights to reveal the effectiveness of strategies and to identify successes and potential opportunities. It makes an indispensable contribution to decision-making in SCM, particularly in re-designing business goals and strategies, and re-engineering processes [42]. In this context, results can be achieved only through the coordinated effort of multiple entities. As a consequence, performance measurement becomes more challenging, since it must serve the purpose of several firms (i.e. the focal firm, the suppliers and the customers) as well as the SC overall. This requires the collection of data from many sources (which are not always reliable), the creation of

a common performance measurement platform, the sharing of information with supply chain partners, and the collaboration with them on the strategy implementation [11]. Therefore, SCPMS, if compared with a traditional PMS, has a broader scope.

SCPM approaches and techniques have been extensively studied. Balfaqih et al. [8] categorized SCPM approaches into three approaches (perspective-based, process-based, and hierarchical-based) and techniques into four (analytical hierarchy process (AHP), data envelopment analysis (DEA), Delphi, survey, and simulation). According to their results: in recent years, researchers have paid more attention to the holistic view of SCPM, perspective-based approached is the most popular approaches, SCOR model has attracted more attention than BSC, and many researchers support that opinion.

Agami et al. [46] divided SCPM approaches into two main categories: financial approaches and non-financial approaches. This work indicates that the literature on the topic of SCPM is almost balance between being theoretical and empirical. It also classifies the frameworks in the reviewed literature using two-dimensional criteria: system dynamicity and scope of implementation. According to their analysis, 83% of the published works discuss static frameworks and 90% of literature dominated by entity-level performance measurement frameworks. Only 3% of the works covered the dynamic and whole SC scope. Accordingly, their conclusion emphasizes the limitations of current SCPM of being static and lack holistic approaches.

Additionally, in their recent work, Maestrini et al. [11] conduct a systematic literature review on SCPMSs. They explain the broad subject scope of SCPMS measurement process by decomposing it into internal and external systems. They also identify many-to-many SCPMSs as a third possible configuration, with a set of metrics shared

by customers and suppliers at the industry level.

The internal SCPMS focuses on the monitoring and control of the processes that take place within the company boundary (the source, make, and deliver sequence processes according to the SCOR model). This system is also referred to as the operational PMS and is widely addressed by the operations management [38, 47] and accounting literature [48, 49]. Instead, the external SCPMS is intended to monitor and control the inter-firm processes and relationships. It can be further decomposed into a supplier PMS (e.g. [50, 51]), and a customer PMS (e.g. [24, 29]).

Furthermore, an interesting insight gained from the literature that is worth considering is that the vast majority of external SCPMS studies focus on the immediate supplier or customer rather than encompassing multiple SC tiers (e.g., a supplier's suppliers or a customer's customers). Though the concept of SC theoretically embeds an extensive perspective, the actual visibility beyond the first tier is very challenging because of, for example, technological barriers or relational inertia [52]. Nevertheless, synthetic information on critical performance from various SC tiers (avoiding information overload) could improve the alignment of the extended SC, thus achieving both single-firm and overall SC objectives [53]. Therefore, multi-tier SCPMSs represent an evolution of first-tier supplier and customer PMSs, extending the measurement process to additional downstream or upstream actors [54]. Finally, some studies [29] and recent empirical evidence [55, 56] suggest another type of SCPMS that does not fall into the categories above. In these cases, the SCPMS is usually developed as a web- or cloud-based solution by a third party IT service provider for the benefit of all supply chain actors. The system enables a flexible many-to-many type of interaction, whereby it can be decided which type of

information is shared and by whom. Thus, a many-to-many SCPMS is defined as “a set of metrics used to quantify both the efficiency and the effectiveness of inter-firm processes shared by multiple buyers and multiple suppliers.” This situation represents an interesting avenue for further investigation, as it seems that the joint initiative at the industry level helps to overcome the lack of standard and typical technological barriers in buyer-supplier relationships [11].

Maestrini et al. [11] addressed the papers dealing with at least one component of SCPMS, and it mostly focused on external SCPMS. They disentangled the studied papers according to two key dimensions of analysis, the system scope and the SCPMS lifecycle phases, which illustrated and identified in Table 2.1, and further explained in the next section.

**Table 2.1: SCPM Life Cycle Phases. Adapted from Maestrini et al. [11]**

<b>Phase</b>	<b>Definition</b>
SCPMS Design	Answering the questions of what to measure and how to select the limited set of metrics, information on the unit of analysis of the measurement process, the performance dimensions to tackle, the specific metrics to adopt, the overall SCPMS framework and the way in which it is built is considered
SCPMS implementation	The procedures to follow to put the SCPMS in place
SCPMS use	Actions stimulated by the measurement process
SCPMS review	The process of reviewing performance measures and targets

According to the analysis of Maestrini et al. [11], state of the art of the SCPMS literature can be summarized and concluded in the following points:

- Internal SCPMSs stay within the company boundaries. Therefore, the activities involved in the implementation, use, and review phases do not differ from those of traditional

internal PMSs. Since the 1990s a large body of literature has been developed on the internal PMS life cycle [38]. Therefore, the focus should be oriented more external SCPMSs.

- Among the external SCPMS related literature, supplier PMSs receive most of the attention, the system design (usually referred to as vendor rating or vendor evaluation) is widely studied, more recent literature is starting to cover the other phases of the life cycle [58]. However, considering the strategic relevance of supplier PMSs to firms, this area still offers several gaps to be addressed.
- Customer PMSs are usually embedded with other frameworks. Therefore, some metrics addressing customer performance can be found in the extant literature. However, limited contribution specifically tackles this scope.
- Multi-tier SCPMSs respond to an extended visibility logic, which is embedded in the general SC concept. Though some conceptual process based external SCPMSs spanning multiple tiers (at least three) of a single SC have been proposed, empirical evidence is still lacking on their applicability, potential diffusion, and usefulness.
- Finally, an unexplored area is many-to-many SCPMSs. They can be considered as new-generation SCPMSs, which have never been empirically investigated by the scientific literature so far but are becoming a reality.

### **2.2.2 SCPM Challenges in Today's Business Environment**

In recent times, there have been challenges in the deployment and implementation of performance-based practices and applications in SCs. These challenges prevent organizations that have deployed



performance measurement initiatives from successfully achieving their goals. Many research papers have investigated performance measurement implementation in SCs [11]. However, due to rapid changes in the business environment, products, and technologies, performance-based initiatives simply diminish and become inefficient in the long run.

From SC value stream perspectives, the success of performance measurement initiatives and applications can be hindered by two types of challenges: measurement system-related and implementation environment-related challenges.

#### **2.2.2.1 Measurement System-related Challenges**

Measurement system-related challenges concern the SCPMS life cycle, which indicates the stage of the system development that is under scrutiny (i.e., design, implementation, use, and review) [53].

In “design” phase, challenges represented in answering the questions of what to measure and how to select the limited set of metrics, information on the unit of analysis of the measurement process, the performance dimensions to tackle, the specific metrics to adopt, and the overall SCPMS framework and the way in which it is built is considered. [38]. The design phase is vital to grantee aligning the selected SCPMS with strategy formulation and communication and forming the diagnostic control mechanisms by measuring actual results. Therefore the challenge is to develop a PMS as an enabler of performance improvement, rather than merely as a control device [59].

In the “implementation” phase, the support of a reliable management information system becomes critical due to the need for interaction with external SC partners for data collection and performance measure reporting [60, 61]. Indeed, SCMPSSs need to

integrate data from different sources, and this might pose several challenges, including a reluctance to share sensitive information, standardization of different data, codification protocols, and data reliability [30].

Next, in “use” phase, the way in which the external SCPMS is used strongly affects the relationship management process with external SC partners, and it is likely to affect the enhancement of both relationship capabilities (e.g., trust, commitment, and collaboration) and operational performance [62]. Challenges in this phase are strongly related to SC visibility problems. SC visibility has been defined as “the extent to which actors within an SC have access to or share information which they consider as key or useful to their operations and which they consider will be of mutual benefit” [63].

Finally, the system “review” phase, which is essential to keep a clear, robust and up-to-date alignment between the SCPMS and the underlying SC strategy. The reactivity to intercept both endogenous factors (e.g., changes in the corporate strategy) and exogenous factors (events occurring to external supply chain partners or the industry as a whole) is critical to guide the SCPMS review [53].

#### **2.2.2.2 Implementation Environment-related Challenges**

Implementation environment-related challenges can be classified to external and internal challenges. External challenges arise due to globalization and dynamicity. They includes product customization, high demand variability and market fluctuation, high variability in supplying the ordered quantity from suppliers, competitive cost, and quality, on-time delivery ability, shorter product life cycles, etc. [65]. In their turn, the external challenges will create several internal challenges for the overall SC and in its member-level. These challenges include

high product variety, low volume manufacturing environment, product complexity, production variability, quality issues, variance in the cycle times, different routings, turbulences in schedule due dates, priorities, etc. This implies that an accurate and timely flow analysis of such complex and dynamic manufacturing and operations environments become fairly difficult and affect the success of SCPMS. Therefore, performance-based applications and SCM practices in such environment becomes more complicated and has an even lower chance of succeeding.

### **2.2.3 Limitation of Current SCPMS and Models**

SCPM is seen to be more than a disparate assortment of individual metrics. It has to be valid, robust, integrative, economical, and compatible [66]. Designing the SCPMS is a challenging task, which needs practical guidelines [20]. Despite that much-respected efforts have been put by researchers to develop a suitable SCPMS, it is found that many limitations have been highlighted in the literature [65, 67]. Based on the reviewed literature, the main limitations of the current SCPMS can be summarized as follows:

- Lack of connection with strategy.
- Incompleteness and inconsistencies in performance measurement and metrics.
- Lack of balanced approach that incorporates financial and nonfinancial metrics.
- Focus on the cost to the detriment of non-cost metrics.
- Lack of holistic approach, i.e., SC must be viewed as one whole entity and measured widely across the whole.
- Inefficient focus on customers and competitors.
- Being much inward looking.

- Loss of supply chain context, thus encourage local optimization and fails to support continuous development.
- Lack of system thinking.
- Being static, short-term, and profit-oriented
- Not provide definite cause-effect relationship among numerous hierarchical individual performance metric.

Moreover, common SCPMS types, their criteria of measurement, and their limitations according to the reviewed literature [46] outlined in Table 2.2.

**Table 2.2: Summary of Common SCPMS Types and Limitations**

<b>Type of Measurement System</b>	<b>Criteria for Measurement</b>	<b>Limitations</b>
1. Activity-based costing (ABC)	Performance measures of activities after breaking it into tasks or cost drivers and allocating cost based on these cost drivers.	Relying only on purely financial metrics, and the non-accurate cost driver's estimation.
2. Economic value added (EVA)	Performance measures of value created by enterprise passing it into operating profits more than capital employed.	Fail to reflect operating SC performance since it only considers pure financial indicators. only assessing high-level executive contributions and long-term shareholder value
3. Function-based systems (FBMS)	Performance measures of functions within each process of the supply chain.	Criticized for viewing the separate supply chain functions in isolation with the overall strategy, and hence results in localized benefits that may harm the whole SC.
4. Dimension-based systems (DBMS)	Performance evaluation of pre-determined key dimensions across the supply chain	They do not reflect the performance of internal functions and operations within the chain since they only focus on top-level measures.
5. Hierarchy-based systems (HBMS)	Performance measures identified on three levels of management: Strategic, Tactical and Operational.	A clear guide cannot be made to put the measures into different levels that can lead to reduced levels of conflict among the different SC partners.
6. Interface-based systems (IBMS)	Performance measures defined between supply chain linkages, i.e.,	In actual business setting, it requires openness and total sharing

	stages.	of information at every stage which is eventually difficult to implement
7. Perspective-based systems (PBMS)	Performance measures from six perspectives of the supply chain: Operations Research, System Dynamics, Logistics, Marketing, Organization, and Strategy.	There might be a trade-off between measures of one perspective with measures of other perspectives.
8. Efficiency-based systems (EBMS)	Performance measures to evaluate the supply chain efficiency.	It determines the efficiency of different units within the supply chain relative to each other and not versus a previously set target value or a best practice. This might sometimes be misleading to managers and stakeholders.
9. SC operations reference model (SCOR)	Performance measures along the five main supply chain processes: Plan, Source, Make, Deliver and Return.	It is considered an exhaustive system that requires a well-defined infrastructure, fully dedicated managerial resources and continuous business process re-engineering to align the business with best practices.
10. SC balanced scorecard (SCBSC)	Performances measures across four supply chain perspectives: Financial, Customer, Internal Business Processes, Innovation, and Learning.	It is a static approach which when applied in corporate setting does not provide an opportunity to develop, communicate and implement the strategy. It provides a conceptual framework only. That is, it lacks an implementation methodology and thus deviates from the merit of the concept itself.
11. Generic systems (GPMS) (Performance Prism, Performance Pyramid)	Performance measures are strategically aligned.	Prism: it offers little about how the performance measures are going to be identified and selected. Pyramid: not provide any mechanism to identify key performance indicators, nor does it explicitly integrate the concept of continuous improvement.

As a result of aforementioned SCPM literature review and its challenges, and to overcome the above drawbacks and limitations, there

is a need for new methodologies to design and implement SCPMS. Such methodology should consider deploying IoT to digitalize SC and combine it with the current IT systems. That to generate an accurate real-time visibility over all relevant data, where the captured data can be utilized for real-time performance-based decision-making processes, or automatically generate the appropriate re-(actions) on the user's behalf to avoid performance violations and wastes, add values, and enable continuous development.

In this regard, Lee [68], Al-Mudimigh et al. [69] and Alfaro et al. [70] stress that the first step in developing an efficient supply chain is to improve the performance of disparate internal systems and processes responsible for managing and coordinating the interactions in the value chain. They show that interfacing activities locally, without a systematic overview, may fail as it will be dependent on an exclusive use of internal measurements. Folan and Browne [71] note that the development of disparate measurement systems may result in superfluous and incompatible performance evaluation. Lauras et al. [72] stated that, because companies are moving towards a more integrated type of operations management across their supply chains:

- It is becoming necessary to measure performance on the various parts of the supply chain in a consistent way, i.e., with the support of a clear, logical and intelligible framework in which the PMS will work [10].
- There is a need to quantify performance for the supply chain as a whole and refer properly to different problem dimensions.

Explicit knowledge of the whole supply chain can be gained by business process modeling, which has been recognized as a good practice to reduce heterogeneity problems. Once they are drawn up, collaborative processes between supply chain partners provide a

common acceptance of the business and define the many interfaces that need to be managed. Lauras et al. [72] demonstrate that, while this primary basis of knowledge is useful in defining Key Performance Indicators (KPIs), the claim that PMS can manage the work cannot be accepted without an investigation into decision-making activities. Therefore, they emphasize decision-making representation and try to prove the added value for the design and operation of the PMS. Decision-making processes are a foundation of management activities. They deliver the control information that the operational activities need, and they are in charge of selecting, booking and monitoring resources for the predicted executions. Folan and Browne [71] specify two kinds of requirements for managing performance with business processes:

- A procedural performance measurement framework shall evaluate the performance of each activity and process.
- A structural performance measurement framework shall evaluate the performance at each level of the organization (internal and external).

Accordingly, to highlight the importance and roles of business process-oriented SCPM, we briefly discuss it in the next section. We focus on SCOR model, which has received a lot of attention from researchers and practitioners, as a process-oriented model.

## **2.3 Process-oriented SCPM and SCOR Model**

### **2.3.1 Process-oriented SCPM**

According to Chan and Qi [54], supply chains is neither a collection of independent, self-centered enterprises through the business relationship nor the coordination of interfaces between the fragmented functions of supply chain components. Therefore, performance

measurement should take a holistic system perspective beyond the organization boundaries because self-focused performance measurement view can only encourage local optimization without considering the global optimization along the supply chain channel [67]. Such approach force supply chains to focus on the integration of business processes. One of the definitions of SCM, by Global Supply Chain Forum (GSCF), is typically described as below:

“Supply chain management is the integration of key business processes from end user through original supplier that provide products, services, and information that added value for customers and other stakeholders.”

The definition highlights SCM initiatives of integrating and managing key business processes within and beyond the boundaries of the individual organization [54]. Lambert and Cooper [73] also claim that successful SCM requires a change from managing individual functions to integrating activities within key supply chain business processes. Process refers to linked activities with the purpose to produce products or services for customers within or outside the company [74]. In SCM, the network of organizations is structured through upstream and downstream linkages among the processes and activities that added value chain [75]. The process-based model of SC blurs organizational and departmental borders between the connected processes and activities, thus diluting the structural barriers and encourage cross-organizational optimization [54].

Process-based performance measurement does not only fit with the nature of SCM but also contributes much more to continuous improvement of SCM. Assessing process performance provides an opportunity for examining the effectiveness of process management [54]. The main advantages of adopting process-based performance measurement that can be achieved in SCM are highlighted as follows



[72]:

- To provide the opportunity of recognizing the problems in operations and taking corrective action before these problems escalate.
- To facilitate linking with the operational strategies, identifying success, and testing the effect of strategies.
- To support in monitoring the progress.
- To assist in direct management attention and resources allocation.
- To enhance communication of process objectives and position among the processes involved in the supply chain, thus improving trust and common understanding.

Next subsection introduces one of the most used process-based performance measurement modeling frameworks, SCOR model, with briefed literature about it.

### **2.3.2 SCOR Model**

According to Lauras et al. [72], business process representation is a necessity to check the common agreement of businesses and put a frontier between what can be shared among partners and what cannot be shared. Because of this search for agreement, the supply chain operations reference (SCOR) model has received a lot of attention from researchers and practitioners.

The SCOR model was developed by the Supply Chain Council (SCC) organized in 1996 by the consulting company “Pittiglio Rabin Todd & McGrath,” AMR Research, and 69 other companies. In 2012, SCC had close to 1,000 corporate members, practitioners and representatives of a wide cross-section of industries [76]. SCOR is the most widespread process-oriented SCPM model designed especially for

modeling SC, and it is the only integrated cross-functional framework that links business processes, performance metrics, software requirements or technology, and best practices. It is also a tool used for implementation, and it is being used by many companies worldwide [77].

According to Robinson and Malhotra [78], SCOR is an integrated process of planning, sourcing, making, and delivering. It spans the value chain from the suppliers' suppliers upstream to the customers' customers downstream. SCOR can be used for a prescribed analysis of SC processes that can be used by managers to characterize, analyze, coordinate, and configure the depth and breadth of a supply chain as well as for the foundation of decisions. They also pointed out that the SCOR model demonstrates the linking of value-adding processes within organization departments and between SC entities; thus, it supports intra-organizational and inter-organizational integration.

The SCOR model scope starts from the initial planning processes (demand forecasts) and ends at customer satisfaction measuring points (installation, invoices, and payment). The model is specific to a product or a family of products flowing through SC organizational entities. SCOR identifies a building block approach consisting of six business processes: planning, sourcing, making, delivering, returning, and enabling [79]. These business processes represent the vertical-neutral abstraction from all demand/supply planning, purchasing/procurement, manufacturing, order entry and outbound logistics, and return processing activities [30]. This approach allows SC to be configured across organizations, internal or external, across industry segments, and across geographies [80].

The six SCOR management processes are further decomposed into three deeper levels. Level 2 (configuration) is where the organization

implements its configuration strategy and determines its capabilities within level 1 processes. Level 3 (detailed operations) includes steps that are performed in a certain sequence to plan SC activities, source materials, make products, deliver goods and services, and handle product returns. Level 4 (implementation) lies outside the SCOR scope, including processes dealing directly with practices and activities. It is extended from level 3 processes according to the uniqueness of each SC organization operations, and it involves industry-, product-, location-, and/or technology-specific processes, activities, and tasks [79]. Typically, any SC can be described using the SCOR model business map by establishing a framework for a subsequent supply chain organizational elements. A thread diagram can be used to convert any SC geographical map to its typical process view (see Fig3.12 in Chapter 3).

Moreover, SCOR offers a consistent KPIs framework for the development of SC performance. That KPIs seeks a balance between short-term versus long-term plans, internal versus external focus, different levels of an organization, BSC methodology views, and multiple stakeholder perspectives [65]. SCOR assumes that it is impractical to describe an SC using a one-dimensional model. Therefore, using the SCOR model, it is possible to describe an SC in five dimensions (i.e., performance attributes): reliability, responsiveness, agility, cost, and efficiency in asset utilization. Each performance attribute has one or more strategic metrics or KPIs (level 1 metrics). These metrics are calculations by which an organization can measure how successful it is in achieving its desired positioning within the competitive market space [80]. Each process in the SCOR model has its performance metrics, and like its process structure, SCOR performance metrics are organized in a hierarchical structure. Three

levels of metrics, levels 1, 2, and 3, are described in the model, where each level serves as a diagnostic for the upper-level metrics. Therefore, the SCOR model can be used as a cause analysis tool [60].

However, as SCOR spans SC wide scope that aligned with operational strategy, material, work and information flow, it is considered an exhaustive system that requires a well-defined infrastructure, fully dedicated managerial resources and continuous business process re-engineering to align the business with best practices [46]. In other words, if the decomposition process of SCOR model is general enough to be applied to many cases, the more detailed levels (Level 2 and especially level 3) may be difficult to identify and monitored using the SCOR elementary processes, that because specificities increase with the granularity of processes representation. Also, the score does not try to close the loop, and there is no clear guidance how KPIs should be used to manage the system. Thus, without a new method, it could be rather difficult to define and implement the necessary corrective actions on this basis alone.

Moreover, although there is much academic work that addresses the SCOR model, the analysis of actual implementation approaches is limited. As presented at various SC events, industrial applications are mainly comprised of ad hoc performance measurement at Level 1 [30]. This is because of a lack of SCOR-enabled analytical and monitoring mechanisms and tools. It becomes too hard and costly to collect both high-level and detailed metrics on a periodic basis, let alone real-time, especially when functional or organizational boundaries are crossed and no clear evidence how that will be reflected on organizations ROI. Automated measurement-based decision-making and applications also require that as-is enterprise process logic is well documented and data can be rolled up from these processes into the SCOR view. Our

research responds to this challenge by developing a new mechanism which tracks SC business processes and gathering real-time information through the IoT environment, using RFID, sensor networks, and other supporting technologies.

The next section introduces IoT technologies, its applications in SC field, and how it could help to enable new mechanisms for better SCPM practices and initiatives.

## **2.4 IoT and SCM**

### **2.4.1 IoT Definition**

The Internet of Things refers to information-sensing devices and technologies such as the Global Position System (GPS), Radio-Frequency Identification devices (RFIDs), etc. It is a real-time, internet-based network. It links processes or objects that need to be monitored, communicate, and interacted with each other. It collects various demanded information, such as location, sound, heat, light, mechanics, etc. IoT is a technology that aims to connect humans to humans, machines to machines, and humans to machines. That makes it convenient for identification, management, and control [81].

IoT is beginning to incorporate other major technology industry trends such as cloud computing, data mining, data analysis, mobile communications, etc. IoT architecture can be divided into four layers [33], Figure 2.1:

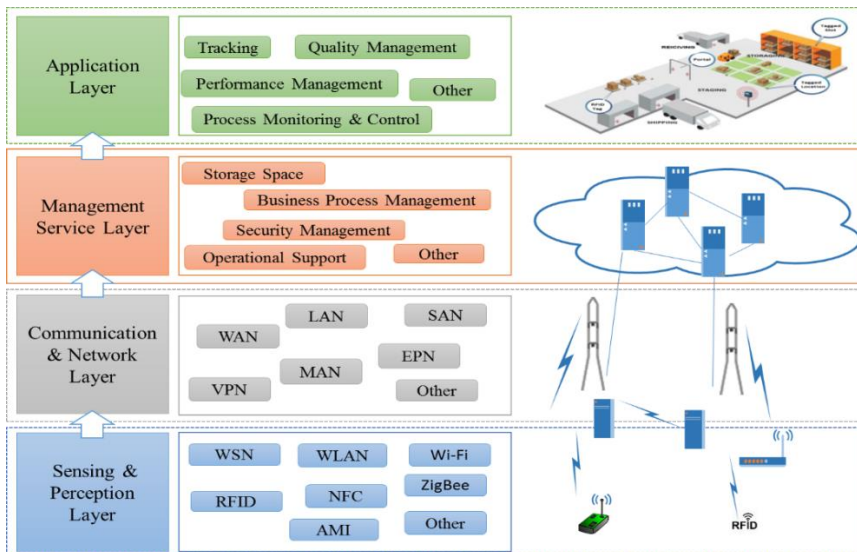
First, the sensing or perception layer. Its main task is to collect and transmit data. This layer usually includes three main components: (1) object identification properties such as an RFID tag, barcode, or any object property that can be sensed (e.g., shape, size, temperature, etc.), (2) reader, which includes sensors and actuators, and (3) short-distance

networking connectivity means such as Wi-Fi, ZigBee, etc.

Second, the gateway & network layer. Its role is to connect objects or things and allow them to share and exchange information. It mainly includes a gateway, internal network or local area network (LAN) to connect the gateway with the sensing layer, and an external network or wide area network (WAN) to communicate with the outside domain.

Third, the management service layer. It relies on middleware technology that provides functionalities to integrate services and applications in the IoT seamlessly. It is in charge of information analytics, security control, process modeling, and device management.

Fourth, the application layer. It is the ultimate goal behind IoT technology. In this layer, collection and transition data are reserved, processed through certain techniques to be used for a plan, and manage and control objects or things.



**Figure 2.1: IoT Technologies Architecture.**

Source: Dweekat et al. [82]

## 2.4.2 IoT Technologies in SCM

The IoT term was initially introduced by Kevin Aston in 1999 to refer to uniquely identifiable, interoperable, connected objects using

RFIDs at Procter & Gamble's (P&G's) SC [83]. The IoT was expected to transform the operation and roles of most existing industrial systems and therefore offered a promising solution for all systems related to SC, such as manufacturing systems, transportation systems, performance management systems, and others [12].

In SC applications, RFID technology supported by or integrated with WSN systems are considered the IoT enabler and dominant technologies [13]. RFID is a promising technology for real-time industry. This technology shows a major breakthrough in Auto-ID (Auto Identification) technology and brings immense advantages and significant improvements in the performance of operations in the fields it has been implemented in like warehousing, distribution centers and retails, logistics, supply chain management, manufacturing, aerospace, defense, healthcare, pharmaceuticals, and libraries [36].

Several researches about RFID adoption in logistics, supply chains, manufacturing and other fields have been reviewed, including [84-88]. These papers explore several benefits of RFID in logistics and supply chain management; they have proven that RFID can help enterprises to increase the exchange of information to promote process efficiency and save costs. Thus, the company can achieve real-time monitoring of RMs, WIPs, FGs, transportation, stock, delivery, sales, as well as monitoring activities such as putting items back on the shelf and returning goods. Moreover, adopting RFID helps enterprises to improve their whole logistics operations to become more visible, transparent, and efficient by increasing automation and decreasing error rate.

An RFID adoption model based on a Technology-Organization-Environment framework was proposed by Wang et al. [33]. This study examined the influence of nine variables in the adoption of RFID in the manufacturing industry. The key findings in this study indicate that six

of the nine variables (i.e., information intensity, complexity, compatibility, firm size, competitive pressure, and trading partner pressure) were found to be significant determinants of RFID adoption. While the remaining three variables (i.e., relative advantage, top management support, and technology competence) can be considered as insignificant determinants in the adoption of RFID technology. Moreover, the lack of RFID common standards as well as the difficulty of integrating RFID with existing enterprise information systems and business processes has been found to contribute to the complexity of RFID adoption [89].

A survey was conducted by Dolan et al. in 2008 among 114 German companies, that have adopted RFID-technology, to determine the percentage of improvements after the deployment of RFID in their production facilities. The results show 59.3% reduction in lead time, 70% reduction production downtime, 62.2% improvements in quality inspection, 7.2% reduction in rework, and 54.1% cost reduction, etc. It was stated that only about half of the enterprises surveyed achieved their intended targets, implying that many organizations have not realized how to utilize RFID in the right manner to gain the intended objectives [14].

Recently, several academic papers have investigated the potential benefits of RFID in supply chains and the possibility of RFID to solve different supply chain problems such as vendor managed inventory (VMI) [91], bullwhip effect [92, 93], inventory accuracy [94-97], and replenishment policies [98, 99]. It is to be concluded that RFID technology ensures the accuracy of inventories by solving the problems that cause transaction errors, shipment errors, delivery errors, scanning errors, incorrect identification, shrinkage errors, theft, vendor fraud, administrative errors, inaccessible inventory, misplacement, and supply



errors. Hence, companies can improve the relevant operations performance.

Based on this reviewed literature, the majority of researches related to RFID are supply chain logistics oriented, with the main target of these researches focusing mainly on inventory management, objects/assets tracking and tracing, as well as object locating.

Regarding IT systems, there is a lack of standards for integrating RFID with the existing enterprise IT systems and business processes like MES or WMS or ERP. A real-time enterprise IT system keeps up with a highly dynamic manufacturing environment and bridges the gap between physical flows of product/part and information flow in enterprise application systems [100]. For instance, in [101] an information system architecture was designed and implemented by integrating an RFID system with MES, known as real-time MES (RT-MES) in the automobile manufacturing industry. In [9], there was a focus on constructing a modern IT architecture that integrates radio frequency identification data systems with MES and ERP to increase scalability and to facilitate the interaction between all three layers. In [102], an RFID-enabled real-time manufacturing information tracking infrastructure (RTMITI) was proposed. Depending on the RTMITI, several real-time operational activities could be supported like real-time manufacturing cost tracking, real-time WIP progress tracking, and equipment and machine status monitoring.

Based on research papers regarding RFID and SCM, there is an increasing trend towards the implementation of RFID technology in SCM, due to the distinguished characteristics and capabilities of RFID in manufacturing and operations applications. However, to the best of our knowledge, no studies or research papers have explicitly and practically discussed the integration and utilization of RFID (i.e., IoT)

technology in SCPM. In these studies, the possibility to integrate the capabilities of RFID and other IoT technologies with SCPM practices and tools to achieve organizational targets and increase the efficiency have been discussed, providing the opportunity for SCs who apply this concept to take the lead within their respective industries. In other words, the usage of RFID can burst conventional performance measurement paradigms and push SC into leadership positions within their industries [32].

However, the deployment of RFID in SCM introduces new challenges regarding processing the enormous amounts of RFID captured event-instances and data, generated in real-time (measured in seconds or milliseconds) during a daily operation run by different resources located along the SC value stream operational level activities. In this regard, few studies [33, 104] proposed architectures of event processing in an enterprise information system using CEP mechanism based on RFID. Next section discusses the complex event processing mechanism and its importance in an enterprise information system.

## **2.5 Complex Event Processing (CEP)**

CEP is a kind of technology and method that is used to obtain meaningful and useful information from the huge amount of events, as well as to control event-driven information systems [107]. In the scope of SC performance monitoring, we define an event as a “change of smart-object state,” (e.g., the product arrives, process starts at the machine, machine setup started, etc.). Generally, events are categorized into primitive events and complex events. Both of these events have their distinct properties, and a relationship exists between primitive and complex events in terms of goals and uses [108].

- A Primitive Event ( $e_i$ ) is an event which is defined as a kind of action that happens at a specific time point and location, due to the change of state of a smart-object, i.e., the start of a new state and the end of the current one [109].
- A complex event ( $E_i$ ) is an aggregation of primitive events over a period of time at a specific location(s) [107]. A complex event is aggregated according to predefined rules which contain event operators to find the relation between a primitive event and/or complex events [110].

In this thesis, event types and instances are generally represented by upper and lower case letters respectively, such as ( $E$  and  $e$ ). Take “start-loading state” for a truck as an example. The truck is ready to start loaded ( $E_{sL}$ ); if the following combined events have occurred: “truck arrival ends-event”  $E_A$ , “labor or forklift available-state”  $E_L$ , “material arrival event”  $E_{M_a}$ , and “order loading triggering event”  $E_{L_t}$ . The events in this example can be expressed as:  $E_{sL} = E_A \wedge E_L \wedge E_{M_a} \wedge E_{L_t}$ , where “ $\wedge$ ” is the logical operator “AND”.

An event can also be detected based on physical movements and activities. For example, the labor state is changed into “labor available–state”, once the event of a labor enter the specified vicinity of the machine location is detected by an RFID-reader.

In this context, several research papers applied CEP technology to enterprise information systems, and demonstrate how the event processing engine works and interacts with other existing information systems [109]. However, since the introduction of RFID technology in the field of performance measurement of SC, the majority of RFID-IT vendors have only provided RFID-platforms that process primitive events or primitive event patterns, with limited RFID-rules that concern real-time re/action in manufacturing applications [110]. Furthermore,

there has been almost no research addressing the application of CEP mechanism to smartly support and enhance the practicing of SCPM in real-time in daily operation runs.

## **2.6 Discussion and Conclusion**

This chapter provided brief information about SCPM as well as the implementation of IoT technologies within organizations and SCs. It can be concluded that IoT can provide automatic real-time data collection of objects with unique IDs without line of sight. Thus it can be used for identifying, locating, tracking and monitoring physical objects and its activities on the operational execution level. In other words, IoT and its real-time data capturing technologies like RFID, WSN, or intelligent devices (e.g., robotics or automation devices) have been proven to be significant new power for humans to sense objects and provide production and operational data in real-time (i.e., in seconds or milliseconds).

However, despite the fact that IoT is seen by many researchers as a revolutionary enabler of automated real-time data capturing system, there remains confusion as to how SCs and manufacturing organizations can use the huge amount of data more effectively to bring more benefits. Therefore, many enterprises have not achieved their intended targets, since these organizations have not realized how to utilize IoT effectively to reach their objectives and gain more benefits. The idea of a comprehensive integration between performance measurement and IoT is still not very well understood and not mature enough for SCM and IoT practitioners. This issue remains one of the top concerns in the SCM field.

Based on the reviewed literature, the following gaps and limitations have been identified in the IoT implementations in SCPM.

- There are almost no comprehensive, standard, clear, and effective SCPM-IoT-IT integration frameworks that have been developed to design SCPMS and transform the current SCs to digital and smart SCs to support a SC performance-based PPAs in real-time.
- Regarding SCM practicing on a daily basis, there is no work that discusses how to use the IoT real-time operation captured information to support the individual PPAs and sustain SCM principles and practices and keep them alive in the long-term.
- Despite the abundance of researches claiming the potential of IoT in SCM, there is a lack of real-time data analysis frameworks that help practitioners to achieve a smooth SC operating environment.

In summary, due to the lack of studies that address IoT-SCPM integration in a holistic SC environment, there is a need to develop a clear, detailed, and comprehensive framework to guide SCM practitioners towards the effective usage of IoT-technology to transform their SCs to a digital SCs, and enhance and support performance-based SCM tools to achieve better performance. This study aims to revolutionize the SC performance measurement paradigm by utilizing IoT benefits to create an extended real-time smart and sensing SC. This can be achieved by developing (1) a digital SC transformation framework and (Chapter 3) (2) a real-time data-driven IT system or platform based on SC performance principles which advocates SCM practices in the short- and long-term (chapter 4).

# **Chapter 3. Performance-based IoT Deployment for Digital Supply Chain Transformation**

## **3.1 Introduction**

Jeremy Shapiro defined a supply chain (SC) as “dispersed facilities where raw material, intermediate products, or finished products are acquired, transformed, stored, or sold and transportation links that connect facilities along which products flow” [111]. While, SCM has been defined as “the integration of the key business process from end user through original suppliers that provides products, services, and information that added value for the customer and other stakeholders” [112]. To evaluate the efficiency and effectiveness of these processes’ integration, many performance measurement models and approaches have been developed such as the balanced scorecard (BSC) and SCOR model, etc. All of these models tried to provide the means to pick the right metrics and define the functions or business processes where necessary information can be retrieved to evaluate the performance, assess whether the SC has improved or degraded, identify the success and potential strategies, or enhancing the effective and efficient decision-making at all organizational levels [40].

However, owing to today’s SC complexity, dynamicity, and the need for decentralization of decision-making, many obstacles have been encountered for efficient performance measurement. Some of these obstacles have been discussed previously in Chapter 2. Moreover, due to globalization, SCs became geographically dispersed. That leads to increasing the gap between data collection, performance

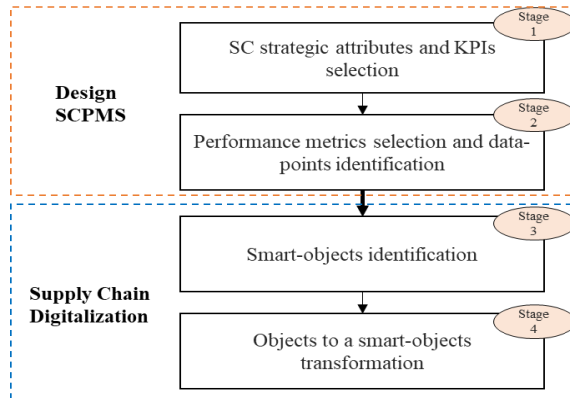
measurement, and decision-making. These problems essentially reflected on the performance measurement systems, and make it more static and non-efficient systems. Accordingly, to overcome these obstacles and to bridge the gaps mentioned above, it becomes essential to deploy the latest technologies (i.e., IoT) to digitalize current SCs in order to facilitate and enable a new generation of smart SCPMS that can be used to enhance real-time decision-making and enable more efficient SCM practices and applications.

In this chapter, we introduce a framework for digitalizing SCs based on their strategic performance view. The framework starts by developing a methodology to design a SCPMS considering the SC strategic fit between all SC members. It also includes a conceptual modeling methodology for deploying IoT technologies to digitalize current SCs and therefore enable real-time performance tracking and monitoring. We use some practitioners ideas as well as the SCOR model and ISA-95 standards to determine the SC KPIs and to identify objects and spots that should be digitalized. In the proposed framework, two fundamental interacting tasks play important roles: SC process modeling and performance measurement. The former requires tracking the flow of information on objects and activities along the SC value stream for monitoring, measuring, and controlling the value added along the processes. And the latter's role is to assign measures or metrics to these processes to evaluate changes and to assess the performance of the overall SC and individual members processes. These metrics should be selected to reflect a balance between internal and external as well as financial and non-financial measures, which can be related to strategic, tactical, and operational levels of decision-making and control [4]. The two tasks interaction will be employed to transform all of the involved objects, processes, and activities to smart

and digital agents, and therefore leads to achieve the targeted performance-based digital supply chain. Finally, this chapter results will be used as an enabler for a new generation of SC smart real-time monitoring and controlling performance-based IT mechanism that we will propose in Chapter 4.

### 3.2 Digital SC Transformation Framework

This section presents a conceptual framework for deploying IoT technologies to transform SC to digital or smart SC. As shown in Figure 3.1, the framework consists of four stages. The first two stages include a systematic methodology to design SCPMS, which aims to achieve the SC strategic fit by selecting a realistic, measurable, and comprehensive performance metrics, and analyzing them to their data components that can be tracked and collected in real-time. The third stage includes another methodology to find out all of the objects that generates or involved in generating the performance data identified in previous stages. These objects will be transformed to digital or smart-objects in the fourth and last stage. That will enable capturing and tracking performance data in real time, and therefore, enable more efficient SCM practices and applications. We discuss these stages with its methodologies in the next subsections.



**Figure 3.1: Digital SC Transformation Framework.**



### **3.2.1 SCPMS Design**

This subsection discusses the first and second framework stages. According to the reviewed literature, designing efficient and effective SCPMS requires some basic and essential steps:

- (1) Understand the business environment by analyzing the SC from the business perspective.
- (2) Analyze the strategic fit among all SC members.
- (3) Identify its performance attributes.
- (4) Select a suitable KPIs.
- (5) Assign appropriate performance targets for each metric in each SC member for performance evaluation.
- (6) And finally analyze the metrics to its detailed data components to help in identifying its sources and find a proper way to collect it.

Accordingly, two systematic methodologies have been developed to apply these steps. The first is to select the appropriate KPIs and identify its target values required to achieve a strategic fit, and the second is to configure the operational performance metrics that required, according to SCOR model, for diagnosing these KPIs and analyze them to their data components. These methodologies outlined in Figures 3.2 and Figure 3.5 and discussed below.

#### **3.2.1.1 Identify the SC strategic performance attributes & select the KPIs**

To design an efficient SCPMS, Figure 3.2 outlined the proposed methodology. Using “Stadtler SC topology [76],” the methodology starts by analyzing the business environment to identify competitive supply chain strategies in order to find out how these strategies are aligned to achieve the SC strategic fit. “Supply Chain Topology” can be

used to describe and analyze the two main SC's characteristics categories: functional characteristics, which can be applied to organizations, or locations within a supply chain. It includes four subcategories: procurement, production, distribution, and sales characteristics. The second category is structural characteristics, which describes the relations among SC members. It consists of two subcategories: SC topography and integration and coordination characteristics (see Table 3.1 in Section 3.3).

Strategic fit refers to consistency between the customer priorities that the competitive strategy hopes to satisfy and the supply chain capabilities that the supply chain strategy aims to build. Therefore, for a SC to achieve a strategic fit, it must accomplish the following [113]:

- 1- The competitive strategy and all functional strategies must fit together to form an overall coordinated strategy. Each functional strategy must support other functional strategies and help a SC reach its competitive strategy goal.
- 2- The different functions in the supply chain must appropriately structure their processes and resources to be able to execute these strategies successfully.
- 3- The design of the overall supply chain and the role of each stage must be aligned to support the supply chain strategy.

Accordingly, it is obvious that the best SCPMS to be designed is that system which can track and monitor two main types of failures along the SC:

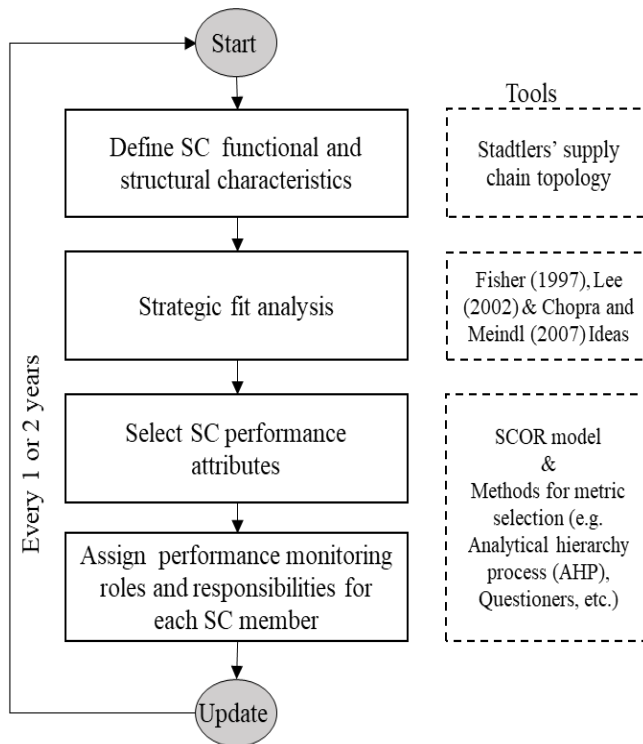
- 1- Failures because of lack of strategic fit.
- 2- Failures because overall SC design, processes, and resources do not provide the capabilities to support the desired strategic fit.

Designing a SCPMS that can monitor these failures required deep analysis to finding out how strategic fit can be achieved and

accordingly select the performance attributes and KPIs that should be tracked and monitored. To do that, five basic steps are required:

1. Understanding SC product/s.
2. Understanding the customer and supply uncertainties.
3. Understanding the supply chain capabilities.
4. Identify/select the performance attributes and KPIs required for monitoring and controlling the SC strategic fit, i.e., designing the effective and efficient SCPMS.
5. Assigning performance monitoring roles and responsibilities for different SC members.

We discuss these steps and analyze them in detail below. All of the information required to apply these steps can be collected using “Stadtler’s topology” (see Table 3.1 as an example for dairy SC).



**Figure 3.2: SC's Strategic Attributes and KPIs Selection Method.**

[1] ***Understanding SC products***

Products are classified into two types based on their demand patterns [114]: functional products, which satisfy basic needs of people usually buy them in a wide range from retail outlets, such as grocery stores. They do not change much over time. They have stable and predictable demand and long life cycles. However, their stability invites competition, which often leads to low-profit margin. The other type is innovational products, which is the products introduced with fashion or technology innovation to give customers an additional reason to buy it. They have high-profit margins but unpredictable demand. Their life cycle is short because as imitators erode the competitive advantage that innovative product enjoy. Companies are forced to introduce a steady stream of innovations, that further increases their demand unpredictability.

[2] ***Understanding the customer and supply uncertainty***

The second step to achieve strategic fit is to understand customers and supply chain uncertainty. To do that, two aspects should be analyzed: demand uncertainty sources and supply uncertainty sources. Customer demand varies along several attributes: lot size quantity, response time, product variety, service level, price, and the desired rate of innovation in the product. Implied demand uncertainty is the resulting uncertainty for only the portion of demand that the SC plans to satisfy based on the attributes the customer desired [113]. On the other hand, SC capabilities comprise other uncertainties that should be understood. Companies that have difficulty delivering according to pre-defined schedule and with a specific quality yields, resulting in high supply uncertainty. Such uncertainty resulted from instability in SC processes or resources, and it varies among different supply attributes

such as frequent breakdowns, unpredictable and low yields, poor quality, limited supply capacity, inflexible supply capacity, evolving production process, etc. [115].

[3] ***Understanding the supply chain capabilities***

After identifying the SC product/s type and understanding the uncertainties it faces, the next question is: What are the capabilities that the SC should focus on to best meet demand in that uncertain environment?

According to Fisher [114], SC is supposed to perform two types of activities:

*Internal activities*, which include activities related to transforming raw materials into finished products and transporting them from one point in the SC to the next.

*External or market mediation activities*, which include activities required to ensure that all products reaching marketplaces match what consumers want to buy or, in other words, match customers' values.

Depending on their product/s type and its demand and supply uncertainty, SC decides on which of these activities they should focus on. For instance, the predictable demand for a functional product makes market mediation easy because a nearly perfect match between its stable supply and demand can be achieved. Thus, the supply chain which makes such product is free to focus on minimizing the internal activities physical costs to achieve efficient processes. That could be done, for example, by minimizing inventory or maximize production capacity. In this instance, the important flow of information and the best performance attributes to monitor are the ones that occur within the chain as the suppliers, manufacturers, and retailers coordinate their activities to meet predictable demand at the lowest cost. SCOR model names these attributes the "internally-focused attributes".

That approach will not work for innovative products. The uncertain market reaction to innovation increases the risk of shortages or excess supply. High-profit margins and the importance of early sales in establishing market share for new products increases the cost of shortages. In addition, short product life cycles increase the risk of obsolescence and the cost of excess supplies. Hence, market mediation costs predominate for these products and the focus should be on the external activities rather than the internal activities. Most important in such environment is to approach early sales numbers or other market signals and to react quickly especially during the new product short life cycle. The critical decisions to be made, for example, about inventory and capacity are not about minimizing the costs, but where in the chain to position inventory and available production capacity to respond against uncertain demand. In this instance, the critical flow of information and the important performance attributes to monitor are the ones that occur not only within the chain but also from the marketplace to the chain. SCOR model names these attributes the “customer-focused attributes”.

The main SC capabilities that one could focus on can be summarized, but not limited by the following [113]:

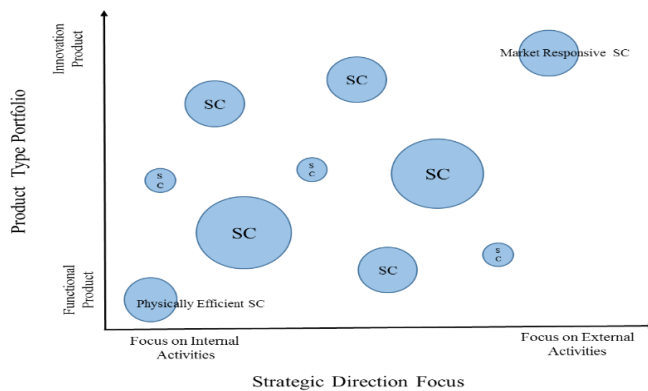
- Response to a wide range of quantities demanded (agile and efficient).
- Meet short lead-time (reliable and responsive).
- Handle a large variety of products (flexible and efficient).
- Building highly innovative products (agile and efficient).
- Meet a high service level (responsive and efficient).
- Handle supply uncertainties and risks (agile).

[4] ***Strategic fit-based performance attributes selection***

After understanding the SC capabilities to respond to the available

uncertainties, the fourth step is to select the performance attributes that can effectively monitor whether the overall SC design, processes, and resources are providing the capabilities to support the desired strategic fit. In this step, it is for the management to decide whether their supply chain is physically efficient SC (focuses on internal activities) or responsive to market (focuses on external activities). Based on that, from the SC performance measurement perspective, supply chains can be classified according to two dimensions: (1) product type portfolio and (2) which activity type it should focus on strategically (Fig3.3). Hence, performance attributes can be selected according to this classification.

For instance, in a physically efficient SC (Fig 3.3), if the SC has purely functional products, in general, the profit margin is low, and demand is relatively predictable, making market mediation easy to achieve. Then it is better to focus on monitoring internal activities. Therefore, performance attributes related to coordinate the SC members activities to meet its predictable demand at the lowest cost should have more focus. These attributes are the internal-focused attributes: i.e., SC costs and asset management efficiency.



**Figure 3.3: Supply Chain Classification According to Product Type and Activity Focus.**

On the other hand, in market responsiveness SC (Figure 3.3), if

products are purely innovative, performance attributes related to achieving customer satisfaction by the decision on inventory positioning, capacity, and SC resources should receive more focus than minimizing costs. Therefore, these best attributes are customer-focused attributes, i.e., reliability, responsiveness, and agility.

However, in practice, it is not common to find purely functional or purely innovative SC products. Therefore, it is possible to have a combination of internal- and customer-focused performance attributes with relative focus on one of them to manage and control a distinct SC (Fig 3.3). Different tools are also available to achieve consistency between supply chain members on the selected attributes (e.g., analytical hierarchy process (AHP), questioners, etc.); we are not going to discuss it here as it is out of this thesis scope.

#### [5] *Assigning roles to different SC members*

The fifth and last step is to assign roles or responsibilities to different members of the SC. Assuming that the developed system is capable of monitoring the overall SC performance and functionally enabled using the mechanism described in Chapter 4, two important aspects or objectives should be decided in this step:

- ✓ **The first** is functional objectives, to ensure that the appropriate level of focus is efficiently oriented to the external and internal activities by each member to achieve the overall targeted strategic fit (i.e., which activities, internal or external, each member should focus on, and how much responsibility each member should accommodate). It is important to understand that, for example, the desired level of external focus required across the SC may be attained by assigning different levels of that focus to each stage of the SC.



- ✓ **The second** is managerial objectives, to decide the data visibility-level each member should be responsible and authorized to access to guarantee the targeted level of synchronization and integration with other members in the SC. This step plays an important role to decide how to share the system control among all SC members, and how much authorities each member can have to access other members' data. According to [55, 56], cloud and B2B supply chain business network technologies can enable this role.

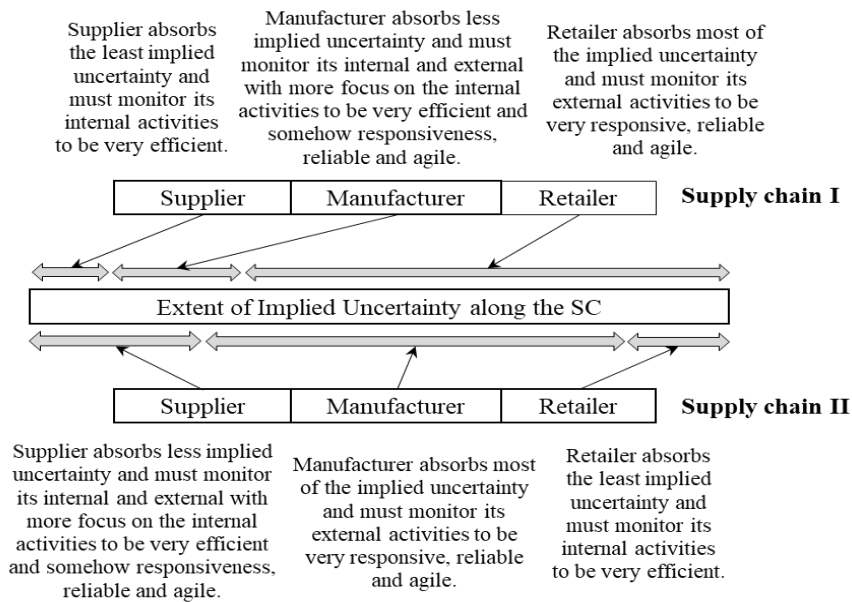
To highlight the importance of this step, we illustrate the following SC scenarios, which is adapted from [113].

IKEA is a Swedish furniture retailer with large stores in more than 20 countries. IKEA has targeted customers who want stylish furniture at a reasonable cost. The company limits the variety of styles that it sells. Therefore, their products can be considered as functional rather than innovative products. The large scale of each store and the limited variety of furniture decrease the implied uncertainty faced by the supply chain. IKEA stocks all styles in inventory and serves customers from stock. Thus, it uses inventory to absorb all the uncertainty faced by the supply chain. The presence of inventory at IKEA stores allows replenishment orders to its manufacturers to be more stable and predictable. As a result, IKEA passes along very little uncertainty to its manufacturers, who tend to be located in low-cost countries and focus on their internal activities to be efficient. IKEA provides responsiveness in the supply chain, with the stores absorbing most of the uncertainty by focusing a little bit more on the external activities and being responsive, and the suppliers absorbing very little uncertainty and focus on their internal activities and being efficient (see Figure 3.4, upper part). In this SC, as uncertainties concentrated at IKEA, then he can have more power to monitor other member's performance in order to

manage and ensure the orchestration and integration between all SC members and to keep his responsiveness at the highest levels. The manufacturer also can have some authorities to monitor both retailers and suppliers inventory information to synchronize and plan their production lines efficiently.

In contrast, another approach may involve the retailer holding very little inventory. In this case, the retailer does not contribute significantly to supply chain market mediation or responsiveness, and most of the implied demand uncertainty is passed on to the manufacturer. For the supply chain to perform well, the manufacturer now needs to be flexible, reliable, and have low response times. An example of this approach is England, Inc., a furniture manufacturer located in Tennessee. Every week, the company makes several thousand sofas and chairs to order, delivering them to furniture stores across the country within three weeks. England's retailers allow customers to select from a very wide variety of styles and promise relatively quick delivery. So, their products are assumed to be more innovative products. This imposes a high level of implied uncertainty on the supply chain. The retailers, however, do not carry much inventory and pass most of the implied uncertainty on to England, Inc. The retailers thus need to focus on their internal activities to be efficient because most of the implied uncertainty for the supply chain is absorbed by England, Inc. with its flexible manufacturing process. England, Inc. itself has a choice of how much uncertainty it passes along to its suppliers. By holding more raw material inventories, the company allows its suppliers to focus on efficiency. If it decreases its raw material inventories, its suppliers must become more responsive. Therefore, England, Inc. together with his suppliers needs to decide on which activities each of them should focus and how much responsibility to accommodate (see Figure 3.4, lower

part). In this SC, England, Inc. should have the authority and be responsible for monitoring his retailers and suppliers performance. Therefore, he will be the owner and controller of the system that can be used to monitor and manage the overall supply chain orchestration and integration.



**Figure 3.4: Assigning Roles and Responsibilities to SC Members According to Given Implied Uncertainties.**

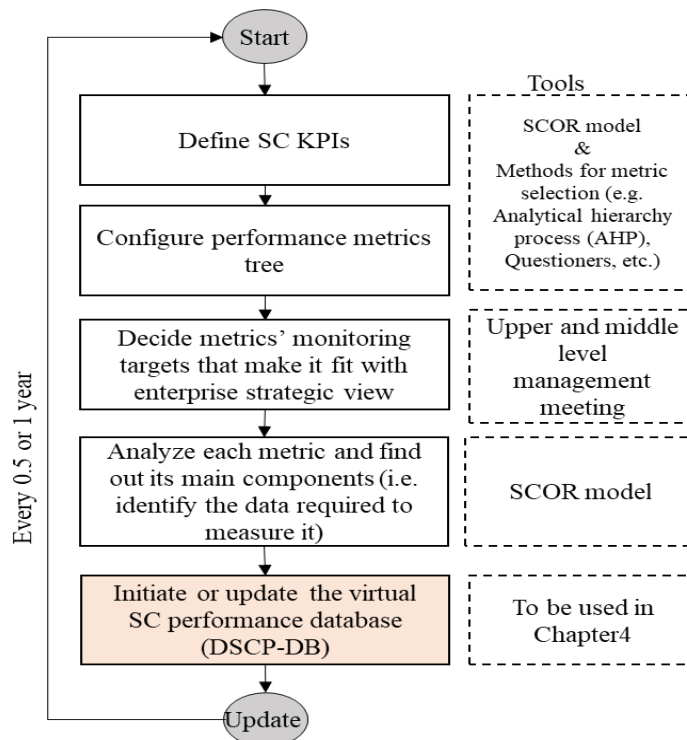
Source: Adapted from Chopra and Meindl [113], p41.

### 3.2.1.2 Configure and analyze operational performance metrics for each SC member

After identifying SC strategic performance attributes and assigning the roles for each member according to their customers requirements and available capabilities, the SC performance metrics “KPIs” for each member can be selected and analyzed to its data components. Figure 3.5 outlined the methodology that can be used to identify these metrics and analyze them to find out the exact performance data sources that should be tracked and collected. As mentioned in the SCOR model

literature, each performance attribute can be examined using level 1 strategic metrics. Many literatures recommend choosing at least one metric from each performance attribute [76, 116].

Using SCOR model metrics hierarchical structure and according to member's capabilities and resources being monitored, the performance metrics tree can be configured. Figure 3.6 outlines an example of a comprehensive performance metrics tree for a distributor. All of these metrics' detailed definition can be found in SCOR model document [79].

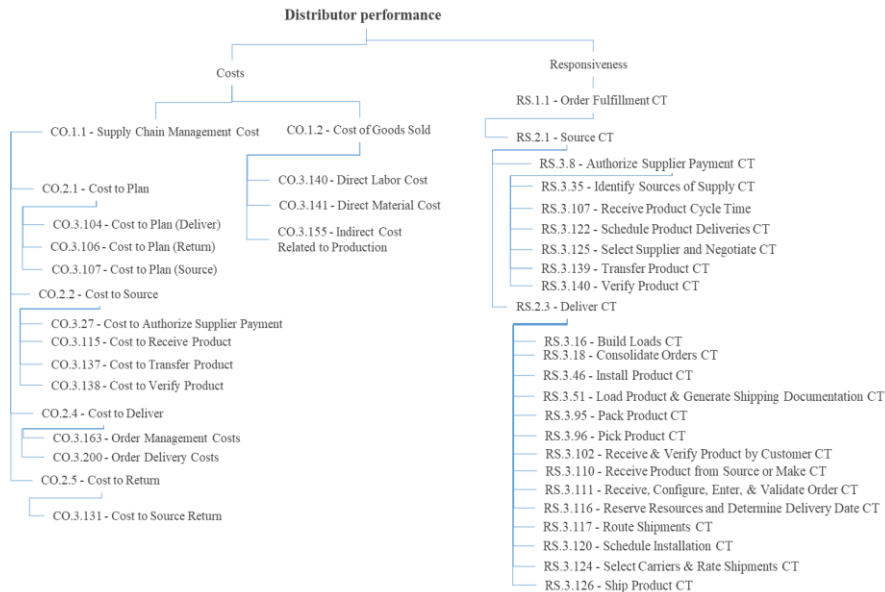


**Figure 3.5: SC Members' Performance Metrics Selection and Analysis Method.**

Each selected metric should have its target value with upper and lower limits to be used as a reference for monitoring (the last step in this method required sending these values to the IT system database to use it for benchmarking and violation detection, more about this topic available in Chapter 4). This value should guarantee the alignment with

member's local strategies as long as overall SC strategic fit. Choosing these metrics and identifying its target values could be implemented using any decision-making tool or technique such as analytical hierarchy process (AHP), questioners, etc.

The final step in designing the SCPMS is to analyze each chosen metric to its data components. This step includes two fold objectives: the first objective is to guarantee that the chosen metric is realistic (i.e., there is data, which can be collected to measure and monitor it). The second is to help find out the exact source of that data; this can be easily done by identifying the SCOR level-3 processes where these metrics being measured and therefore finding a way to collect its data.



**Figure 3.6: Suggested Distributor Performance Metrics Tree.**

Source: SCOR Model, version 11.0 [79].

### 3.2.2 Smart Objects Identification

After designing the SCPMS and analyzing the performance metrics that should be tracked and monitored, the next stage is to deploy IoT technologies to transform the SC into a digital SC by finding out what exactly should be digitalized. Figure 3.7 outlines a new methodology,

which uses SCOR model business process structure with ISA-95 standards to do this job. Based on the results from the last step of the previous stage, the data sources required to monitor our SC are already known and connected with SCOR model level-3 processes where the chosen performance metrics should be measured. Accordingly, the smart-object identification method, Figure 3.7, can be used to systematically find out the exact physical SC objects that should be transformed to smart-objects. We demonstrate this method in detail in the following steps.

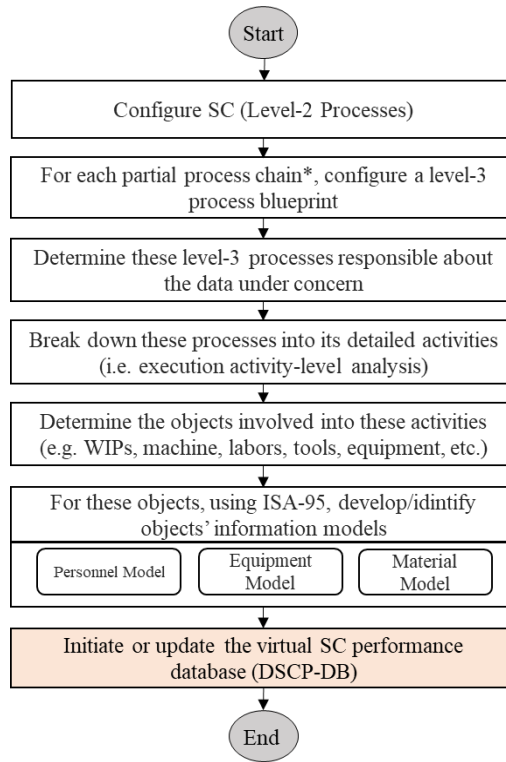
#### 1. Configure the SC using SCOR Level-2 Processes

By abbreviating the procedure of Stadtler et al. [76] to configure the SC, any distinct SC can be represented using SCOR model processes in three steps.

- a. Define the business unit to be configured, i.e., according to product/s type, functional or innovative.
  - b. Depict, geographically, the entities involved in SC business process level 1, enter the major flows of materials as directed arcs between locations and entities, and assign SC business level-2 processes for each entity (Figure 3.12).
  - c. Develop a level-2 SC business process diagram by (a) defining partial process chains for the modeled SC; i.e., the sequential level-2 sourcing, making, delivering, and returning processes planned by a single “sP1” planning process. (b) Connect each partial process chain using “sP2-sP5” planning processes. (c) Define a top-level “sP1” planning process, if possible (Figure 3.13).
2. In this step, all SC entities related to the chosen SC KPIs or their data sources are more deeply analyzed. Hence, for each partial

process chain, a SCOR model business process level-3 blueprint is configured, and each process inputs and outputs can be identified (see Figure 3.14).

3. For each level-3 process, if required, break it down into its detailed activities, which may involve the SC resources “objects”. These objects may be finished product, WIP, labor, machine, equipment, etc.
4. By deciding the objects involved in these activities, its data structure can be configured and analyzed using ISA-95 standards. ISA-95 defines three main object information models: personnel, material, and equipment models. At least one of these models can be used to identify the structure and characteristics of the object information under consideration (for more information about ISA-95, see ANSI/ISA-95.00.01-2010 and ANSI/ISA-95.00.02-2010).
5. The last step is to connect these objects information with the technical part of this thesis. To do that these objects should be transformed to smart-objects by deploying IoT technologies. We show how to do that in the next section. Moreover, the objects information should be sent to the SC members IT system databases, more about this available in Chapter 4.



**Figure 3.7: Smart-object Identification Method.**

### 3.2.3 Deploying IoT for Transforming SC Objects to Smart-Objects

To achieve the intended purposes of this chapter and to enable the functionality of the DSCPM introduced in Chapter 4, the targeted SC objects real-time traceability systems should ensure 100% data capturing with high accuracy. This will not only reinforce the effectiveness of DSCPM functionality but also minimize the potential loss of that data and eliminate the risks of human intervention in data capturing.

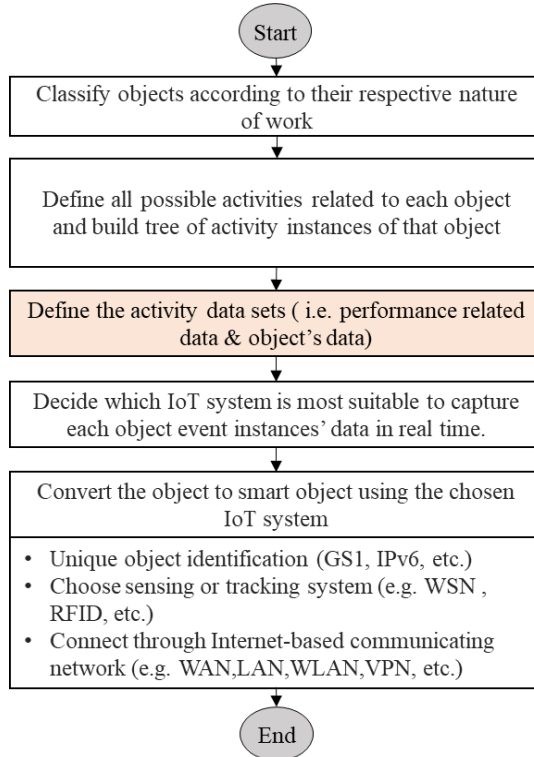
Based on the literature review, this stage presents a step by step systematic method, Figure 3.8, to convert/create a smart or an intelligent environment on the SC execution-level to effectively capture all required information in real-time, which can be used later through



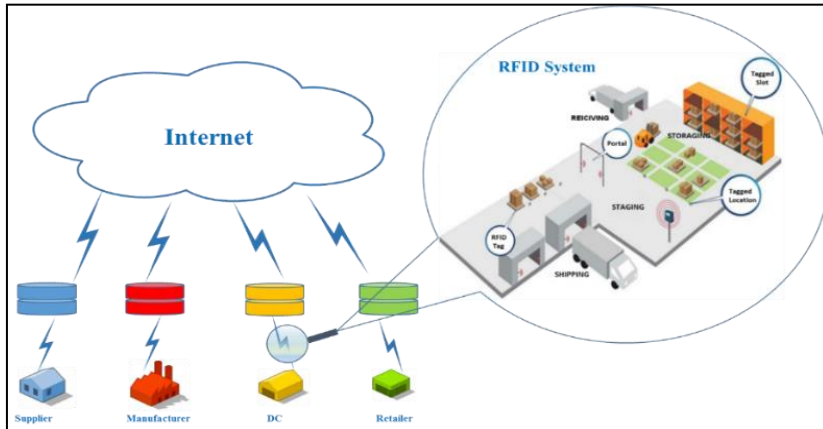
DSCPM-modules to serve for achieving SC goals and targets. The deployment steps of IoT system in SC are demonstrated in Figure 3.9, and explained as follows:

1. In the first step, all of the identified objects in the previous stage should be classified according to their respective nature of work along the SC value stream processes, and by considering their information model identified by ISA-95. Such classification will make it easy for developing a data structure standard and therefore enable better intercommunication between the objects and IT system and between the objects themselves simultaneously.
2. All possible events that could be generated by/on each object along the SC value stream during the daily run should be defined, and a tree of these events should be constructed. It is very important here to note that all of the activities we are looking for should be identified, by considering in our mind that we are tracking what is going on in real-time for the SC products along its journey across the entire SC value stream starting from the original natural resources used to produce it. We assume these products as WIPs until it arrives at the final customer hands. Therefore, WIPs are considered as the activities “events” stimulant. Figure 3.10 illustrates a sample of SC objects tree of activities.
3. For each activity, define activity data set ( $d_{e_i}$ ). This data set includes the event-instance related data and its key attributes, especially those related to performance measurement. For example, the processing-event executed on order (O-ID) in location (L-ID) from worker (OP-ID), with the use of equipment (E-ID), and using Material (Mat.-ID), under process parameters (Pa.1, Pa.2, Pa.3, etc.....), with the help of using Tool (Tool-ID) can be represented in the event-data set as below:

$d_{e_i} = \langle O_{ID}; L_{ID}, OP_{ID}; E_{ID}; Mat_{ID}; Tool_{ID}; \{Pa. 1, Pa. 2, etc. \}, etc. \rangle.$

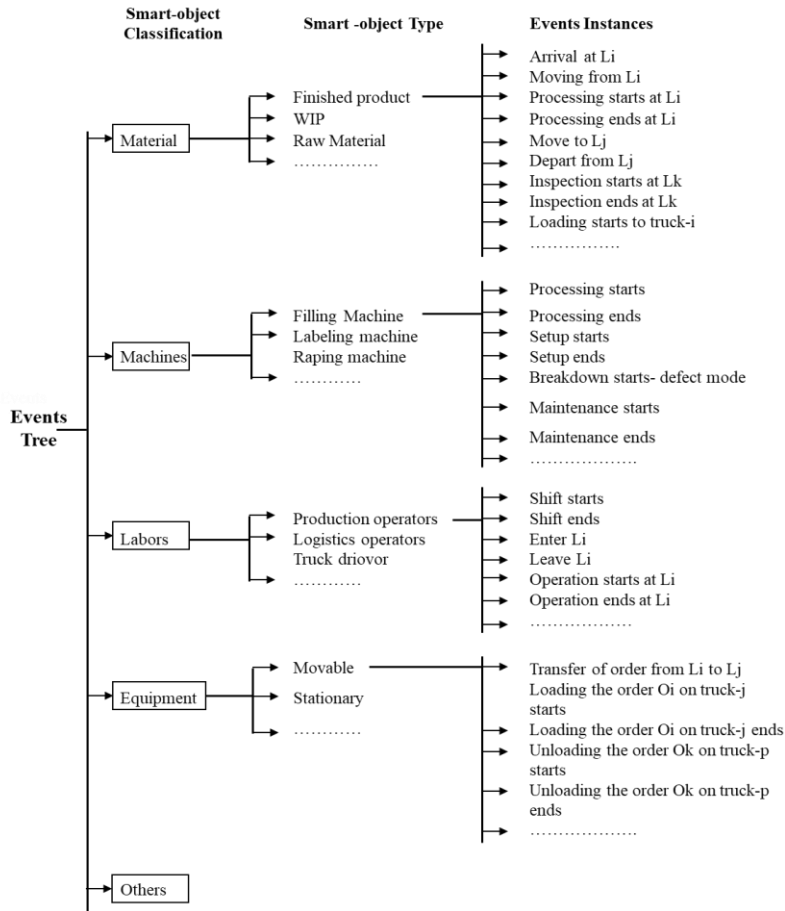


**Figure 3.8: IoT Deployment for Transforming SC objects to Smart-objects Method.**



**Figure 3.9: IoT Deployment in SC Execution-level.**

Source: Dweekat et al. [82].



**Figure 3.10: Tree of Events of SC Objects (example).**

4. The last step in this methodology is the most important one. It requires a highly skilled IT and networking people to work on it. In this step it is the time to decide which IoT system/s are needed to capture the identified data sets in real time. We divide this step into four sup-steps as following:
  - a. In the beginning, every object whatever its nature, layout spaces and locations, products or buffers, passages and routes, doors and gates, and working centers, vehicles, etc. should be uniquely identified. The GS1 system and Internet Protocol version 6 (IPv6) can perfectly satisfy this requirement. GS1 is a

system that provides for the use of unambiguous numbers to identify goods, services, assets, and locations worldwide. These numbers can be represented in barcodes or tags to enable their electronic reading wherever required in business processes. These identification numbers are also used in Electronic Data Interchange (EDI), XML electronic messaging, Global Data Synchronization (GDSN), and GS1 Network Systems. The system is designed to overcome the limitations of using the company, organization, or sector-specific coding systems.

IPv6 is the most recent version of the Internet Protocol (IP), providing an identification and location system for computers on networks and routing traffic across the Internet. IPv6 addresses hierarchical allocation methods that can facilitate any required aggregation across SC entities. Through these means, all SC entities can be sensed and perceived [118].

- b. The second step is to determine the sensing or tracking system to enable collecting real-time data from objects and enhancing communication between them. Many technologies have been developed and are being developed for this purpose. RFID and WSN are the most popular and advanced technologies in this field. Taking RFID-tags deployment as an example, it can be used to convert the typical SC resources into smart objects. The type of RFID-tag (i.e., passive or active) is used based on particular criteria such as object criticality or necessity for real-time interaction. For example, some objects need to update their status during the operation, such as updating the remaining life of the product on the actual execution time. In addition, the resources and products can be classified into different smart-groups, namely: (i) Machines and their related components such

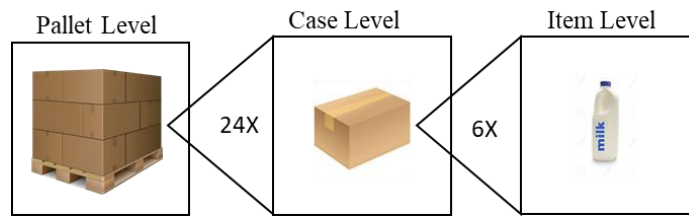
as critical spare parts or measuring devices, (ii) Tools such as jigs and fixtures, cutting tools, etc., (iii) Equipment and material handling assets such as trucks, conveyors, forklifts, pallets, containers, shelves, etc., (iv) Labor such as Production Operators (PO), Logistic Operators (LO), Inspection Operators (IO), etc., and (v) Products or materials such as Raw Materials (RMs), WIPs including sub-assemblies, and Finished Products (FGs). The volumes of data and process duration play an important role in this part of the step. Once these objects are attached with RFID-tags, they become smart objects, and thus identifiable, trackable, and traceable in real-time with all information about their statuses and movements. This enables them to be monitored and interact live with all smart-objects through DSCPM engines which will be mentioned in the next chapter. Commonly, sensing and tracking systems includes network technologies that enable efficient communication between objects and sensing devices according to different criteria (e.g., cost, speed, beneficial result, energy saving and cost reduction, etc.). There are many different forms of wireless networks, such as GPRS, Bluetooth, Wi-Fi, infrared data transmission (IrDA) and 433MHz wireless communication, and short-range wireless technology standards like ZigBee, WiMedia, dedicated wireless system, etc. Each of these wireless communication form has unique characteristics and need special requirements for transmission speed, distance, and power consumption, etc.

- c. The last step is developing the internet-based communicating network. What we mean by “developing” is not literally developing the network itself, but rather making an efficient

combination of advanced network technologies to enable SC applications, specifically SCPM applications, considering that we are dealing with a dynamic ecosystem. Hence, this requires ubiquitous access to the internet, seamless handover, flexible roaming policies, security constraints consideration, and an interoperable mobility protocol with the existing internet infrastructure. In summary, integration, interoperability, and security are the major features that we should consider when we choose our SC IoT network.

The last point to highlight in this method is that before starting the unique identification using auto-ID mechanisms, like RFID-tags, it is critical to know the depth, scope, and granularity of the required product-related data, especially since that we are working on the SC level. It is important to decide the identification level of the products and materials, especially the current trends are shifting the focus to track the individual items. Thus, the granularity of data can be increased/deepened to item/product level [BRM10], where product level traceability increases the real-time visibility and improves the accuracy of control. As seen in Figure 3.11, based on Ilic et al. [119] the object-level of tracking can be classified as follows:

- Pallet-level: In pallet-level tagging, an RFID-tag is applied to the pallet as a logistic unit which is used to transport items from one destination to another; here the tracking of item level is ignored, such details are not needed.
- Case-level: In addition to pallet-level tagging, an RFID-tag is applied to every case unit.
- Item-level: In addition to the both mentioned levels, an RFID-tag has applied also to every single item, including RMs, WIPs, subassemblies, and components.



**Figure 3.11: Products and Material Traceability Levels[119].**

In some smart real-time SC operational cases, another important aspect should be considered such as the speed at which a real-time decision is made. This depends upon some operational parameters such as the time of processes being executed on each object-level (i.e., pallet, case, and item levels) as well as the flexibility of these processes. If that time is on the order of the day, a response in 3 hours may be acceptable as real-time; if processing time is on the order of a few hours, real-time responses are probably needed in less than 20 minutes.

### **3.3 Framework Demonstration Using a Theoretical Case Study**

A simplified beverage SC example is used as case study scenario to demonstrate the proposed framework and to clarify some of its practical implication. The SC under consideration represents a single business unit and consists of a raw material and packaging material suppliers, production plant, distributor, and five retailers. The manufacturer receives the required materials from suppliers and produces a beverage product with expire date fixed by 11 days (e.g., natural milk product). After packaging, the finished products are transported to a Distribution Center (DC). Each customer (retailer) is served from the DC. The product is made-to-stock and is ordered by the retailer as a final theoretical customer in this case study, (Fig 3.12 depicts the case study SC).





**Table 3.1: Topology for Beverage Supply Chain**

<b>Functional Attributes</b>		
<b>Function</b>	<b>Attributes</b>	<b>Content</b>
Procurement	Number and type of products procured	Few, standard (RM) and specific (packaging materials)
	Sourcing type	Multiple (RM), double (packaging materials)
	Supplier lead time and reliability	Short, reliable
	Material life cycle	Long
Production	Production process organization	Flowline
	Repetition of operations	Batch production
	Changeover characteristics	Not available as per the case study assumptions
	Production bottlenecks	Known, almost stationary
	Work time flexibility	Low, partial additional cost required
Distribution	Distribution structure	Three stages
	Delivery pattern	Dynamic
	Deployment of transportation means	Unlimited, routes (3 stages)
Sales	Availability of future demand	Forecasted
	Demand curve	Seasonal
	Product lifecycle	Several years
	Number of product types	Few
	Degree of customization	Standard products
	Bill of materials (BOM)	Convergent(blending), divergent (packaging)
	Portion of service operation	Tangible goods
<b>Structural Attributes</b>		
<b>Structure</b>	<b>Attributes</b>	<b>Content</b>
Typography	Network structure	Mixture material flow
	Degree of globalization	South Korea
	Location of decoupling point(s)	Deliver to order
	Major constraints	Flow line capacity
Integration and Coordination	Legal position	Intra-organizational
	Balance of power	Customers (retailers)
	Direction of coordination	Mixture information flow
	Type of information exchange	Forecasts and orders

Source: (Stadler et al. [76]).

**Table 3.2: Supply Chain KPIs.**

	Performance Attribute	Level 1 Performance Metrics
<b>External</b>	Supply Chain Delivery Reliability	Perfect Order Fulfillment
	Supply Chain Responsiveness	Order Fulfillment Cycle Time
	Supply Chain Flexibility	Upside Supply Chain Flexibility
<b>Internal</b>	Supply Chain Cost	Cost of Goods
		Supply Chain Management Cost
	Supply Chain Assets Management Efficiency	Cash-to-cash Cycle Time
		Return on Fixed Supply Chain Assets

According to the SCOR model (Rev. 11.0, [79]), expiry waste percentage can be identified as the total wastes resulted from product expiring before customers demand it. It can be calculated using the formula: Expiry Waste % = [expiry waste came from all supply chain members inventory] / [Total sale]. Table 3.3 summarizes the calculation components for the metric.

**Table 3.3: Expiry Wastes Percentage Data Components.**

Unit	Component	Formula	Note
%	Expiry Waste Percentage	[Expiry waste came from all supply chain members inventory] / Total Sales	
\$	Expiry waste came from all supply chain members Inventory	$M \text{ waste} + D \text{ waste} + \sum_{k=1}^5 (R \text{ waste})$	M: Manufacturer D: Distributor R: Retailer
\$	Total sales	$\sum_{k=1}^5 (R \text{ Sales})$	

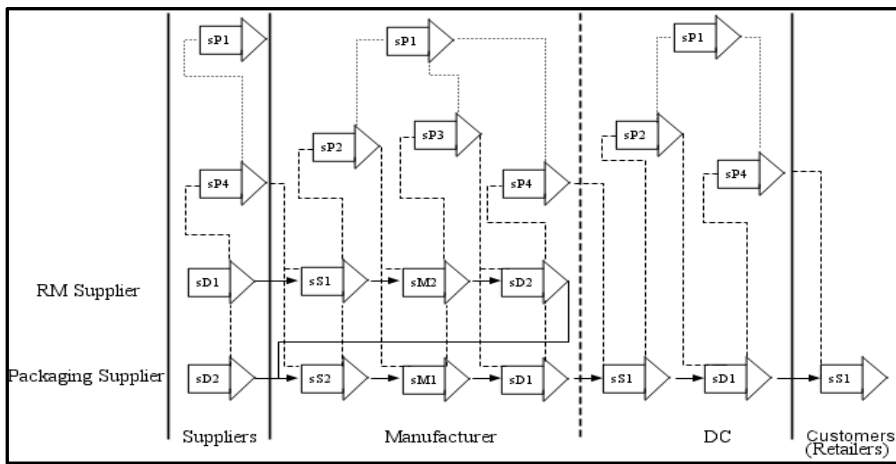
To decide the rules and responsibilities for each SC member, it is clear that the retailers and distributors should focus on their internal activities to control the inventory levels. That can help them to avoid products expiration in their stocks. On the other hand, plants should focus on the external activities to ensure that they are producing the exact amounts for the markets. Therefore, they need to follow the

products quantities and information along their downstream network to make the right decisions regarding what to produce. Distributors also can handle some of the problems by focusing somehow on the external activities to manage the distribution network in a way that helps in reducing the expected wastes due to expiration.

## ② SC Digitalization

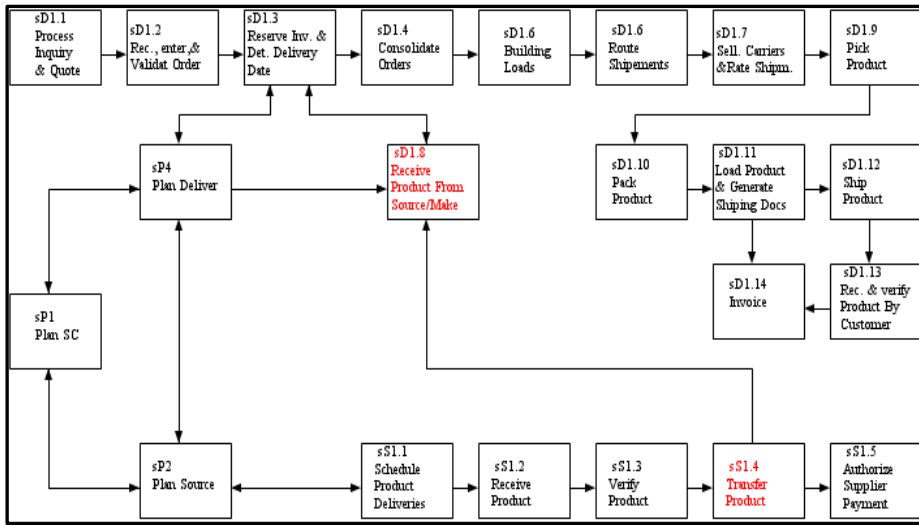
Monitoring and managing the Expiry Wastes Percentage requires seeing all of the inventories inside the supply chain, and tracking its positions and information (e.g., quantities, shelf life remaining time, etc.). That can be done efficiently by deploying IoT (i.e., RFID). We demonstrate that in the following steps.

- a. The first step is developing a SCOR level-2 process thread diagram for the overall SC (Fig 3.13).



**Figure 3.13: Case Study Supply Chain SCOR level-2 Process Thread Diagram.**

- b. The second step is developing a SC process level-3 blueprint for each partial process chain. For simplicity, we focus only on distribution entities. Fig 3.14 shows an example of the distributor partial process chain. We assume the same work can be done to collect all data required in retailers and manufacturer.



**Figure 3.14: DC Partial Process Chain Blueprint (using SCOR level-3 process).**

- c. The third step is analyzing each partial process to determine the SCOR level-3 processes directly responsible for inventory data required to measure the Expiry Waste % metric. In the DC partial process example, sD1.8 and sS1.4 (red-colored processes in Fig 3.14) are the processes responsible for the inventory and its data.
- d. The fourth step is to determine the objects related to the data under concern and define the objects information models, from ISA-95. In our example, different objects should be transformed into smart objects such as the product itself, the stocks where the inventory holds, the distribution fleets, receiving and sending docks, operators, etc. According to ISA-95 standards, these objects' information can be defined using the material model, equipment model, and personal model, and hence object information attributes can be determined.
- e. The last step is to identify and develop the IoT system required to enable perceiving, collecting, exchanging, and communicating data. That can be done by identifying all of the activities the smart-objects are performed in the daily run. According to the

requirements to capture these activities and the targeted data generated by it, IoT can be deployed and therefore enable measuring and monitoring the performance under concern. IoT deployment for tracking the product itself, as an example, can be demonstrated as follows.

- 1- Uniquely identify each element to be measured. In our example, this can be done easily by following ISA-95 standards and using the GS1 standard (e.g., the Tag Data Standard, “TDS,” or Global Trade Item Number, “GTIN”). Therefore, each production unit (milk bottle) should have its identification number.
- 2- Choose the information perception system needed to collect the required data. An RFID system is one of the best systems in our example. It can be used to collect all object information (in our example: expiry date or time to expire and position for each product).
- 3- Develop an efficient communication network between all SC entities and systems. Fig 3.9 depicts a suggested network structure for our example.

Finally, this scenario is further developed and expanded to show the effect of deploying IoT technology in SC performance measurement applications in Chapter 6.

### **3.4 Conclusion**

Performance measurement is an essential element of effective planning and control as well as decision-making. In dynamic ecosystems such as supply chains, performance measurement is considered a great challenge. Performance measurement in today’s SC requires two main characteristics: designing a representative SCPMS

that spans all the SC members and their core functions and activities and enable the automated data capturing process by digitalizing the correct parts of the SC.

In this chapter, we proposed a conceptual framework that is helpful in achieving these characteristics. The proposed framework can help in designing internal and external SCPMS to accommodate and handle today's SCM challenges and limitations. It can be used to build the basis for SCM applications, enabled by IoT, to monitor, manage, and control the overall supply chain in real-time and in more integrated, cooperative and collaborative manner. The framework represents a structured systems building methodology tailored to show how to deploy IoT technologies in the field of SC performance measurement. This approach could help in establishing new performance measurement applications, and it is believed that both practitioners and researchers will benefit from it.

# **Chapter 4. IoT-enabled Dynamic Supply Chain Performance Mapping based on Complex Event Processing**

## **4.1 Introduction**

The most popular model for implementing performance-measurement initiatives in supply chains is SCOR model. However, today's supply chains and its manufacturing systems are characterized by high dynamic behavior, uncertainty, and high variability. Therefore, it has become obviously difficult to address or represent and monitor these circumstances with the current simple and static performance measurement systems. As a result of this, there is a need for a dynamic computer-based performance measurement tool that is able to automatically monitor the flow and continuously monitor the supply chain processes to not only support and enhance the implementation of performance-based practices and applications, but more importantly, to sustain these applications.

In this context, using IoT technologies to convert supply chain objects to smart-objects as discussed and IT systems have made it easy to digitalize processes workflow information. However, since over a decade, the available IT systems and application software still cannot provide enough flexibility to handle the rapidly changing business processes [120]. Therefore, for next generation of supply chain information systems, there is a need to develop a performance-oriented IT system which should be dynamic and flexible enough to keep pace with today's highly dynamic working environments and to quickly adapt the rapid changes in products and processes from performance

perspectives. Such systems should be able to create a smart real-time working environment by involving smart real-time mechanisms that diagnose and prevent anomaly and wastes in real-time and keep performance-based practices and applications alive for the long-term.

Accordingly, this chapter introduces a framework that describes the integration of real-time data capturing technologies, (i.e., IoT), with business process and workflow modeling concepts (i.e., according to SCOR model) to develop a computerized real-time performance-oriented IT system, known as Dynamic Supply Chain Performance Mapping (DSCPM). DSCPM is an event-driven system that uses CEP concepts to handle the enormous amount of triggered events at a work execution-level as well as at the higher enterprise levels. Using CEP concepts to process IoT data and to support performance-based practices and applications, the overall performance at the execution-level can be improved and enhanced. This framework also provides more flexibility to allow performance management specialist to express and create Real-time Performance Control Rules (RT-PCRs) for monitoring and enabling decision-making in the real-time.

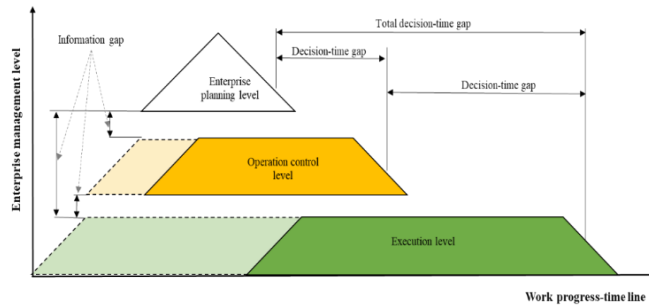
To validate the DSCPM framework and demonstrate how IoT data can support smart supply chain environments, the subsequent chapters discuss some DSCPM-modules based on CEP to smartly support different performance-based practices and applications (e.g., lead-time analysis, real-time costing, real-time waste detection, etc.). To verify the feasibility of the constructed RT-PCRs, the simulation software AnyLogic has been used to validate some of these rules.

## **4.2 Real-time Enterprise Integration**

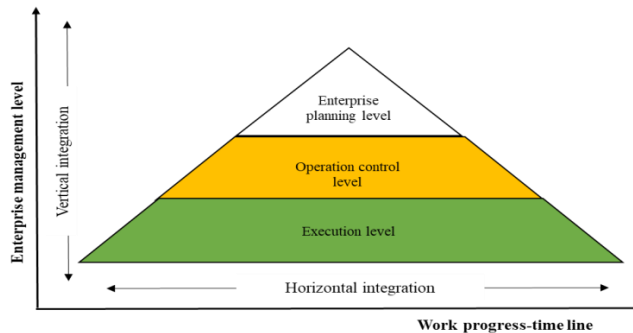
One of the main challenges facing supply chains management systems in today's dynamic environment is the inability to capture the



sudden changes in real-time or at the proper time and make quick decisions about it. This is caused due to the time and information gaps or asynchrony between execution events, (i.e., products flow and the associated events on the execution level from one side, and the associated information flow on the operational and higher enterprise level from the other side), as seen in Figure 4.1. This issue is a very crucial factor in the effectiveness of the decision-making process. Sometimes the taken decisions do not tackle the actual state at the execution level. In this context, besides being able to monitor the current performance, the enterprises have to be increasingly agile to respond to such challenges rapidly. Therefore, it is important to bridge this time and information gaps through the real-time integration of all enterprise levels together using real-time performance-oriented IT systems, see Figure 4.2.



**Figure 4.1: The Time-gap between Information Flow and Physical Activities at Different Management Levels in Enterprise.**

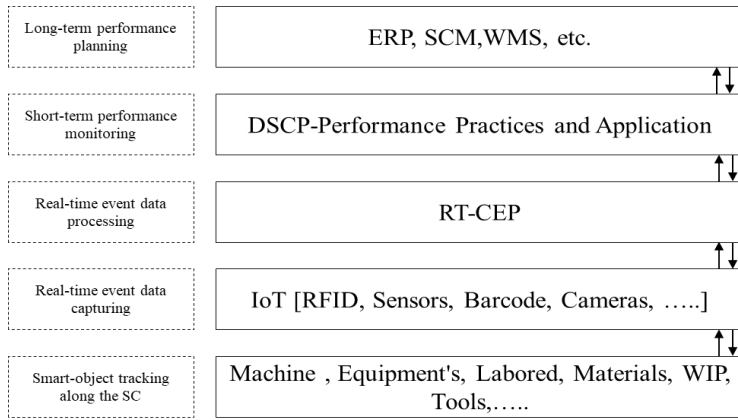


**Figure 4.2: Real-time Performance-based Enterprise Integration.**

The envisaged DSCPM is proposed to bridge these gaps and guarantee an overall real-time integration along the horizontal and vertical direction based on SCOR model business processes and its performance metrics hierarchy structures. The vertical integration of information and knowledge between the execution-level and top management is required to bridge the time-gap vertically between enterprise management levels; where the horizontal integration is required for integrating the information and actions between the resources (i.e., smart-objects at a particular enterprise level) [121].

### **4.3 Integration of DSCPM in Real-time Supply Chain Infrastructure**

After the execution-level is turned to a smart environment as demonstrated in the previous chapter, the event-driven performance-oriented system, DSCPM, should be integrated with the existing enterprise IT infrastructure. Therefore, this section briefly introduces the integration of the envisaged system with the enterprise planning systems (e.g., ERP, SCM, warehouse management system (WMS), etc.), see Figure 4.3. In this framework, CEP is a great method to be integrated into the IT infrastructure to support and facilitate the functionality of DSCPM. Thus the Real-time Complex Event Processing (RT-CEP) layer is the interface between IoT-systems at the execution-level, and the DSCPM level, as well as with other enterprise levels. RT-CEP can be considered as IoT middleware software. For effective integration with IT systems, the Open Platform Communication unified Architecture (OPC-UA) standards can be used to address the communication between the IoT middleware software and IoT-data readers and other execution-level systems, e.g. PLC, HMI, sensors, etc., which can be used in combination with IoT system [122].



**Figure 4.3: Integration of the DSCPM within the Enterprise's IT System for Real-time Performance Monitoring.**

At the RT-CEP layer, the enormous amounts of generated events pre-processed and forwarded to the DSCPM and higher levels in the enterprise IT system, where DSCPM has different engines for different functions, as illustrated in the next section.

#### **4.4 Dynamic Supply Chain Performance Mapping Framework (DSCPM)**

This section presents the core of this thesis that tackles the integration of IoT data-capturing system with supply chain business processes and performance metrics to enhance a performance-based smart supply chain environment. The integration framework, namely Dynamic Supply Chain Performance Mapping (DSCPM), is a computerized event-driven performance-based IT system that contains different smart performance-based control modules to monitor, enhance, sustain and achieve the aims of performance measurement-based initiatives in supply chain environment. Since this system deals with IoT captured event-instances, DSCPM functionality is based on CEP concepts to manage the massive event-instances and to convert them into more beneficial information and accordingly, generate optimal

decisions in real-time. An overview of the DSCPM components is depicted in Figure 4.4. The DSCPM framework is composed of five main engines:

- ❖ **First:** Event Extraction Engine (EEE), it is a real-time performance-related data collection and transformation engine. It is used to reflect and integrate the current state of the smart-objects (i.e., resources) on the execution-level with the enterprise environment for the sake of performance tracking and monitoring. Therefore, EEE serves as a linkage between the physical world (i.e., smart objects on the execution-level) and virtual world (i.e., IT system).
- ❖ **Second:** Work Flow Engine (WF-Engine), it is the engine that provides the means to compare what is going on in the actual world and what should be done according to the virtual world. WF-engine designed to do two functionalities: the first is to generate the Actual Value Stream Map (AVSM), which is the DSCPM-interface with the execution-level. It translates the smart-objects and performance related data into the flow regarding time and location, (i.e., VSM-format). The second functionality is to generate the Virtual Value Stream Map (VVSM), which is the DSCPM-interface with the enterprise levels. It translates the targeted performance-based execution data that has been developed in the higher enterprise levels into the context of event-instances (i.e., VSM-format). Before starting customers orders execution or releasing the products for production, each order or product should have a VVSM that represents its targeted performance-based data.
- ❖ **Third:** Real-time Rules Engine (RT-RE) in this engine, the Real-Time Rules Expression Builder (RT-REB) module gives the performance management specialists the ability to express or construct. With the assistance of the “Rule Construction Elements” (RCE) module, the suitable rules for the other DSCPM-Engines can be constructed. For

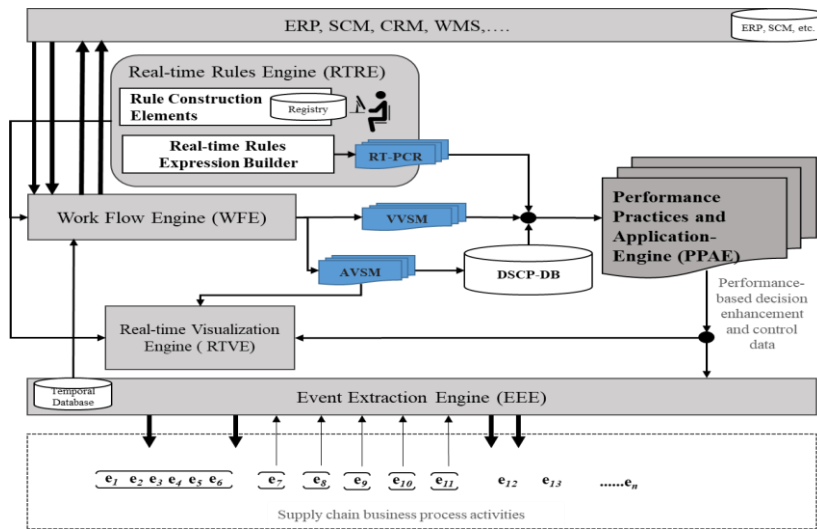
example, rules for the EEE to extract the needed events, and rules for the Performance Practices and Applications-Engine (PPAE) to control working processes based on performance targets, etc. See Figure 4.4.

- ❖ **Fourth:** Performance Practices and Applications-Engine (PPAE), it is considered as the head of DSCPM. This engine enables a smart real-time violation detection and re-(action) mechanism without the need for human intervention since they are unable to monitor all work-related information in details and accordingly make quick decisions. RT-RE supplies this engine with different RT-PCRs, which in their turn utilize the event-instances in AVSM and DSCPM-database (DSCPM-DB) as well as VVSMs-data for smart real-time monitoring and controlling of the supply chain processes and workflow on performance targets basis. Thus, this engine bridges the gap between the targeted performance-based environment represented by VVSM and the physical situation represented by AVSM and therefore enable the continuous development and smart supply chain property
- ❖ **Fifth:** Real-time Visualization Engine (RT-VE), it displays mainly the AVSM of each order/product at the local Touch User Interface (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 AVSM, performance-based control data (i.e., decisions or reactions), and targeted performance values from VVSM to display them in VSM-format.

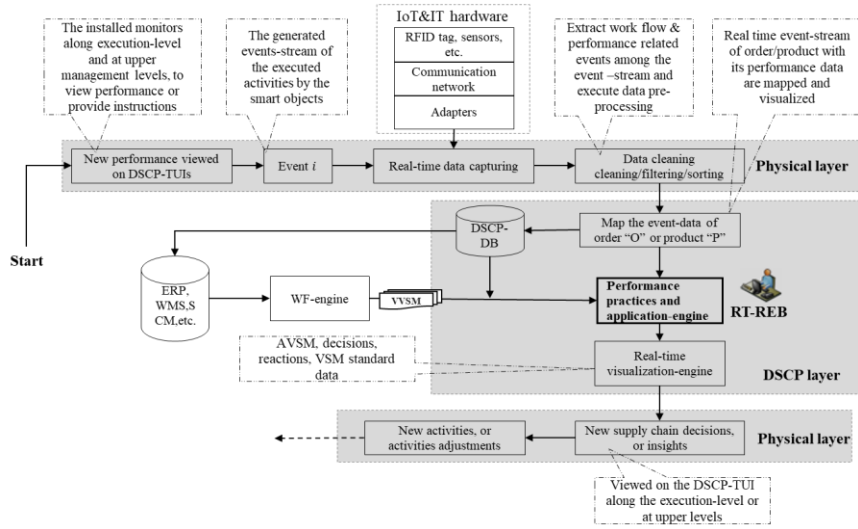
In this context, after creating and saving a RT-PCR on a specific module in PPAE, it will be activated during the execution run in order to generate a quick alarm or re-(action) towards the performance violation. That enables capturing the unplanned and unexpected incidents and disturbances that are the root causes of violation, waste, or value loss. Moreover, a certain RT-PCRs could represent a control

algorithm of a specific management policy. Other RT-PCRs could be used to study, online or offline, the behavior of the supply chain object (i.e. resource) using specific patterns to predict and detect the interruptions and incidents in advance and accordingly generate real-time re-(action) in order to reduce any type of wastes in term of material, time, motion, utilization, etc. In addition to that, these rules could also be expressed to detect the opportunity for further continues improvements.

The working mechanism and the interaction between the DSCPM-Engines are illustrated in Figure 4.5. Some of the modules of PPAE will be validated in theoretical case studies as further discussed in the coming chapters. In the following subsections, the components of the DSCPM framework are discussed and elaborated with emphasis on event-instances and CEP.



**Figure 4.4: Overview of Components of the DSCPM for Smart Supply Chain Performance Monitoring.**



**Figure 4.5: The Working Mechanism of the DSCPM.**

#### 4.4.1 Event Extraction Engine (EEE)

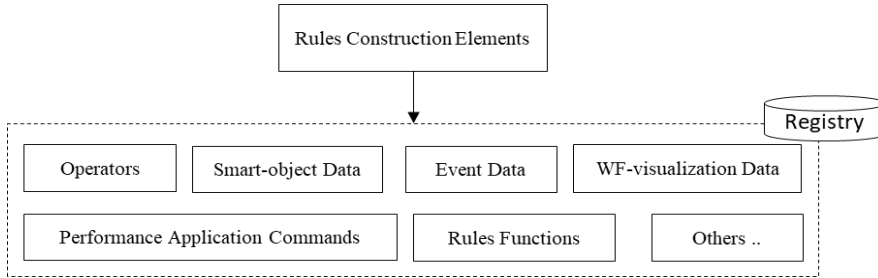
The EEE is used to extract and process the enormous volume of IoT captured execution event-instances and their data in real-time (measured in seconds or milliseconds) during a daily run. It is also called a Real-time Complex Event Processing Engine (RT-CEP) as seen in Figure 4.4. In this stage, several event-processing operations must be applied to extract and process IoT captured data with the meaningful format, such as event data capturing, filtering, cleaning, clustering, sorting, aggregating, etc. This level in the event data life cycle is considered as events pre-processing stage [123]. Several IT research papers have discussed several event extraction methodologies using CEP, e.g. [108-110]. After that, the pre-processed execution data can be sorted into specific formats and saved as event-instances in a temporal database, which become ready to be utilized by other DSCPM-Engines. The utilization of the saved event-instances in the temporal database is done by subscribing them by different RT-PCRs in other DSCPM-Engines. Using CEP concepts, some correlation or

aggregation operations between event-instances are done in PPAE modules, to generate the performance violation warning or optimal re-(action)s at the right time, right location, and for the right person. Each event type should be defined using proper RCE in order to be detected, otherwise, it will be deleted during event-data filtration and sorting.

#### 4.4.2 Real-time Rules Engine (RT-RE)

##### 4.4.2.1 Real-time Rule Construction Elements (RCE)

This part of the RT-RE contains pre-defined RCE. These elements can be viewed in a pop-up box to be used while creating or expressing the RT-PCRs to facilitate the construction process. The pre-defined elements or “meta-data” are saved in an event identification registry. This registry can be considered as a type of data-dictionary, and it is used as a solid basis for building RT-PCRs. The proposed RCE is shown in Figure 4.6.



**Figure 4.6: The RCE of the RT-REB.**

##### 4.4.2.1.1 Operators

The operators are used to build a relationship between events inside the body of the rules. In previous literature, some operators for extracting and defining the relationship between events have been presented; these operators can be used in building the RT-PCRs. For more flexibility in the DSCPM, and because of the applications dynamicity and rapid development in data capturing technologies (i.e.,



IoT and related technologies), this module enables the users to define new kinds of operators depending on the complexity of rules, which are based on the complexity of the system being monitored. Some operator types are discussed below:

### **Logical-operators**

Logical-operators are the most commonly used operators to construct the relations between event-instances [108]. Examples of logical-operators include (i) OR ( $\vee$ ): Disjunction of two events, (ii) AND ( $\wedge$ ): Conjunction of two events, (iii) NOT ( $\neg$ ): Negation of an event E, etc. To construct relations between the main parts of the RT-PCR, which consist of event relations, further logical operators can be defined in this engine.

### **IoT-operators**

Because the majority of events are captured from execution-level using IoT in the form of primitive event PRIM (EPC, L, T), IoT-operators represent these events in the form of a smart-object ID-code or Electronic Product Code (EPC), (e.g. Order-ID, WIP-ID, operator-ID, equipment-ID, material-ID, machine-ID, etc.), Timestamp (T), and Location of event (L). According to [108, 124] works, some IoT-operators illustrated below:

1. Observation operator  $\rightarrow$  OBSERVATION (sensor-EPC, EPC, timestamp).

This operator represents the raw reading data generated from sensors (i.e., reader), including sensor EPC, tag or object EPC, and the reading timestamp.

2. Transaction (event) operator  $\rightarrow$  TRANSACTION ITEM (transaction-ID, EPC, timestamp).

This operator represents the items in a transaction. It includes a transaction or event ID, EPC of the object in the transactions, and the timestamp when the object's transaction occurs.

3. Containment(aggregation) operator  $\rightarrow$  CONTAINMENT (EPC, parent-EPC,  $T_S$ ,  $T_E$ ).

This operator represents the period ( $T_S, T_E$ ) in which the object EPC is contained in a parent object parent-EPC.

4. Data compression operator  $\rightarrow$  DCOMPR(PRIM) = comprData (EPC, L,  $T_1$ ,  $T_2$ ).

This operator to represent object staying at location L during the time interval ( $T_1, T_2$ ).

5. Path compression operator  $\rightarrow$  PCOMPR (comprData) = comprPath (EPC, ( $L_1, D_1$ ), ..., ( $L_n, D_n$ )).

This operator represents the path that object EPC traveled by, where  $L_i$  is the  $i$ th location in the path, and  $D_i$  is the total time that the object stays at that location.

6. Group compression operator  $\rightarrow$  GCOMPR(PRIM) = comprGroup(g-ID, L, T).

This operator to represent the objects that tend to move and stay together in a bulky manner (i.e., order package). G-ID is a generalized ID, which points to the only bulk, rather the original EPCs.

IoT-operators are used by the RT-PCRs for tracking, defining and mapping the AVSM of the actual order or product flow (i.e., the path or route), as well as to translate the performance targets data into time-based workflow through the VVSM. For example, a segment of the AVSM path event-data of Order “OA” at Business Process “BP<sub>*i*</sub>”, which consists of three activities, “A, B, and C”, is represented in the following path's event-data vector:

$$\begin{aligned} \text{AVSM}_A = \dots < O_{A-EPC}, L_A, T_S >; < O_{A-EPC}, L_A, T_E >; \\ < O_{A-EPC}, L_B, T_S >; < O_{A-EPC}, L_B, T_E >; \\ < O_{A-EPC}, L_C, T_S >; < O_{A-EPC}, L_C, T_E > \dots \end{aligned}$$

This part of AVSM's path event-data views the traveled path by OA identified by EPC, where  $L_i$  is the  $i$ -th location in the path, and  $T_i$  is the timestamp of each event-instance.

The path event-data can be graphically visualized in traditional VSM-format through the WF-Engine with all associated execution and performance-related data. This facilitates the understanding of the actual interaction between resources or objects on the execution-level and enables real-time performance monitoring. Moreover, the path history of orders with all product-states can be accurately tracked or traced, for further flow analysis and upper-level performance estimation. The event-instance related data and its key attributes, especially those related to performance measurement, are simultaneously recorded in the DSCPM-DB, where the operational aspects of each product-state along the business processes activities are described. For example, the processing-state that lies between  $< O_A, L_A, T_S >$  and  $< O_A, L_A, T_E >$  is executed on order (O-ID) in location (L-ID) from worker (OP-ID), with the use of equipment (E-ID), and using Material (Mat.-ID), under process parameters (Pa.1, Pa.2, Pa.3, etc.....), with the help of using Tool (Tool-ID) can be shown in AVSM and saved in DSCPM-DB. In this state, more event data can be defined to be subscribed. This event-data can be recorded in the event-data set:

$$d_{e_i} = <$$

$$O_{ID}; L_{ID}; OP_{ID}; E_{ID}; Mat_{ID}; Tool_{ID}; \{Pa. 1, Pa. 2, Pa. 3, etc\}, etc \dots >.$$

This set of data can be invoked by RT-PCRs that already subscribed this event-instance in their CEP-code. In other words, the timestamps in

IoT-operators and the associated event-data sets can be utilized by different PPAE's modules simultaneously to support different performance practices and applications in real-time. For instance, the processing-time at specific business process can be utilized by different PPAE modules, such as:

1. Real-time dynamic business process monitoring and controlling Module: For example, this event-data set is utilized to display the real-time status, such as the actual processing time of individual order/products (if it is within the acceptable limits or not).
2. Perishability management module: automatically determining and updating the exact remaining life of a perishable product, a distribution can be made at the right quantity and right product based on the current data, to support a smart distribution network for such products.
3. Continuous improvements module (Kaizen-events): utilize this time for offline performance analysis (e.g., machine utilization, labor performance, time-based waste analysis) and find new improvement opportunities. Moreover, the event-data set could be utilized for further analysis, like studying the impact of human factors (e.g., labor fatigue/gender/skills) on the variability of the processing time or quality of final products.
4. Real-time cost tracking Module: Incur the exact machining cost-rate based on the duration of the processing-state of each product at this machine, detailed description in Chapter 5.

### **Time-operators**

Time-operators required representing the event relations in terms of time. The events referred to here are the captured events by IoT, as long as the transaction events from enterprise information systems such as

ERP and SCM. The latter events can be similarly captured, processed, represented by event data sets with all of the performance measurement related data, and wherever and whenever it is needed in the DSCPM (e.g., order's receive, enter, and validate events).

In supply chain applications, an event is defined to be an occurrence of specific activity by a specific object or group of objects in time, which could be either a primitive event, occurs at a point of time, or a complex event which is a pattern of primitive events happens over a time period. From now on and in the following discussion, we use “E” to represent an event type, and “e” to represent an event instance.

First, we need to define the time-based functions for the occurrence of an event, which will be needed for the rules expression:

- $t_{\text{Start}}(e_i)$ : Starting time of an event instance,  $e_i \in E_i$ .
- $t_{\text{End}}(e_i)$ : End time of an event instance,  $e_i \in E_i$ .
- Duration of  $E_i$ : The duration of the Event-state “E” (e.g. transport-state), which represents a specific smart-object state, where:  $D_{E_i} = t_{\text{End}}(e_i) - t_{\text{Start}}(e_i)$ .

Time-operators are important for detecting the timestamps of each order/product-state along the supply chain value stream processes and activities, examples of temporal complex event operators are:

- The sequence of events SEQ(;): Event  $E_1$  must be completed before  $E_2$  starts without time constraints between their occurrence (similar and different event types). For example, (i) assurance that a certain process isn't overstepped by another process (ii) a machine setup-event must be applied before the processing event starts, order receives confirmation must be applied after receiving the order.

**RT-PCR semantic:**  $(E_w; E_m)$  iff  $(e_{ws}, e_{we} \in E_w) \wedge (e_{ms} \in E_m) \wedge t_{\text{Start}}(e_{ms}) \geq t_{\text{End}}(e_{we})$ .

Where  $E_w$ : product unload in customer place event and  $e_{ws}$ ;  $e_{we}$  are the start and ends primitive event.  $E_m$ : receive and verify product by customer event;  $e_{ms}$  is its start event.

- The sequence of events-time conditioned (SEQ, T): This determines the periodic event occurrence of similar event-instances within a specific time interval. For example,  $(e_1; e_2, 10 \text{ minutes})$  means  $e_2$  occurs 10 minutes after the occurrence of  $e_1$ . For performance measurement purposes, we can use this operator to monitor and control the cycle time, which depends on the processing time between two consecutive units, to meet customer demand and prevent overproduction wastes.

**RT-CEP semantic:**  $(e_{p_{1s}}; e_{p_{2s}}; \dots; e_{p_{is}}), 10)$  iff

$(e_{p_{1s}}; e_{p_{2s}}; \dots; e_{p_{is}} \in E_p)$ .

- Concurrent events ( $E_1 || E_2$ ): This determines whether two events  $e_1$  and  $e_2$  occur at the same time like the arrival of material and their sub-assemblies events, or if the events  $E_1$  and  $E_2$  overlap. For example, the event “start external setup” occurs during the event “machine is running”. In case of events overlapping, there are two types of events-overlapping; namely partial overlapping and full overlapping.

**RT-CEP semantic:**  $(e_1 || e_2)$  iff  $\exists e_1 \in E_1 \ \& \ \exists e_2 \in E_2 \ \wedge \ ((t_{\text{Start}}(e_1) - t_{\text{End}}(e_1)) || (t_{\text{Start}}(e_2) - t_{\text{End}}(e_2)))$ .

For external setup, the rule can be expressed as follows: IF  $(E_p || E_s)$  is external, WITHIN  $(e_{p_s}, e_{p_e} \in E_p)$ ; START  $e_{s_s}$  iff  $(e_{s_s}, e_{s_e} \in E_s) \wedge t_{\text{Start}}(e_p) \leq t_{\text{Start}}(e_s) < t_{\text{End}}(e_s) \leq t_{\text{End}}(e_p)$ .

In this examples, a setup command is generated between processing start- and end-events:  $e_{p_s}; e_{p_e}$ , where  $e_{s_e}$  does not exceed  $e_{p_e}$ .

This means that  $E_s$  ends before the processing event  $E_p$  ends.

In the case of time-operators, more operators can be defined depending on the complexity of the system. This feature distinguishes DSCPM from other systems, thus making the real-time controllability of PPATs more flexible and adaptable with any changes.

### **Location-operators**

To track the flow, location-operators can be used to represent the event relations through their location. Location-operators take the location of smart-objects into consideration. The following are some examples of location-operators:

- Same location constructor ( $\langle \rangle$ ): The same location operator determines whether two or more events occur at the same location. This operator can be used to detect all used resources in the work process at a certain location while an order/product is being processed. The derived rule should be able to extract the event data from different dimensions, such as data of the worker who has executed the process at the recorded location, the used machine, and tools at the same location, as well as other used-resources at this location. Therefore, the processing event data at this location can be used in different dimensions. For example, control the interaction between smart-objects to avoid time waste, control the implementation of PPAT.
- Remote location constructor ( $\langle \rangle$ ): The remote location operator determines whether two or more events occur at different locations.

Depending on manufacturing system requirements, other operators can be defined as the causality operator ( $\rightarrow$ ) to define the dependency between events.

#### **4.4.2.1.2 Smart-object data**

This part of the RCE defines all types of objects that exist on the

execution-level that become a smart-object after being attached with IoT data capturing and holding a device such as RFID-tag, as presented in Chapter 3. Smart-objects must be predefined in a registry to facilitate the expression of RT-PCRs. So any changes in the existing resources will be adapted and considered through RL-PCR.

In this work, we consider two types of tracked smart-objects: Static Smart-Objects (SSO) and Dynamic Smart-Objects (DSO). Examples of SSO include machinery, tools, equipment, shelves, inventory spots, conveyors, as well as any other objects which are associated with a specific business process and used by its activities. The status of SSOs changes in terms of time. The other type, DSOs, include Products/WIPs, labors, containers, movable material handling equipment, trucks, etc. The status of DSOs changes continuously in terms of time and location. Both SSOs and DSOs have dynamic-related event data due to the changes in their current status. Each event-instance contributes to the changes in the smart-objects status, either in the short-term (e.g., utilization of machine, availability, maintenance planning) or in the long-term (e.g., depreciation of machine or life cycle time of, product, tools, and spare parts).

It is important to pre-define the characteristics, the attributes, and the features of each object to be considered in RT-PCRs. As mentioned in Chapter 3 this information can be identified using ISA-95 models. Usually, this information is saved in the ERP database, and if needed they will be invoked through the RT-PCRs. For example, the information related to labor may include skill level (e.g., senior, intermediate, or junior) and gender (male or female) to decide if he/she can execute a specific process or not. This information can be updated by building an algorithm and data mining model which studies the behavior of each worker at the execution-level, such as his impact on



the average processing times at different location or his learning curve. Another example would be truck features such as the maximum capacity of a truck or the capability to handle a certain ballet size, etc.

#### **4.4.2.1.3 Event data (event identification)**

This part of the RCE systematically defines all types of event-instances, which are relevant to each smart-object at the execution-level and needed in the RT-PCRs, see Figure 4.7. For supply chain performance measuring applications, the two type of events should be defined: primitive event and complex event. In our research, we more focus on capturing complex events than the primitive events for three important reasons:

- Primitive events seem to be easy to capture due to the availability of mature technologies such as Edgeware servers.
- At the operational level, we are mainly tracking performance data, which is usually generated from primitive events patterns. Therefore, because performance data resulted from events patterns integration or accumulation, the complex event is the main event type that can help in our approach.
- At the upper management level, from one side it is required, according to SCOR model processes hierarchy structure, to accumulate and integrate the operational level events to represent upper-level activities or business processes. From the other side, to measure upper-level performance metric, according to SCOR model metrics hierarchy structure, it is required to accumulate or integrate some operational level metrics to diagnose that metric. Building complex events that can do these roles can directly bridge the information and time gaps between the organization management levels.

Accordingly, as discussed in Chapter 3, one of the effective methods to define all execution events is to split the workflow activities along the supply chain value stream into primitive events. However, we build on the method used in Chapter 2 to concentrate the focus on defining all events related to each performance-based practice and application (PPA) separately. That to facilitate building the RT-PCRs required applying these applications. To do so, a simple step-by-step methodology as shown in Figure 4.7 can be used to build the Tree of Event Instances (TEI); this is illustrated in Figure 4.8. We discuss this method as follows:

*Firstly*, all objects, which already identified in Chapter 3, on the execution-level (e.g., order/product, movable equipment, logistics operators, etc.) should be indexed such that:  $SO_i$ , where “i” is the index of the object,  $i = 1, 2, 3, \dots n$  and  $n$  is the number of active smart-objects on the execution-level.

*Secondly*, all objects are classified according to their respective nature of work or in other words, their working groups, i.e.,  $SO_{i,j}$ . Here the groups of the smart-object (e.g., Tools, Labor, Equipment, etc.) are represented by the subscript  $j$ , where  $j = 1, 2, 3 \dots m$ , and  $m$  represents the number of objects working groups.

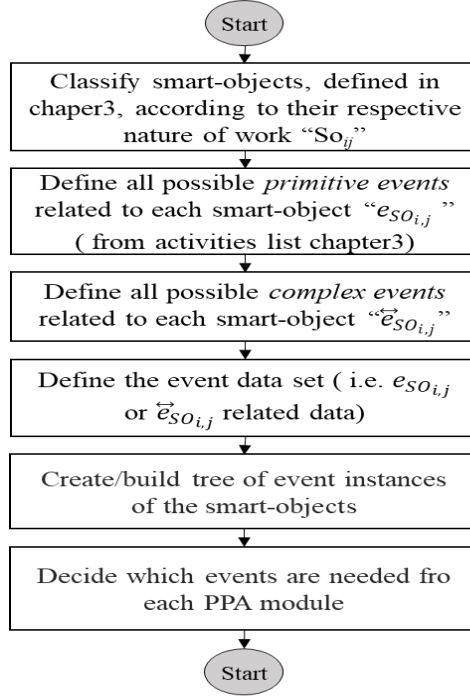
*Thirdly*, all possible primitive events which could be generated during daily runs should be defined (i.e.  $e_{SO_{i,j}}$ ).

*Forth*, from the primitive events, all upper-level events should be identified, (i.e., a complex event,  $\vec{e}_{SO_{i,j}}$ ).

*Fifth*, after the event type, is defined ( $E_i$ ); the event-data set ( $d_{e_i}$ ) (i.e., event-related data) that accompanies or coincides with the event-instance ( $e_i$ ) should also be defined as well. Eventually, these event-data sets should include all of the data required to monitor the

performance, which has been decided to be monitored to enable the PPAs being developed.

Finally, decide the needed events for each module in PPAE.



**Figure 4.7: Methodology to Create Tree of Event Instances of the Smart-Objects.**

For example, if we assume RFID supported by the sensor system being used. Each event type “E” represents a specific status and can be defined as  $E = [E_{ID}, L_{x,y}, T_s, T_e, C, PD]$ . With each event type having its unique ID,  $L_{x,y}$  is the location of an event and it is known from the RFID-reader location,  $T_s, T_e$  are the event starting and ending instances,  $C = [e_1, e_2, \dots, e_n]$ ,  $n \geq 0$ , are the conditions which allow this event type to happen. The conditionality facilitates the self-learning, real-time control and automatic error detection of smart-objects,  $PD = [r_1, r_2, \dots, r_n]$ ,  $n \geq 0$  are the performance data related to PPATs application collected by invoking data collection sensors or information system inquiry once a specific event detected. For example: for dairy products, when arrival event detected, environment

temperature recorded or the remaining time to expiry date calculated. Other process attributes or parameters are also defined in the RFID-tag, such as the expiration date of the product.  $A = [\text{attr}_1, \text{attr}_2, \dots, \text{attr}_n]$  where  $n \geq 0$ , is a set of attributes, which characterizes the event type. For example, using real-time “expiry products’ waste monitoring” rules to decrease waste costs in the supply chain. Once RFID has detected the “arrival-event” of product “ $P_i$ ” to the retail stock, the remaining time before expiration (i.e., process attributes that are considered for this particular process for “ $P_i$ ” at retail) can be calculated and thus, automatically update the information systems (e.g. ERP, WMS) with these information to be used in wastes management system policies and applications.

Figure 4.8 shows that performance management practitioners can decide which smart-objects and the associated event data are required for the corresponding PPAT.

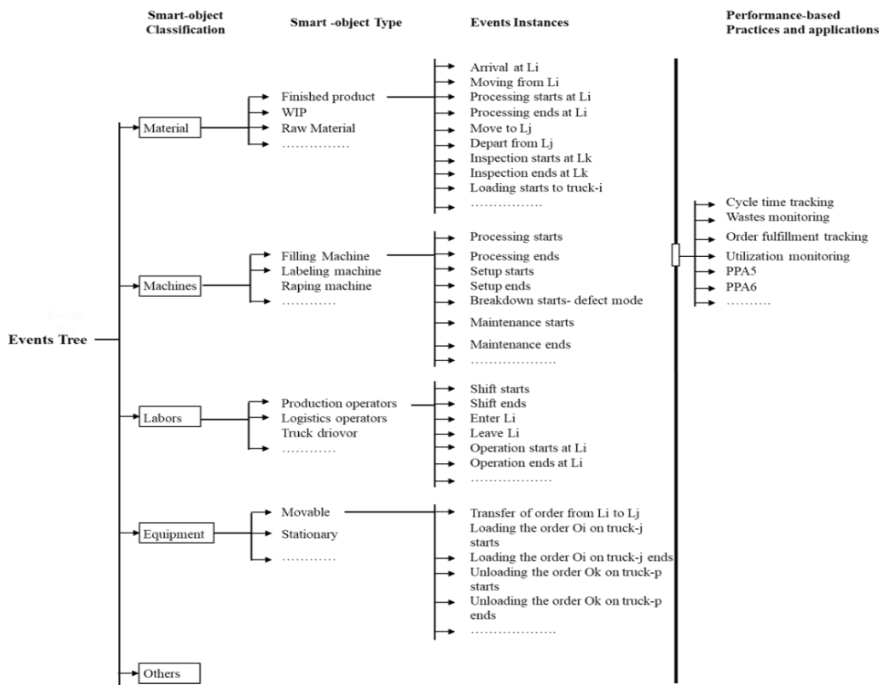


Figure 4.8: The Tree of Events Instances of the Smart-Objects.

#### **4.4.2.1.4 WF visualization-data**

This part of the RCE contains pre-defined graphical symbols, borrowed from traditional VSM. Each symbol represents a specific product-state. These WF symbols will be automatically imported, according to the current product-state along the workflow stream on the execution-level, from the registry to provide the possibility to graph the AVSMs of the tracked orders/products and visualize it on the user interface (e.g., workers, supervisor, middle management, or top management). The relevant actual working data will be listed on each symbol at the corresponding AVSM. This way of process visualization facilitates the real-time interaction between workers and the resources on the execution-level, and it enables a more efficient and faster decision-making by middle and top management.

#### **4.4.2.1.5 Performance application commands**

As mentioned before, the supervisors and workers are enabled to see all execution-related information in details and accordingly make quick reactions or decisions. Therefore, the registry of the RCE contains predefined performance-based policy or performance tools commands, which can be used on the “re-(action) part” of RT-PCR body. If the “conditions part” of the triggered RT-PCT is met, the commands in the “re-(action) part” will be automatically generated without human intervention, such as WIP-withdrawal, dispatch, start processing, start setup, inspect, package, rework, etc. The generated commands can be visualized on the authorized worker’s DSCPM-TUI in order to be executed in near time or immediately to enhance performance-based practices during daily runs and avoid wastes.

#### **4.4.2.1.6 Rules-functions**

This part of RCE is important to enrich engineers with different mathematical functions that help to express more complex RT-PCRs used for on and off-line event data analysis, such as process or object performance analysis, supporting complex real-time decision-making, analysis for further improvement opportunities, etc.

#### **4.4.2.2 Real-time Rule Expression Builder (RT-REB)**

The RT-REB is used to write different types of rules to support the functions of DSCPM-Engines. The performance management specialists can use the Graphical User Interface (GUI) of DSCPM to create the RT-PCRs offline. The proposed functions of the RT-REB are as follows:

1. Building the appropriate RT-PCRs for each module in PPAE.
2. Building the event processing rules for EEE to process the IoT-captured primitive events, such as events filtration rules to clear redundant events and save them in the temporary database.
3. Building rules to aggregate primitive events into complex events to detect specific working conditions or to evaluate a specific business process performance (i.e., complex events) and save them in DSCPM-DB for further uses.
4. Building rules for the WF-Engine to translate the actual execution-related data into AVSM, and to translate the targets performance-based monitoring data into event context in VVSM.

Our focus in this thesis is limited to describing the RT-PCRs that can help in bridging the information and time-decision gaps, described in section 4.2, and can be used in PPA-engine for real-time monitoring and controlling of PPAs during the daily run.

RT-PCR can use the “rule-based system” concepts to perform real-

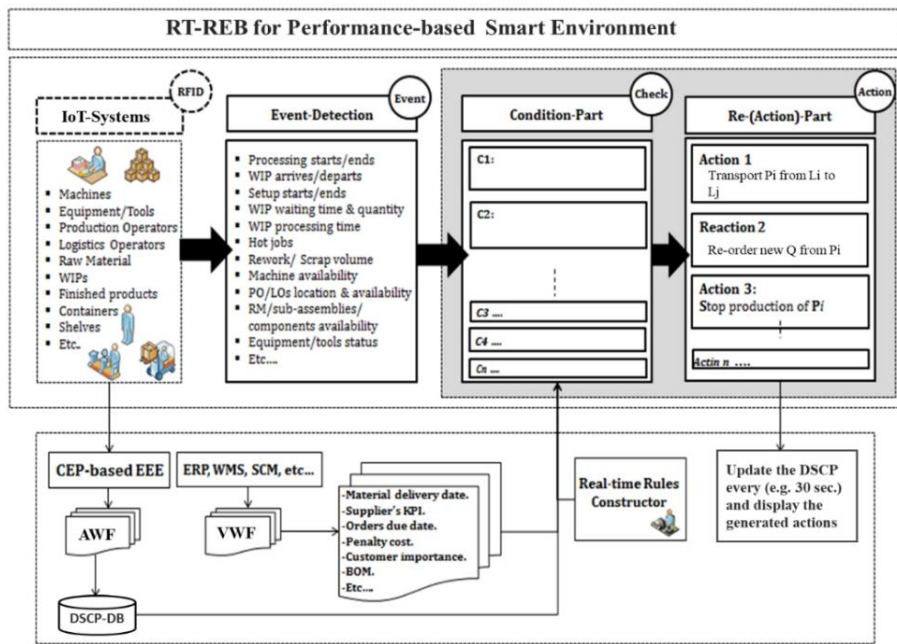
time analysis. Accordingly, the body of the RT-PCRs encompasses two main parts including:

1. Conditions part: it is represented by events aggregation, which represents a certain situation. It contains specific event-data, constraints, attributes, and parameters. During the execution run, the RT-PCR checks the validity of these conditions by invoking the subscribed events data (i.e., aggregated events) from the DSCPM-DB and AVSM.
2. Re-(action) part: if the conditions part with the defined constraints is met, then the re-(action) part of the RT-PCR will be triggered to generate the predefined alarms or re-(action)s to be executed by the right labor at the right time, in the right place. The re-(action) part defines how the system must react when the predefined events or performance level occur and cause a specific status or condition during the run. See Figure 4.9. However, a complex RT-PCR could have a different and more complex format.

The RT-PCRs under concern in this work are classified according to their default functions into two types, including:

1. Local RT-PCRs, which are directed to monitor and control a specific business process activity and measure its performance (e.g., processing time for certain process, accumulated costs, stock value for certain SKU in a certain place, etc.).
2. Global RT-PCRs, which are directed to
  - (i) Achieve the horizontal integration (i.e., bridging decision-time gape) by controlling the interaction between different smart-objects at the overall execution-level to support a specific PPAT such as invoke a certain inventory management policy.

- (ii) Achieve the vertical integration (i.e., bridging information gap) by the aggregating business process real-time workflow and its performance vertically from the operational level to the business level. Therefore, enable a more efficient and faster decision-making. (e.g., rebalancing inventory levels in different stocking places inside the supply chain, move products with certain conditions from retailer to another to avoid wastes, adjust demand forecasting numbers for a certain product, etc.).



**Figure 4.9: RT-REB for Performance-based Smart Environment.**

According to the type of their generated re-(action), the RT-PCR types can be classified into three types:

- i. Operational RT-PCRs: generate re-(action)s that are executed on the execution-level, such as “transfer product or apply a discount” if the remaining life before expiry exceeds the



threshold, or change a distribution vehicles route due to new analysis or decision results.

- ii. Analytical RT-PCRs: generate re-(action)s to execute an on-line analysis. The results of this re-(action)s can be used by other RT-PCRs or saved for further analysis, such as “update the average” of lead time based on the processing start/end-instances to monitor the Demand Lead Time (DLT), “estimate and update demand forecasting” of specific SKU or product group, “incur cost” for cost tracking purposes, in other words they are abstract RT-PCRs.
- iii. Hybrid RT-PCRs: used for operational and analytical re-(action)s. For example, if the result of the analytical RT-PCR re-(action) requires a rapid a physical re-(action) on the ground. The associated operational RT-PCR will be triggered to generate the urgent re-(action)s. Therefore, each RT-PCR should have a unique ID to be activated by other rules.

Therefore, this re-(action)s are executed either by smart objects or on it, at the execution-level, to keep performance-based initiatives alive and avoid wastes and disturbances. In this regard, all re-(action)s commands should be predefined, agreed by all of the management levels, and saved in the registry of RCE. As a result, RT-PCRs aim to build a relation between IoT-captured events to identify a specific working situation and generate a re-(action)s with certain commands for labors or any other objects.

The RT-REB is one of the best DSCPM features, which distinguish it from other performance-IT systems. It is expected to provide many advantages for smart performance measurement environments including:

- i. Enable a smart real-time performance-based re-(action)s mechanism without the needs for human intervention.
- ii. The DSCPM modules can rapidly adapt to the critical situations and incidents during the execution of the working processes, leading to the limitation of wastes and better performance.
- iii. Performance-based initiatives and applications will be kept alive and valid in short periods of time (i.e. daily production runs) and in longer periods of time to prevent and treat any problem, such as those related to the short-life cycle of products and the rapid changes in market behavior, as well as the high customization level in sourcing, production, and supplying systems.
- iv. The real-time monitoring and controlling of PPATs become more flexible and adaptable in a dynamic environment.
- v. RT-PCRs can contribute to the self-learning process of some resources like machines and equipment, to avoid wastes and problem in advance. The real-time knowledge management can be improved and enhanced, with regards to the extraction of working-related data from the DSCPM-DB, to find new improvement opportunities using data mining and deep learning techniques.

#### **4.4.3 Work Flow-Engine to Generate AVSM**

In the WF-Engine, the actual flow of each order/product along the supply chain value stream with all associated execution data will be tracked and visualized in VSM-format. So it represents the current situation on the execution-level, as seen in Figure 4.10. The real-time tracking of flow in the AVSM is executed using WF-Engine as follows:

- 1- Performance management specialists develop and express the AVSM tracking rules through the RT-REB. The algorithm shown below describes a simple order tracking RT-PCR. The AVSM-tracking rules subscribe all flow-related event instances (i.e., primitive events) and the associated execution-related data to extract them in real-time.

---

**RT-PCR<sub>i</sub> = AVSM-Path**

---

```

01 IF VVSMOi released
02   THEN
03     FOR  $\forall P_{ij} \in VVSM_{O_i}$ 
04       FOR  $\forall P_{ijk} \in VVSM_{O_i}$ 
05         TRACK  $\forall P_{ijk} [L_{iID}(T)]$ 
06           RECORD in Series  $\langle P_{ijk}, L_{iID}, T_i \rangle$ 
07       ENDIF
08     FOR each  $\langle P_{ijk}, L_{iID}, T_i \rangle \in AVSM_{ijk}$ 
09       RECORD  $d_{AVSM_{ijk}} = \langle$ 
10          $O_{ID}; P_{ID}; L_{ID}; OP_{ID}; E_{ID}; Mat_{ID}; Tool_{ID}; \{Pa. 1, Pa. 2, Pa. 3, etc\}, etc \dots \rangle$ 
11     ENDFOR
12 END
```

---

O: order, P: product, L: location, T: time, OP: operator, E: equipment, Mat: material, Pa: parameter or performance data

- 2- Once a subscribed event-instance is detected in the temporal database, it will be invoked through AVSM-rule for further flow analysis.
- 3- The AVSM-rule defines the order/product-state (e.g., processing-state, transport-state, inspection-state, load/unload state, waiting-state, etc...) that the product passes.
- 4- After ordering/product-state is defined (i.e., Name, timestamps, duration, location, performance-data, etc.) in real-time, the AVSM-rule activates the action = “import” to import the corresponding pre-defined graphical symbol and draw it in the user interface. This will define the current progress and actual route of order or single products in term of time and locations. The visualization will be done in coordination with the Real-time Visualization Engine (RT-VE).

5- The associated execution-related events and performance-related data can be synchronized with products flow-related events extracted and aggregated to be processed and visualized.

The WF-Engine can execute in parallel several real-time tracking processes to track all released order/product types on the execution-level. Therefore, each product type in each order has specific AVSM-rule to track its items along the SC value stream (i.e., AVSM<sub>ijk</sub>, where  $i = 1, 2, 3, \dots, n$ ;  $i$  is the order-index;  $n$  is maximum number of released orders on the execution-level.  $j = 1, 2, 3, \dots, m$ ; where  $j$  is the product type-index;  $m$  is a maximum number of released product types in order.  $k = 1, 2, 3, \dots, w$ , where  $k$  is the product-index;  $w$  is the maximum number of items from this type). For visualization issues, the AVSM is classified into two types:

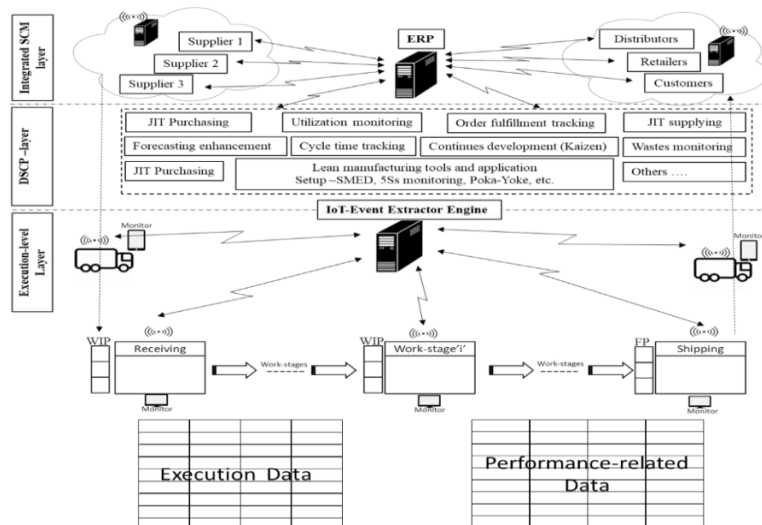
- Local-AVSM: visualizes the current item which is being processed by the labor at the local TUI, (i.e., Fine AWF). Figure 4.10 depicts this type.
- Global-AVSM: visualizes the overall situation at the execution-level (i.e., Simi-fine AWF), that contains all Local-AVSMs of the released order/product types with the possibility to see the details. This type is visualized at the supervisors and higher administrative levels user interfaces.

The AVSM of each item with the associated execution and performance-related data will constantly be visualized on the TUI of the authorized labors/users. The visualization time frame (i.e., weeks, days, hours, minutes, and seconds) of AVSMs and the performance-based control data should be considered in short and long-term performance practicing. For example, the labors monitor the working progress through the local-AVSM with detailed information and current performance control data up-to second or minute depends on the

execution parameters, while the supervisor monitors execution progress through global-AVSM within time frame of hours (i.e., control charts, histogram, etc.) and the manager within time frame of days.

The WF-Engine synchronizes tracking of the physical flow of smart-products with capturing the associated data in real-time, which indicates that IoT significantly contributes to eliminating human intervention in data collection processes that eliminates the potential of errors and the wasted time in case of traditional data collection processes as well.

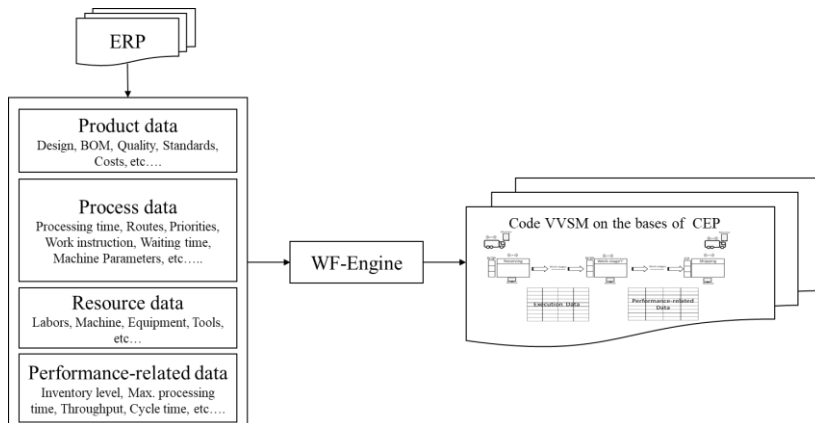
Moreover, The AVSM supplies the management with the accurate picture and any required data of the resources along the business processes. This would help a companies or supply chains that has many scattered equipment and tools to track the status of resources and updates it over the time, checks their current availability, and measure their performance. This enhances the real-time planning process and optimizes the interaction between the available resources to reach the, targeted performance, optimum usage rate, and eliminate the associated waste.



**Figure 4.10: Work Flow with Execution and Performance-related Data.**

#### 4.4.4 Work Flow-Engine to Generate VVSM

WF-Engine also used to generate the VVSMs. The VVSM represents the standard workflow along the business processes with all standard performance-based execution data, i.e., the ideal or planned targeted performance. So it is considered as a targeted performance technical information database of the current orders/products being processed. That involves all targeted performance data in term of flow. Releasing the order/product to execution operation starts by building the standard workflow templet for each new order/product to rapidly adapt to the execution processes. The targeted flow and the associated performance-based execution data are set during the pre-execution phases such as product development, product design, process design, sourcing planning, production planning, distribution planning, supplying planning, etc. This creates an integrated performance supply chain by selecting performance metrics and its targets that guarantee integrating product and process planning, scheduling with execution, control, and decision-making. Simulation software could be used for process design data to achieve targeted performance.



**Figure 4.11: Integration of ERP Execution-related Data with DSCPM through the VWF-Engine.**

In this context, to bridge the gap between the targeted performance

represented in the VVSM and the actual physical situation represented by AVSM, it is important to translate the content of VVSM into event context within business process-format to automatically retrieve the targeted performance in real-time if unexpected incidences occur, and keep PPAs alive and effective (i.e., this done by different modules in PPAE). As seen in Figure 4.11, the WF-Engine is used to translate or code the standard VVSM data into events context, where the path of product-flow is translated into the path event-data vector as described in IoT-operators section. The path event-data vector will be saved in WF-registry with all execution and performance-related data. It accurately describes, in details, the standard workflow route with all product-states that the product must pass through in terms of time and location, with the associated performance-based execution data, such as: processing-time, inventory level, order size, setup times, working procedure, product-states with standard time instances, duration, locations, required machines, tools, materials, and equipment for each state location, quality standards, standard data such as execution process steps with the optimum sequence and required equipment, tools, skills level, and subassemblies at each step with durations, the standard working parameters such as temperature or pressure, standard cost-rate of each cost driver (i.e. resources), etc.

In context of real-time enterprise integration, after releasing a specific VVSM at the execution-level and during execution, if employees at the higher enterprise levels make any related changes (e.g., hot job, material shortage, adjust the design, etc.) by inserting, updating, or deleting data entries in the database of the enterprise information systems (e.g., ERP, SCM, CRM, etc.), these changes can be translated directly through the WF-Engine and viewed as event-instances in relevant VVSMs, that to make a quick real-time re-(action)

in order to avoid wastes and NVA activities.

In an ideal situation, workers receive the standard work instructions from the WF-Engine in the form of VVSM through RT-VE. However, due to inherent variability causes (i.e., natural variability, random outages, setups, defects, etc.) in any manufacturing system, the ideal or planned situation can't be achieved in reality [125]. Therefore, to retrieve the targets and regulate all execution activities to mitigate the impacts of variability, a real-time comparison between the virtual world and physical world should constantly be executed as described in Figure 4.12. The differences between what is planned in VVSM and what is being produced in AVSM can be detected through different RT-PCRs in the PPAE and visualized on TUI through the RT-VE.

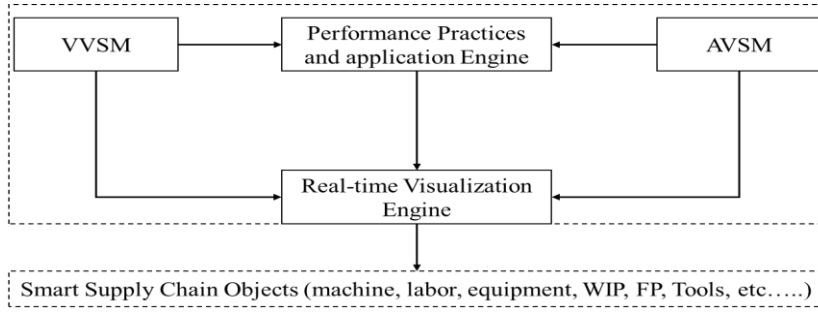
To detect the discrepancies through RT-PCRs; some events data and values from both VVSM and AVSM can be subscribed to conditions part of the RT-PCR. During the execution, the subscribed events values are constantly invoked, if there are any differences, re-(action)s will be generated in accordance to re-(action) part of the RT-PCR. In this case, the actual performance-control data is visualized to be considered by labors.

#### **4.4.5 Real-time Visualization Engine- (RT-VE)**

This engine displays mainly the AVSM of each order/product at the local TUI of workers and supervisors. The RT-VE is equipped with rules to invoke and process the current execution data from AWF to display them in VSM-format. For instance, the local-AVSM<sub>i</sub> of product "P<sub>i</sub>" will be visualized on the TUI of PO<sub>i</sub> at Location<sub>i</sub>, once an "arrival-event" of "P<sub>i</sub>" at Location<sub>i</sub> is detected. Moreover, the RT-VE will invoke and display from VVSM the performance-based work instructions, sudden related changes by the employees in the higher



enterprise level, and other important information needed for execution to ensure that the  $PO_i$  automatically acts according to the plan without being told. Finally, RT-VE displays the generated re-(action) towards the unplanned and unexpected execution incidents and disturbances through PPAE. As result, RT-VE collects the actual execution status from all execution data sources (i.e., AVSM, VVSM, and PPA) and visualizes it at local users TUI. This is depicted in Figure 4.12.



**Figure 4.12: The Interaction between DSCPM-Engines.**

## 4.5 Conclusion

This chapter presented the core of this thesis, where the integration of IoT system with Supply chain performance measurement concepts is proposed. The integration framework is based on real-time tracking of smart-objects by IoT in term of time and location with the associated event and performance data and viewed on VSM-format. This framework is represented through developing a computerized real-time performance-oriented IT system, DSCPM, which is proposed to handle the enormous amount of triggered events on the execution-level as well as higher enterprise levels to enhance performance-based application implementation in short and long-term.

The DSCPM is equipped with RT-RE that supply the real-time running DSCPM-Engines (i.e., WF, PPAE) with the needed rules based on CEP concepts. The PPAT is considered as the head of DSCPM

which involves several modules, each of which is specified to control a specific performance-based application and it is equipped with the required real-time control rules called RT-PCRs. The RT-PCRs enable DSCPM to smartly detect any execution interruptions, incidents, or any performance violation incidence and accordingly trigger real-time re-(action)s or to call for a decision-making at the right time to reduce any waste and therefore achieve smart real-time targeted performance-based environment.

With the implementation of this framework, the flexibility and adaptability of PPATs is expected to be increased and become versatile in facing the challenges of supply chain performance measurement and monitoring. This framework could be further enhanced, by standardizing the CEP-rule semantics for constructing the RT-PCRs that can be easily translated into any programming language (code). A complex event compiler could be used to check the validity of a RT-PCRs code according to the information in the meta-data, as well as to conduct syntactical and lexical analysis and correction of the RT-PCRs expression.

# **Chapter 5. DSCPM-enabled Smart Real-time Performance Measurement Environment**

## **Introduction**

This chapter includes two parts, the first part introduces a DSCPM-enabled real-time time and performance-based analysis framework. The framework is to track the demand lead time of an individual product/order along the SC value stream in real time. It helps in identifying workflow time-components, and accordingly, measure the performance and discover any anomaly or waste, and therefore enable effective decision-making process. The second part introduces another innovative real-time IoT-based SC costing framework. The framework is developed for bridging the gap between SC operational aspects and financial costs in real-time. It is executed in real time by DSCPM-PPAE. Such costing method is vital in identifying the root causes of redundant costs and their location, so they are targeted with the highest priority in the continuous development process.

## **PART1**

### **5.1 DSCPM-enabled Real-time Time and Performance-based Analysis Framework**

The performance of today's demand-driven supply chains environments can be measured through a set of main metrics, such as throughput rates, order fulfillment, on-time deliveries, Demand Lead Time (DLT), total costs, space and equipment utilization, travel

distances, inventory levels, labor productivity, set-up times, wastes, etc. [79, 126]. These measures can be represented in terms of time since time is almost the main basis of these metrics. For instance, longer travel distances mean consuming more time. Therefore, the time-based flow is con

sidered as the most critical success factor of SC performance improvement. However, using the conventional time-study approaches to evaluate the current performance, or whether the desired results have been achieved through improvements are prone to data errors, time-consuming, labor-intensive and inaccurate snapshots of the current performance. In this context, IoT is suggested to significantly improve the real-time performance measurement by means of providing a timely feedback about the current performance. However, utilizing the IoT captured data for time analysis and performance violation identification is still limited and scarcely reported [123] since there are hardly any studies discussing how IoT captured data can be utilized to analyze the DLT and investigate the SC value stream process inefficiency in terms of time.

This part of this chapter is concerned with studying the performance of working environments using the product time-based flow (i.e., Demand lead Time (DLT)) along the SC value stream. Therefore, a new approach is developed to enhance the real-time analysis of product-flow time and associated performance-parameters data to be used as the main basis to detect the deviations and unexpected events that lead to none value added (NVA)-states, either for real-time use or searching for new improvement opportunities. This approach starts with designing the VVSM by breaking down the product DLT into contiguous time segments or components called “product-state” which can be tracked and defined in real-time using RT-PCRs. In this context, the

consequences of deviations and interruptions are leading to longer DLT. In this manner, to protect the targeted performance from an inevitable anomaly due to continuous changes, and prevent the dominance of deviations and waste root causes, the deviations, incidents, unexpected, untimely, and unplanned event-instances must be made immediately visible and targeted to be avoided and eliminated through a real-time decisions.

This part also introduces a time-based analysis approach called “Real-Time Smart Decision-making Analysis” (RT-SDA), which is inspired from the “cause and effect diagram”. It can be used to smartly detect the problems that cause the performance deviations and wasted time, and investigate the root causes behind these deviations, in order to facilitate for a smart and timely decision-making.

#### **5.1.1 DSCPM-enabled Real-time Analysis of Demand Lead Time**

The Demand Lead Time (DLT) analysis is recognized as an extremely important topic in the progress towards success in SC performance monitoring and measuring [76, 79]. DLT is the total time from the moment of receiving and confirming the order of a product/s at the beginning of the SC value stream until the time the product/s delivered to customer point. The DLT includes several time-components connected with the activities applied on the products such as: receiving the order, processing time, picking time, packing time, loading time, shipping time, inspection time, receiving the product at customer time, installing time, etc. Generally, it is the total time during which the product stays in the SC value stream till it received and confirmed by the customer [125].

By utilizing the powerful features of DSCPM framework and the significant knowledge in the captured real-time data through IoT, this

section introduces a framework for real-time analyzing and estimating of the DLT based on its time-components or product-states. The actual product-states in AVSM are estimated and continuously compared with the standard product-states as per standards established in VVSM. At any point in time, if a deviation is detected (i.e., extra time is consumed or deviation in performance parameters), a real-time performance analysis process will be conducted by DSCPM\_RT-SDA module to identify the causes that lead to this deviation and investigate the root causes of each problem. The root cause analysis can help managers and operators to make the right decision at the right time. In the next section, the time-components of the DLT will be discussed. Note that the product-state and time-component are used interchangeably and have the same meaning.

### **5.1.2 Time-Components of DLT**

According to SCOR model, SC value stream usually consists of a series of individual processes and activities starting from the order receiving to material handling, processing, storage, shipping, inspections, and ended with delivering the products to the end customer. The duration of these activities contributes to the total DLT. In this regard, for precise and effective real-time analysis to identify and localize the criticalities and weaknesses along the SC value stream, the DLT will be decomposed into several time-components, where each activity type (as it defined in Chapter 3 and Chapter 4) along the value stream should be classified under a specific time-component. In terms of flow, each time-component represents a specific “product-state” that the product passes through, which indicates that specific activities are being performed (e.g., receiving-state, processing-state, transporting-state, waiting-state, loading-state, shipping state, etc.). In this case, each

product-state can be tracked in real-time, so that any critical states that consume more time, and cause performance violation, disruptions, incidents and serious order delays are defined and targeted to be investigated and improved.

For simplicity, we limited our explanation in this research on stocked product configuration, to define DLT time components. Accordingly, Figure 5.1 represents general physical activities and product flow at a single SC entity which receive products from an upstream supplier, process it (e.g., repacking) and deliver it to a downstream entity. The DLT in terms of flow is made up of several product-states. The total value stream DLT is the sum of all product-state durations along the SC value stream. According to the definition of cycle time by Hopp and Spearman 2008 and Inspiring from Ramadan [19] work and SCOR model, suggested product-states in SC value stream can be defined as in Table 5.1.

The real-time tracking of the event-instances of each product-state is illustrated in Figure 5.1. Each product-state has start/end event-instances concerning the workflow timeline. The difference between two successive event-instances is the duration of this state. Based on the SC configuration and environment complexity, product-states could be further divided into more detailed product-states, and other product-states can be defined such as inspection-state, rework-state, etc. Table 5.1 describes the DLT with the assumption that the products flow to satisfy downstream orders that consist of multi products (i.e., order). The queue-state  $Q_t$  represents any waiting-states except the defined states in Table 5.1. For example, an order was completed 10 minutes ago and now is waiting to be moved internally by forklift or transported externally by a truck; the state here is considered to be  $Q_t$ . Another  $Q_t$  state occurs, if a new order quantity of a certain products arrives at a

loading zoon where the equipment is still loading a previous order, so it must wait its turn; the state here is not  $L_t$  but  $Q_t$ . The same applies if the products must wait for a machine/equipment that is being set-up or repaired; then it is  $WTSt$  or  $WTRt$  respectively. In an ideal scenario  $Q_t$  is not defined. Therefore, it is 100% NVA time.

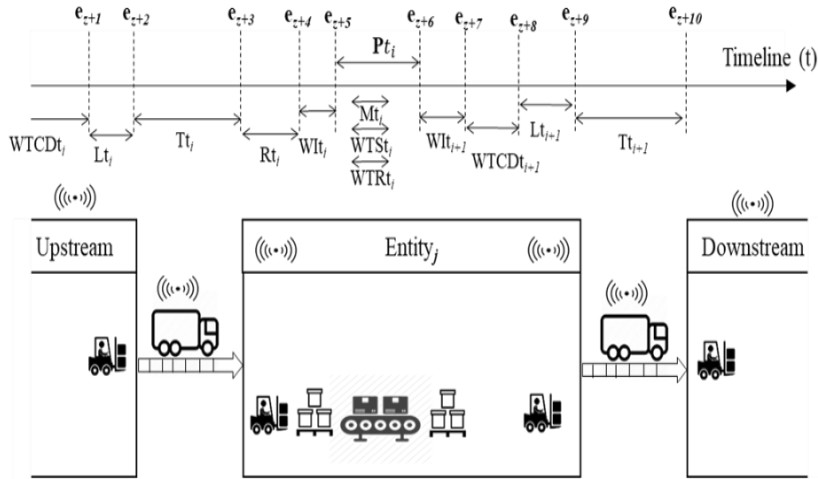


Figure 5.1: The Product-states at a Single SC Entity.

Table 5.1: The Product-states of the DLT at a Single SC Entity.

Product-state	State Description
Receiving-state <b>Rt</b>	The time in which products being received from the upstream entity and stacked in the received inventory place including unloading and inspection.
Processing-state <b>Pt</b>	The time in which product is actually being processed (e.g., transforming, assembly, picking, and packing, etc.) inside SC entity.
Moving -state <b>Mt</b>	The time in which product is being moved to the next workplace within a single entity.
Loading-state <b>Lt</b>	The time in which product is being loaded on transporting mode to be shipped to a downstream entity.
Transporting-state <b>Tt</b>	The time in which product is being transferred or shipped from upstream to a downstream entity.



Waiting-in- inventory- state <b>Wit</b>	The time in which product is suspended within or between upstream and downstream entities waiting as inventory.
Queuing-state <b>Qt</b>	The time in which product is suspended within or between upstream and downstream entities waiting to be processed or waiting for a resource, or waiting to be moved or shipped.
Waiting-to-Setup-state <b>WTSt</b>	The time which the product spends waiting for the completion of the machine or equipment setup. This could actually be less than the setup time if the setup is partially completed while the product is still being moved to the working-place.
Waiting-to-Repair-state <b>WTRt</b>	The time which the product spends waiting for a machine/equipment which is being repaired.
Waiting-to-consolidate deliver-state <b>WTCDt</b>	The time, which the product spends waiting to consolidate for either processing or shipping.
Waiting-to-Match-state <b>WTMt</b>	The time which the products spend awaiting the arrival of their sub-assemblies to be matched with them.

### 5.1.3 Estimating the Duration of DLT\_ Product-States

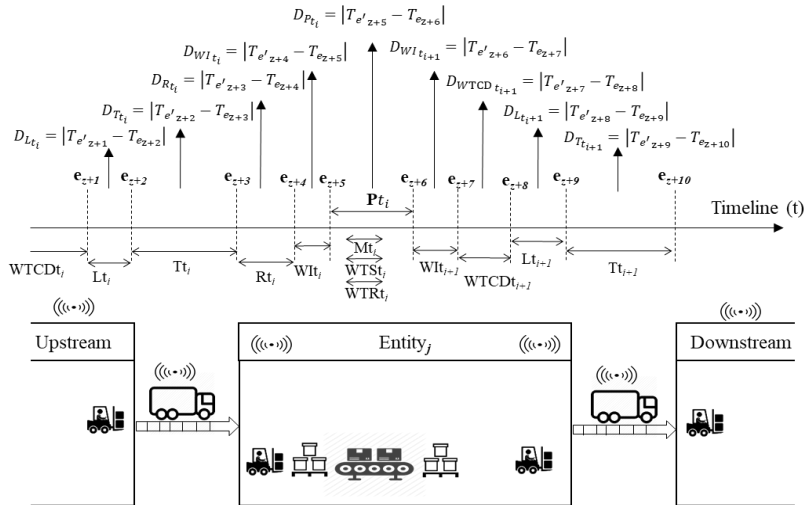
The duration of each product-state along the SC value stream can be estimated in real-time and mapped in the AVSM based on the CEP method using RFID, Time-operators, and IoT-operators. Figure 5.2 defines the method of real-time tracking and estimating the duration of each product-state. For instance, to track the DLT along a product value stream in real-time, there are ten event-instances ( $e_{z+x}$ ) that are representing the product/order flow through the SC core Entity<sub>j</sub> and upstream and downstream entities. The time interval between two homogeneous and successive flow-events represents a specific product-state. For example, the timestamp of the event-instances  $((e'_{z+2}, e_{z+3}) \in$

$E_{T_{t_i}}$ ) represents the start/end of the transporting-state ( $T_{t_i}$ ) from upstream entity to the core Entity<sub>j</sub>. The duration ( $D_{E_i}$ ) of ( $T_{t_i}$ ) can be estimated by taking the absolute value of the subtracted timestamp ( $T_{e_z}$ ) of ( $e'_{z+2}$ ) from ( $e_{z+3}$ ), this can be represented as follows:

$$D_{T_{t_i}} = |T_{e'_{z+2}} - T_{e_{z+3}}|; e'_{z+2}, e_{z+3} \in E_{T_{t_i}}.$$

The prime symbol (') in ( $e'_{z+2}$ ), is used for “event-start” to distinguish it from the “event-end” of the previous product-state, for example ( $e'_{z+1}$ ,  $e_{z+2} \in E_{L_{t_i}}$ ) and ( $e'_{z+2}$ ,  $e_{z+3} \in E_{T_{t_i}}$ ). The same procedure is applied to estimate the rest of the product-states throughout the entire product value stream, as follows:

- $D_{L_{t_i}} = |T_{e'_{z+1}} - T_{e_{z+2}}|; e'_{z+1}, e_{z+2} \in E_{L_{t_i}}.$
- $D_{R_{t_i}} = |T_{e'_{z+3}} - T_{e_{z+4}}|; e'_{z+3}, e_{z+4} \in E_{R_{t_i}}.$
- $D_{W_{L_{t_i}}} = |T_{e'_{z+4}} - T_{e_{z+5}}|; e'_{z+4}, e_{z+5} \in E_{W_{L_{t_i}}}.$
- $D_{P_{t_i}} = |T_{e'_{z+5}} - T_{e_{z+6}}|; e'_{z+5}, e_{z+6} \in E_{P_{t_i}}.$
- The same mechanism can be used until  $D_{L_{t_{i+1}}}$ .



**Figure 5.2: Estimating the DLT\_Product-States Using Event-Instances.**

The total DLT at the core Entity<sub>j</sub> starting from loading product/s from

upstream entity until delivering it to the downstream entity can be estimated directly through the following expression:

$$DLT_{Entity_j} = |T_{e'_{z+1}} - T_{e_{z+10}}|; e'_{z+1}, e_{z+10} \in E_{Flow\_Entity_j}.$$

Therefore, real-time tracking of the individual product-states provides an insightful understanding of the product flow and the critical product-states that the product passes through. For instance, the actual amount of time spent in the inventory-state for an individual product becomes easy to be estimated, allowing for an estimation of the time deviation between VVSM and AVSM. Now, since the associated inventory-state dataset ( $d_i$ ) which includes the key performance attributes are simultaneously recorded in the DSCPM-DB, the potential performance factors, or root causes that influence the amount of deviation can also be defined or measured. For example, if we assume a perishable product with a fixed shelf life (e.g. milk or yogurt), long deviation means more waste or outdating probability. Therefore, real-time decision-making is required to mitigate such problems. Moreover, other influencing factors and violations root causes on DLT can be investigated such as using wrong places for storage or applying wrong process parameters on the inventory-state (e.g. wrong storage temperature), strategies, dispatching rules, product specification, etc.

The DLT at the signal Entity<sub>j</sub> in Figure 5.2 is estimated by the sum of the product-state durations together, as Equation [5.1]:

$$DLT_{Entity_j} = D_{L_{t_i}} + D_{T_{t_i}} + D_{R_{t_i}} + D_{WI_{t_i}} + D_{P_{t_i}} + D_{WI_{t_{i+1}}} + D_{WTC_{t_{i+1}}} + D_{L_{t_{i+1}}} + D_{T_{t_{i+1}}} \quad [5.1]$$

The  $WTS_t$ ,  $WTR_t$ , and  $Q_t$  are considered when the product passes through them.

Subsequently, the total DLT over the entire SC value stream of specific product/order “x” is estimated through the summation of identical

product-state, as the Equation [5.2] below:

$$DLT_{AVSM_x} = \sum_{i=1}^n D^x_{Product\_state_i} \quad [5.2]$$

Where:  $AVSM_x$  is the product/order's actual value stream map,  $n$  is the number of states that the product/order passes through along its value stream path,  $i=1,2,3,\dots,n$ , and  $D^x_{Product\_state_i}$  is the duration of the identical product states.

This can generally be expressed to show all types of product-states in Table 5.1 for product/order “x” along the overall SC value stream as follows:

$$\begin{aligned} DLT_{AVSM_x} = & \sum_{l=1}^L D^x_{L_{t_l}} + \sum_{t=1}^T D^x_{T_{t_t}} + \sum_{n=1}^N D^x_{R_{t_n}} + \sum_{p=1}^P D^x_{P_{t_p}} + \\ & \sum_{m=1}^M D^x_{M_{t_m}} + \sum_{k=1}^K D^x_{W_{I_{t_k}}} + \sum_{q=1}^Q D^x_{Q_{t_q}} + \sum_{s=1}^S D^x_{WTS_{t_s}} + \\ & \sum_{r=1}^R D^x_{WTR_{t_r}} + \sum_{d=1}^D D^x_{WTCd_{t_d}} + \sum_{w=1}^W D^x_{WTM_{t_w}} \end{aligned} \quad [5.3]$$

Where:

$DLT_{AVSM_x}$  : Demand lead time for the actual value stream map of product/order “x”.

$D^x_{L_{t_l}}$  : Product/order “x” loading-states’ duration along the SC value stream and it is extended from  $l = 1,2,3 \dots L$ .

$D^x_{T_{t_t}}$  : Product/order “x” Transporting-states’ duration along the SC value stream and it is extended from  $t = 1,2,3 \dots T$ .

...

$D^x_{WTM_{t_w}}$  : Product/order “x” waiting-to-match-states-states’ duration along the SC value stream and it is extended from  $w = 1,2,3 \dots W$ .

#### 5.1.4 Real-time Performance Analysis and Monitoring

Now, each product-state become an active point in term of its timeline and execution place to be constantly monitored and tracked.

Therefore, if one of the product-states at a specific work-point frequently exceeds the VVSM designated time or if one of the designated conditions or parameters violated, then an investigation is to be conducted to determine the root cause of violation occurrences. That to define the amount of the effect in terms of time and accordingly enable real-time decision-making process. Such decisions can be made by human, or it can be automated using machine learning or deep learning algorithms, which is out of our research scope, and we leave it for future work.

Therefore, based on DLT, in-depth analysis regarding performance targets can be automatically conducted as well as enabling a statistical analysis. Through time quotients along the SC value stream, the ratio of VAT/NVAT product-state to total DLT can be estimated in real-time. This can be beneficial in the tactical and strategical decision-making and investigation of root causes that have been targeted for future improvements. According to Equation [5.3], the following ratios can be estimated:

$$\begin{aligned}
 - \text{ ProcessingState Ratio} &= \frac{\sum_{p=1}^P D^x P_{tp}}{DLT_{AVSM_x}} \\
 - \text{ TransportState Ratio} &= \frac{\sum_{t=1}^T D^x T_{tt}}{DLT_{AVSM_x}} \\
 - \text{ InventoryState Ratio} &= \frac{\sum_{k=1}^K D^x WI_{tk}}{DLT_{AVSM_x}} \\
 - Q_t \text{Ratio} &= \frac{\sum_{q=1}^Q D^x Q_{tq}}{MLT_{AVSM_x}}
 \end{aligned}$$

Other quotients such as the rework-state duration, waiting-to-repair-state duration and downtime-duration, and equipment-states (e.g., equipment utilization rate) can also be considered.

During the operational run, a general overview of the real-time performance in terms of the DLT can be continuously monitored

through data analysis tools such as the “control chart” to display up-to-the-minute deviations for example. These data can, of course, be used to immediately support archiving and support operational purposes (e.g., JIT-replenishment, smart real-time control, real-time cost tracking, and analysis, etc.).

#### **5.1.5 Real-time Smart Decision-making Analysis (RT-SDA)**

It is well-known that performance violations along the SC value stream cause a significant deviation between the actual DLT and the designated standard DLT. The time difference reflects the number of discrepancies between the virtual and actual status in terms of activities. To reduce time differences and enable decision-making, the performance violations related to process-state segments must be made immediately visible, so that they can be avoided or treated directly by timely decision-making. This section presents a tool called “Real-time Smart Decision-making Analysis” (RT-SDA). This tool was inspired by the cause-and-effect diagram to effectively determine the criticalities and weaknesses in each product-state along the SC value stream in order to achieve three related goals:

- 1- Detect the impact of the performance violations especially on the amount of the DLT (if applicable) and therefore exploring the amount of NVAT.
- 2- Enable real-time decision-making at the proper time and in the right place.
- 3- Enable continuous development process.

With RT-SDA, the root-causes of each performance violation event can be defined in terms of time and location along the SC value stream. Thus, this tool serves as a real-time explorer in systems riddled with hidden performance violations events to find inefficient processes and

their locations along the SC value stream. In other words, during the execution run, if the performance target or time consumed at a pre-defined product-state is more than the designated allowable duration in VVSM or if an undefined state has been detected in the AVSM, this will indicate that something is going wrong in the execution-level, and the potential causes of the deviation may include: non-value added activities being executed, more materials being consumed, or excess resources being wasted, etc. Therefore, an immediate decision-making or a further deep analysis is required. The RT-SDA module is equipped with suitable RT-PCRs to constantly estimate the time or performance deviation and investigate the potential causes. The algorithms presented in the next sub-section will be used to determine the causes and record the times of each activity (if applicable), which is essential in the building of the RT-SDA.

#### **5.1.6 The Working Mechanism of the RT-SDA**

This section discusses how RT-SDA could be configured to help the SC to identify and monitor the potential performance violations, which is inherent to the individual product-state along the SC value stream. This postulates that almost every performance violation root-cause is directly or indirectly related to time, which lengthens the actual DLT, such as, high-level inventory lead to lengthening the inventory-state and leads to more outdated or expired products, using the wrong equipment may lead to lengthening the processing-state or quality problems that need rework, etc.

As mentioned above, the idea of the developed RT-SDA is inspired by the cause and effect diagram. In this regard, Figure 5.3 represents the working mechanism of the RT-SDA as a graphical real-time performance violation explorer which detects firstly the amount of

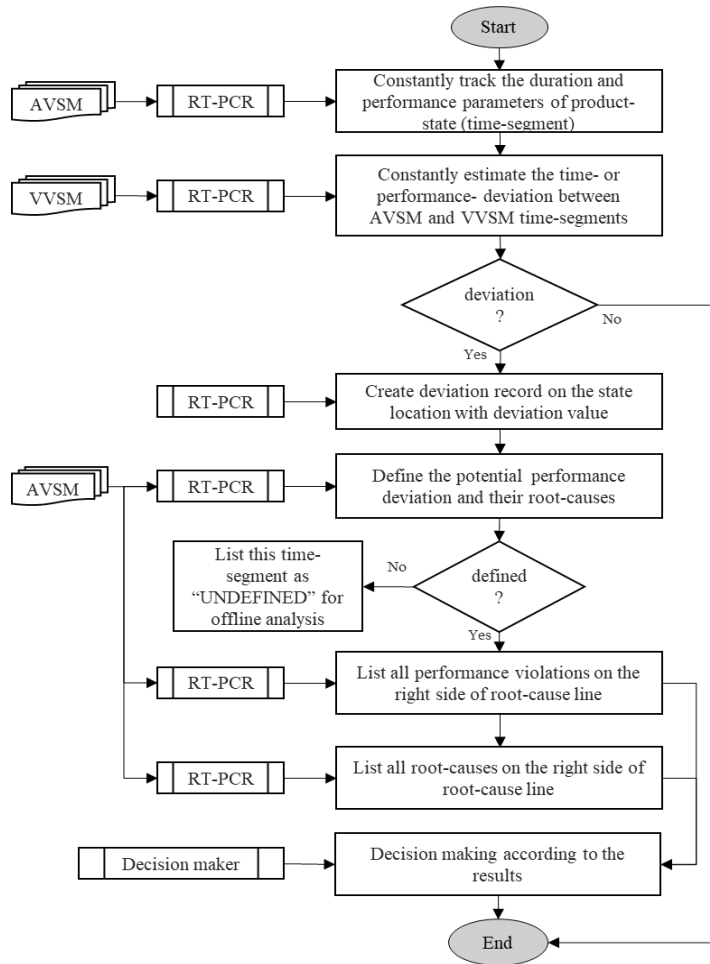
deviation (i.e. NVAT ratio) in terms of time or performance and location on the SC value stream timeline, this time can be listed on the record. With the help of using causality analysis, event correlation, and hierarchical relationships between event-instances in the RT-SDA\_RT-PCRs, the potential violations, and their root-causes can be identified. The deviation reasoning process takes knowledge from the event-data set and deduces main root-causes. According to the root-causes, the decision-making process will be enabled.

The initiation of RT-SDA starts with the constant estimation of the differences between standard and actual product-state data-set values. Once a deviation at any location is detected, the RT-SDA will trigger a root-cause analysis to uncover the causes that lead to this deviation. Accordingly, decision-making processes enabled to mitigate these causes. The following steps describe the working logic of the RT-SDA module to investigate and identify the root causes of time-based performance deviation and enable decision-making process, see Figure 5.3. The violations and its root causes can be graphically displayed as Figure 5.4:

1. The standard product-states (duration, performance limits, and location) along the value stream time-line should be predefined in VVSM.
2. RT-PCRs will be expressed in AVSM to keep track of the actual product-state and its duration and performance parameters along the SC value stream.
3. After each product-state, the time-deviation will be estimated, parameters data will be collected, and the value of the deviation will be entered in the “state-time deviation” record.

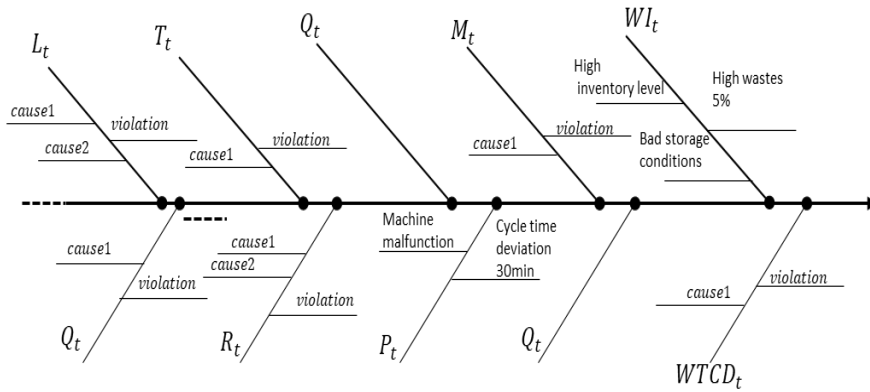


4. If an undefined product-state has been detected, a new record will be created automatically and the value of the deviation will be entered.
5. Next, the potential main performance deviation, which has resulted from time-deviation, parameter deviation, or undefined product-state, will be listed with the help of using the causality analysis and hierarchical relationships between event-instances in RT-SDA\_RT-PCRs. The potential deviation will be listed on the right side of the “Deviation root causes line”, while their root-causes will be listed on the left side on the same line. It may include some deviation as a root cause of other deviation (i.e. high inventory level causes inventory waste and thus longer demand lead-time as an inventory-state deviation).
6. Then, the time impact-ratio of each deviation on the DLT will be estimated (if applicable). If the root causes are not time-based, their impacts will be translated into time if possible.
7. The sum of the total time duration of all main deviations and their root causes should meet the time deviation for a specific product, i.e. this will be known by comparing the actual and standard DLT.
8. If a part of the deviation still has unknown causes, the RT-SDA will list it as undefined-time to re-investigate the product-state details and eventually assign the actual deviation root cause to this time or state.



**Figure 5.3: Working Logic of RT-SDA.**

9. The amount of time- and parameters- deviation reflects on the gap between the actual execution environment and a perfect, planned environment.
10. The root-causes will be a guide to the SCM practitioner (e.g., managers, operators, etc.), to decide on the decision which is most suitable to avoid or mitigate the deviation.



**Figure 5.4: Graphic Representation of the Detected Root-Causes.**

### 5.1.7 The RT-SDA\_RT-PCRs

As aforementioned, the RT-SDA module is equipped with suitable RT-PCRs. These smart real-time performance deviation detection rules will be constructed based on the CEP method and with the usage of Rule-Based Expert system concepts (IF-THEN) as well as Event Correlation logic. Therefore, the RT-PCRs should be able to extract the causal and hierarchical relationships between event-instances based on the event-data set (i.e., operational execution related-data). Thus, facilitating the real-time analysis of the interaction between smart-objects to identify the root-causes.

For effective RT-PCRs, the following prerequisites should be filled:

1. Define the product-states of individual products in the Real-time Rule Input Elements (RIE) as shown in Table 5.1.
2. Define the expected standard duration and performance limits at each product-state to be used in products VVSM.
3. Predefine the expected undesired performance violations and conditions along the SC value streams execution-level for each product-state.
4. Investigate the potential causes for each performance violation or condition and define them in the DSCPM\_RT-SDA module. For

example, if we assume a perishable product and the outdating wastes rapidly increases, the potential causes include:

- ➔ Inventory level is high (inventory system bad behavior mode)
  - ➔ Receiving wrong products from upstream entities (unsuitable product)
  - ➔ Late distribution (unsuitable distribution system)
  - ➔ Downstream demand problem (demand fluctuating)
5. Defining a real-time decision-making or correction that needs to be triggered as a part of the real-time controlling mechanism, (this is optional and required for automated decision-making systems).

For an effective functionality of RT-SDA, all potential root-causes according to the technical expertise and historical data should be pre-defined in the DSCPM-RT-SDA to be automatically identified through RT-SDA\_RT-PCRs diagnosing process. However, during operational runs, some situations are unclear. Therefore, since the workers are provided with the user-friendly interface, the PO is enabled to select the actual root-cause from the listed root-causes if they are not automatically identified by RT-PCRs for any reason, or typing in the actual root cause if it is not originally pre-defined in the DSCPM-RT-SDA. For the real-time investigation process, the RT-PCRs are fed knowledge and information about each product-state and the interaction between smart-objects from the events-date set as well as historical data from the DSCPM-DB. Therefore, the real-time tracking of events data in AVSM and traceability of the recorded data in DSCPM-DB significantly benefits the functionality of the RT-SDA.

In general, the IF-THEN heuristic rule serves as a performance violation or condition checking operation where the “IF” term represents the condition (i.e., a sequence of events), while the “THEN” term represents the appropriate action that will be taken or the outcome

of the condition at the “IF” part, when it has been detected to be true [127, 128]. In other words, if the current situation meets one of the “IF” conditions, the corresponding reaction part “THEN” will be triggered. The “time-deviation” is considered as an initial condition for further conditions checking actions to narrow down the possible root-causes, and then precisely pinpoint the right root-causes, this is described as follows:

**RT-PCR<sub>i</sub> = AVSM-D<sub>productstate</sub>**

---

```

01: ESTIMATE   $P\_D_X (e^i_{T_{t_i}}; e^{i+1}_{T_{t_i}}) \in E_{T_{t_i}}$ 
02: IF  $[D_X (e^i_{T_{t_i}}; e^{i+1}_{T_{t_i}})] > [V_{VSM-D_X}]$  THEN DO 03, ELSE, GO TO STEP 09
03:          CHECK  $[RT-PCR_{condition} \dots]$ 
04:          IF  $[RT-PCR_{i\_condition}]$  is matched with a predefined performance
                    violation type
05:          THEN
06:          CHECK  $[^iE_{defined} - \text{event-instances} \dots]$ 
07:          IF  $[^iE_x]$  is detected
08:          RETURN  $[^iE_x]$  as “root-cause”
09: END

```

---

**Line 01** checks if a product state time exceeds the waiting-time threshold in transportation product state ( $Tt_i$ ). In **line 02** if the time is exceeded, **line03** will check the conditions (i.e. event-instances) of each violation type through a predefined RT-PCR<sub>i\_condition</sub>. **Line04&05** will initiate RT-PCR<sub>i\_condition</sub> that its conditions have been matched to narrow down the root-causes being searched. **Line06** checks the related event-instances. **Line07&08** return the root-causes that lead to consume more time and violate the performance. **END**.

This above RT-PCR illustrates a simple expression to define the potential root-cause if a time-deviation is detected. The next section addresses a simple real-time decision-making analysis scenario.

### 5.1.8 Real-time Decision-Making Analysis Scenario

Suppose dealing with perishable product moving between distributor and retailer. The proposed initial condition of this scenario is:

at the retailer, the pattern of waiting in inventory-state of consecutive products is increasing and resulted in more wastes. (Plot the time and waste deviation in  $WIt$ -state). To identify the potential root-causes, further sub-conditions should be checked, such as check the remaining time before expired when arrival and inventory level in retailer.

- Control at receiving product

In the occurrence of “receiving finish” event at the retailer, if the remaining time before outdating start to decrease less than the designated limit (e.g., 6 days while the designated limit is 8 days), then the RT-PCR identify that the distributor sending wrong product or the limit should be readjusted.

- Control of inventory

If the inventory level at a retailer is increasing, the RT-PCR identify that the distributor sending more products than the limits, or the inventory system parameters become unmatched with the current demand patterns.

According to that, reactions or decisions should be made as such: adjusting the limits or the inventory system parameters. Applying a sail camping, or transferring some products to another high demand sales spots, etc. In addition, this implies there is a potential for more development in the supply chain current practices. A basic algorithm to be used in the detection of events that cause longer waiting in inventory and outdating wastes shall be presented as follows:

**Definitions:**

$D_{WIt}$	=	Duration of waiting for state at retailer
$UCL_{VVSM}$	=	Upper control limit
$LCL_{VVSM}$	=	Lower control limit
$\rightarrow \notin$	=	Goes to be not an element of $[x:y]$
$I_L_{retailer}$	=	Inventory level at retailer

$\uparrow/\downarrow$ =	Values in Increasing /Decreasing
$T_{VVSM}$ =	Time in VVSM
$T_{AVSM}$ =	Time in AVSM
$Rem\_T$ =	Remaining time before outdating
$Rem\_T_{retailer\_Rt}$ =	Remaining time before outdating at receiving event

#### **RT-PCR<sub>t</sub>=Retailer- WI<sub>t</sub>**

---

```

01:    IF (Plot [ $D_{WI}$ ] at Retailer  $\uparrow$  AND  $\rightarrow \notin WI$  [ $UCL_{VVSM} : LCL_{VVSM}$ ]) OR Plot (outdate-products) at retailer  $\uparrow$  AND  $\rightarrow \notin WI$  [ $UCL_{VVSM} : LCL_{VVSM}$ ] THEN
02:          CHECK [RT-PCR =  $Rem\_T_{Retailer}$ ];
03:          CHECK [RT-PCR=  $Q_L$ , Retailer];
05:    IF ( $Rem\_T_{retailer\_Rt} \downarrow < LCL_{VVSM} = 8$ )
06:          THEN retailer is in (Receiving products with law
                                      $Rem\_T$ )
07:          RETURN (Distribute or sending wrong products) =
                                     root-cause1
08:          REPORT (correction or decision should be made)
09:    IF ( $[I_L\_retailer]_{AVSM} \uparrow > [I_L\_retailer]_{VVSM}$ )
10:          THEN retailer in = (high level inventory)
11:          RETURN (problem in inventory system or new
                                     demand pattern) = root-cause2
12:          REPORT (correction or decision should be made)
13:          CHECK [ $T = Rem\_T_{Retailer}$ ];
14:          If ((products quantity with  $Rem\_T \downarrow <$ 
                                      $LCL_{VVSM} = 8$ )  $\uparrow > LCL_{VVSM}$  (e.g. 500 pcs))
15:          RETURN (potential outdating)
16:          REPORT (correction or decision
                                     should be made)

```

## **17: END**

**Line01** checks if the deviation is in increasing mode, which goes out of control. **Lines02-03** check the initiation condition of two rules. **Lines 05,06** check the remaining time for outdating at receiving–state finish, **Line 06-08** return its root-cause and then sends a report. **Lines 09-12** check the quantity of inventory level at the retailer and return the potential root-causes. **Line 13, 16** checks if the available products remaining time before outdating ranges between the control limits without a risk of high outdating and reporting if there is a potential outdating to enhance making an immediate decision. **END**.

Notice that, if the actual values are within the range of the upper and lower control limit (i.e., UCL and LCL respectively) values, the system will accept this deviation as normal and allow for further processing. The gap between UCL and LCR should be narrowed through further improvements such as the elimination of variability causes. The discussed scenario shows how RFID captured real-time data can be analyzed by RT-SDA to detect the suspicious behavior of some SC objects (e.g., product, machine, labor, etc.) and notify the managers or operators to make real-time decisions to fix the problems in advance during the operational run.

### **5.1.9 Part1 Conclusion**

The objectives of this real-time analysis on the DLT are to provide up-to-the-minute reports of the actual SC operation-level performance including:

- Identify where the value is being added in terms of times.
- Identify the deviations in terms of time and other performance parameters with the standard allowable values.
- The amount of deviation in terms of time can be quantified; the influences of the NVA activities that are applied during the



DLT can be identified and prevented through future improvement efforts.

- Improve the process understanding.

As a result of the analysis of the DLT of individual products through the DSCPM with the help of the RT-SDA, the estimation and design of the DLT of processes will become more accurate, especially for the sensitive or new customized products on the market in recent times, as well as, more accurate operation plans (e.g., accurate delivery date for customers, accurate resource planning, etc.) will be made available. Besides that, the usage of the RT-SDA will allow companies to identify the causes of performance deviations and wastes in their supply, production, and distribution lines effectively and make timely decisions to improve their performances leading to lower costs. Further analysis is to be carried out on these causes, to eliminate them and to improve as well as to optimize the material flows, so as to cut down on lead-time and enhance the productivity and efficiency.

## **PART2**

### **5.2 DSCPM-enabled Real-time SC Costs Tracking System**

While SCs are striving to be efficient, they need to have a real-time assessment tool that aims to measure the monetary impacts of implementing SCM initiatives and practices to bridge the gap between the operational and financial views in one pool, and thereby demonstrating and approving the resulted improvements with higher degrees of confidence. The traditional costing systems are designed to support product-oriented mass production systems that do not differentiate between direct and indirect costs. These traditional cost accounting systems are valid for long production runs of a standard product, with unchanging characteristics and specifications. This is not possible in today's high customization systems [129]. For instance, using the traditional costing systems in SCs, the costs of labor, material, and overhead including ordering, holding, and shortage costs cannot be precisely incurred into the products or orders. As a result, the actual manufacturing costs are not accurately reflected [130].

Moreover, the traditional costing systems do not concern themselves much with differentiating between value-added and nonvalue-added activities [131]. Therefore, Using average costing techniques to calculate the individual product cost in today's mass-customization production and dynamic environments is unfeasible because it may mislead the manufacturers and cause them to make wrong decisions relating to operational issues, pricing, profitability, make/buy, and so forth [132]. Moreover, some products consume more time and resources and thus more costly than others in the SC value stream, so it is important to define the parameters that cause extra costs

[19]. In addition, traditional accounting systems which are based on the monthly accounting period in a real-time are not useful for quick decisions and process control purposes from financial perspectives, since the reports come out too late and do not represent the monetary impacts of the current process-related decisions [130].

According to SCPM literature, some companies tried other accounting systems such as Activity-based Costing (ABC) or lean accounting, which are oriented to solving the problem of overhead allocation [46, 133]. However, it is found that an ABC system cannot be adopted because it is too complicated to collect information, as well as to monitor the changes in activities [46, 134]. Due to limitations and problems of traditional costing systems and ABC, other alternatives have been developed. For instance, a limited scope by lean manufacturing accounting was developed based on VSM, where all cost allocations become direct along the value stream [135]. Another work have discussed the integration methodology of costing systems with lean manufacturing [136]. This integration starts with the lean tool VSM which lacks any economic measures for “value” like profit, throughput, operating costs, and inventory expenses [137]. However according to Ruiz et al. [136] and Stickler [131], these proposed costing techniques developed based on VSM principles are still not mature enough to be brought into reality; that because the major portion of product-flow in lean manufacturing is not trackable, their cost will be not traceable, and thus uncontrollable.

Recently, with the availability of mature process-oriented SC modeling frameworks such as SCOR model, which can be used to span SCs from supplier’s supplier to customer’s customer aligned with operational strategy, material, work and information flow [78]. And after IoT insertion in industry, it is become possible to develop and

enable a real-time SC cost tracking technique using, for example, RFID and supported sensor system [102]. It is clear that almost no study tries to tie the product cost accumulation along the SC value stream and the timing together in real-time to mirror the costs and the impact of SCM practices at each stage of product life along the SC value stream. This part of the research presents a real-time SC cost tracking framework. The framework is an extension of Ramadan et al. [19] work, which is limited by tracking only manufacturing costs incurred within the shop floor boundaries. Instead, this costing framework can track the development or accumulation of actual product costs during the flow of product along a SC value stream starting from sourcing the original raw materials (i.e., natural resources) to the last step of delivering the final product to the final customer hands. It can be used to develop real-time cost-tracking tools. This tool can further analyze the incurred costs with respect to the utilized resources and consumed material to recognize the most critical and costly work-stages. In other words, tracking and viewing the details of process and activity costs including all resources consumed in each moment and in every step.

### **5.2.1 Conceptual Framework of RT-SCCT in DSCPM**

This part of the research outlines a new practical product costing approach called “Real-time SC costs tracking module” (RT-SCCT). This module is considered as a new generation of costing techniques that can span to cover the overall supply chain stages and members based on a cooperative and collaborative SC environment. RT-SCCT module is proposed to run through DSCPM to enable the SC members to monitor the gradual real-time development of the products’ associated operations costs during flow along their SC value stream as well as monitoring the operations’ performance in terms of cost.

Operations costs in this thesis mean “the manufacturing and operational costs including all direct and indirect costs that occur along the SC value stream and should be considered when deciding the final product cost”. The target of RT-SCCT is only to track the operations costs which belong, according to SCOR model, to Level 3 detailed operations includes all steps that are performed in a certain sequence to plan SC activities, source materials, make products, deliver goods and services, and handle product returns. According to Groover and Miell [138], operations costs which occurred inside a single supply chain member can be broken down to direct labor, plant, equipment and machinery depreciation and energy, indirect labor, and parts and materials. Any other expenses are estimated separately (e.g., engineering, research and development, administrative .etc.).

The RT-SCCT module is designed to estimate the actual operations costs synchronously while the operations are being executed, and to highlight the costly processes and activities to enable continuous development process. Another potential benefit of this module is its ability to estimate the costs of VA and NVA activities, and distinguish between them and analyses the impact of NVA activities on the other parts of the SC systems components and decisions (e.g. which inventory system or policy to use) as long as on the final prices of the products. RT-SCCT module can be defined as a real-time SC cost tracking method that estimates the cost of the sourcing, making, delivering, and returning activities being executed and the material being consumed simultaneously with the flow of the corresponding object. After that, the RT-SCCT reports the cost information with deep cost details to the relevant users on the real-time operational run under regular conditions. The target of this work goes beyond “How much does the product cost?” to include the ability to investigate and analyze

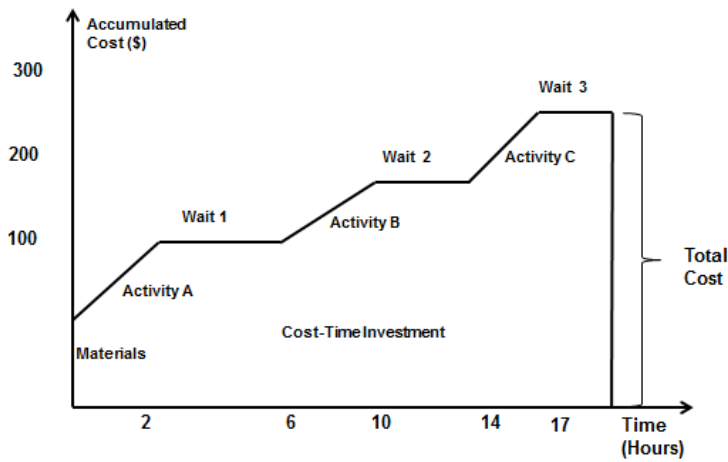
the impact of each stage along the SC value stream on the total product cost, as well as define the impact of each NVA activity on the final product cost and to support better timely decision-making processes.

### **5.2.2 Real-time Supply Chain Cost-time Profile (RT-SCCTP)**

Using SCOR model business processes , it is possible to map the SC processes along the SC value stream with the corresponding resource usage, with respect to time and locations, as shown in Chapter 3. However, that could not alone resolve the concerns regarding costs or monetary aspects. In response to this gap, and to translate the timing in SC workflow into cost, we propose to integrate a customized version of Cost-Time Profile (CTP) tool in RT-SCCT module to display costs accumulation with respect to time simultaneously. This version represents an expanded CTP to cover the overall supply chain processes along the extended SC value stream including all SC members and resources.

CTP is a powerful tool developed to view the cost accumulation of production activities over the time across the entire value stream of the manufacturing flow. It was developed by Westinghouse Electric Corporation as a diagnostic technique to visualize any process. CTP helps identify opportunities that reduce cycle-times and costs; it is also applied to waste management. CTP analysis helps identify actions to improve productivity and quality [19]. Figure 5.5 gives a simple illustration of a CTP. The diagonal lines represent the costs of activities. The gradient of each line depends on the activity cost-rate which is derived from how many resources this activity consumes over its time duration. The consumed materials are represented in the CTP as vertical lines. The CTP only focuses on “direct” costs rather than overhead (indirect) costs. The costs that are incurred during a waiting-state

probably fall under the category of overhead costs [19].

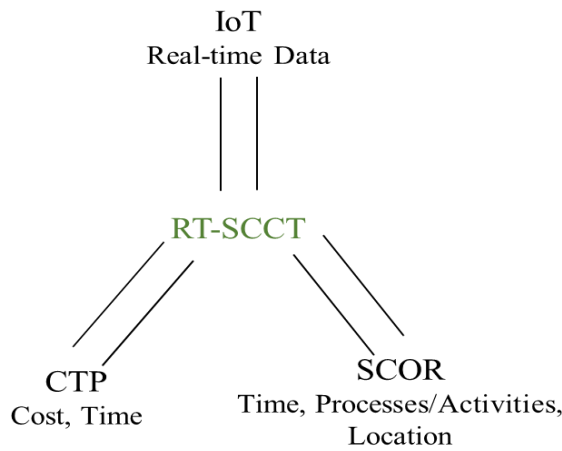


**Figure 5.1: Cost-Time Profile Components [139].**

However, in real-time, the construction of CTP during operational execution run needs a clear methodology for estimating the activities timing and duration. In addition, CTP visualizes the costs without any details. The costs should be effectively broken down to a suitable level of detail. Furthermore, the waiting time is considered to have no effects on the accumulated cost (horizontal line). In SCM context, this is not correct, especially when we talk about SC activities which may include a lot of waiting times. For instance, the products waiting times incur additional and important costs to be highlighted and measured due to holding costs and space utilization besides other aspects like lengthening the time of the investment on the product before recovering its cost through sales. Historically and according to many literatures, these costs are very hard to be monitored due to the lake of proper and accurate data [76, 140].

Accordingly, for real-time SC cost tracking, this work integrates the features of three tools together. Firstly, the cost-time profile concerns with the accumulation of costs simultaneously with time, but without operations aspects. Secondly, SCOR model to map the SC value stream

or workflow focuses on the aspects of the operations with respect to time, but it does not track the accumulation of product costs during the product flow from upstream to downstream. Thirdly, IoT or RFID deals with tracking the flow of products with respect to time and locations to estimate the duration of each product-state and define the applied activities alongside their corresponding consumed resources. The integration of the three tools is represented through RT-SCCT module in DSCPM as shown in Figure 5.6.



**Figure 5.6: Integration of SCOR, IoT, and CTP in RT-SCCT.**

### **5.2.3 Real-time SC Costing Method**

Designing a costing system must take into consideration the nature of production and market environments. In this matter, the increasing product customization in global markets is forcing the SCs to adopt mass customization production environment. This means that each customized product with special requirements and specifications required by customers has a different SC value stream with different resource requirements, material types, components or sub-assemblies, work-instructions, inventory conditions, supplying and distribution channels, etc. This implies that the cost of an individual product and the associated services will vary according to the product's requirements.



Because of this, it becomes necessary to estimate the cost of each product separately and find out the impact of operational performance on its manufacturing cost. In SC applications, it is also common to deal with orders, which consists of a quantity of one product type or different products types. Therefore, the developed framework assume dealing with individual product going through the supply chain as it is possible and easy to integrate all of the calculation to the order or product group level.

The total costs of an actualized  $VVSM_x$  includes all events costs (e.g., material consumption events, machining events, labor events, shipping events, etc.) which are classified according to their characteristics into time-driven operations costs and material-usage driven costs as shown in Equation [5.4]. Now, the cost of individual AVSM is estimated by adding up the cost of the consumed materials at specific points and the time-driven costs, which are incurred continuously, from the moment of releasing  $VVSM$  of products or WIPs until the product is delivered to its final destination or went out of the system.

$$C_{AVSM_x} = \underbrace{\left[ \sum_{i=1}^n D^x_{Product\_state_i} \times TCostRate^x_i \right]}_{T_{tc}} + \underbrace{\left[ \sum_{j=1}^m M^x_{L_j} \times C_{BOM^x_j} \right]}_{T_{mc}} \quad [5.4]$$

- $C_{AVSM_x}$  : Cost of  $AVSM_x$  for product “x” along the overall SC value stream.
- $T_{tc}$ : Time-driven operations costs based on product-states’ duration.
- $D^x_{Product\_state_i}$ : The duration of product-state “i” for product “x”.
- $TCostRate^x_i$  The total cost-rate for  $D^x_{Product\_state_i}$
- $T_{mc}$ : Material usage-driven costs.

- $M_{L_j}^x$ : The consumed material, which is mounted directly with the product “x” at specific location along the SC value stream.
- $C_{BOM_j}^x$ : The cost of the material/components as defined in the bill of material (BOM) for product “x” in VVSM.

The time-based cost-segments extend from  $i=1, 2, 3, \dots, n$ , and material consumption’s occurrence accumulated from  $j=1, 2, 3, \dots, m$ , where  $m$  is the number of material accumulation occurrence along the SC value stream.

The Total cost-rate of each product-state “i” is composed of several cost-drivers where each cost-driver has its unique predefined cost-rate. This is summarized in Equation [5.5]:

$$TCostRate_i = \sum_{y=1}^Y CostDriver_y * ICostRate_y \quad [5.5]$$

Where:

- $TCostRate_i$ : The unique cost-rate of a specific product-state “i”.
- $CostDriver_y$ : The consumed resources “y” (i.e. cost driver) in term of time during a product-state.
- $ICostRate_y$ : The individual cost-rate of each consumed resource “y” (in term of cost/unit time).

The cost-drivers exist in each product-state extending from  $y=1, 2, 3, \dots, Y$ , where  $Y$  is the number of cost drivers participate in product state “i”.

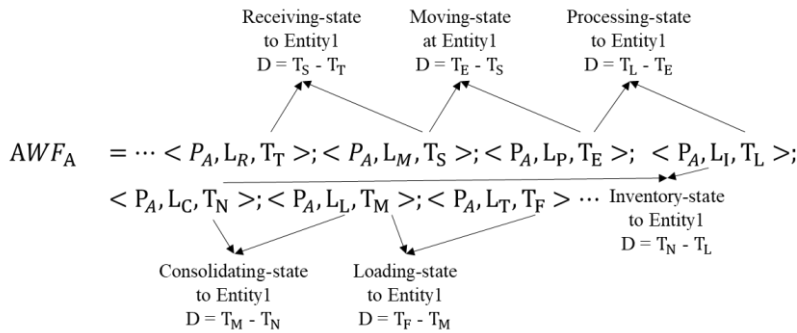
To add the cost-drivers related cost-rate to the total cost, the cost-drivers being consumed during a specific product-state must be defined in real-time through IoT real-time remote location constructors, which is defined in Chapter 4. The next sections present the product-states along the SC value stream in terms of time and their relevant cost-drivers to estimate the cost-rate of each state. This cost will be incurred

on the total cost pool once a product passes through this state in real-time.

#### 5.2.4 Time-driven SC Operations Costs

The operations costs of any product are primarily dependent upon how quickly it flows through the SC value stream [130]. Which means that the products that require more time to be processed consume more cost. During the workflow progress, the products or WIPs pass through different work-stages in different SC members where different product-states exist and continuously change; each state has a different time-duration, operational parameters, and cost-drivers, which means that each product-state has a unique cost-rate.

In this context, as discussed in part 1 of this chapter, the duration of each product-state is based on the captured events timestamps through the event-data vector of AVSM as shown in Figure 5.7. The cost of each product-state depends on the duration and the cost-drivers being consumed. The duration can be estimated, as well as the consumed resources (i.e., cost-drivers) can be detected in real-time using the RT-CEP method.



**Figure 5.2: Product-state Durations Based on Event-data Vector Paths.**

Each product-state represents a time-component of the DLT. Therefore, the cost at one SC entity is the sum of the costs of product-

stats at this entity as shown in Equation [5.6]:

$$Entity_c = R_c + M_c + P_c + WI_c + WTCD_c + L_c + Q_c + etc... [5.6]$$

Where:

Entity<sub>c</sub> : cost at one SC entity (e.g., distributor), R<sub>c</sub> : Receiving cost. M<sub>c</sub> : Moving cost, P<sub>c</sub>: Processing cost, WI<sub>c</sub> : Inventory cost. WTCD<sub>c</sub> : waiting to consolidate delivery cost, L<sub>c</sub>: Loading cost, Q<sub>c</sub>: Queuing time cost, other state-costs are possible.

Similarly, the time-based total SC operations cost (T<sub>tc</sub>) of the entire AVSM is the summation of product-states' cost (i.e., cost of DLT components) along the all SC entities' value streams which include all working stages and any other states between them, such as the waiting in ports-state cost if it is an international SC and the transport cost, etc. This is illustrated in Equation [5.7]:

$$T_{tc} = \sum_{e=1}^n (R_c + M_c + P_c + WI_c + WTCD_c + L_c + Q_c + etc.)_e + \sum_{j=1}^t (Other - states_c)_j [5.7]$$

Where:

e=1, 2, 3.... n is the number of SC entities, and j=1, 2, 3.... t is the number of other states along the product value stream outside entities, for example, product states at ports or airports when products shipped through such outlets.

For accurate and effective real-time cost tracking, the individual costs per time-unit of cost-drivers such as labor and resources must be known and predefined depending on the type of SC, and its members' manufacturing and other operational systems. This is discussed in the next sub-section.

#### **5.2.4.1 Estimating the Cost-rate of Product-states**

Using the traditional costing techniques to allocate the operations costs to products based on volume-related drivers distorts the product cost [136]. In the DSCPM, the real-time tracking of the individual products flow during the operational run enable the manufacturers to determine the exact information needed for the RT-SCCT module like labor, machines, tools, equipment, space, etc. being used by each product AVSM. In other words, any used resources in any product-state for any specific product can be detected from IoT real-time location constructors and considered as a cost-driver in the real-time cost estimation. From this information, the cost of each product-state can be estimated, and therefore the total SC value stream costs can be calculated.

The first step towards real-time SC cost tracking is to convert the costs of resources being consumed (cost-drivers) through the released VVSMs into direct costs and estimate their individual cost-rate. This will be useful to identify the violation of costs as long as the cost of wastes, which are mainly hidden within overhead and indirect costs. The indirect or overhead costs are converted and incurred as direct costs. Therefore, there is no distinction between direct and indirect costs. All costs that contribute to any operation along the product flow through the SC are considered and incurred as direct costs in terms of \$/time-unit. For example, convert the machine/equipment/facilities depreciation, power, or spaces cost into direct cost by estimate its cost-rate per minute or second to be incurred in real-time as a direct cost into product cost simultaneously with product processing-state.

The individual cost-rates of the resources being consumed (cost-drivers) through AVSMs include labor costs, machine costs, tools costs, equipment costs, facilities-costs, and other costs. Some examples which

illustrate “how to estimate the cost per time-unit” are discussed below.

- Labor cost-rate ( $Dl_c + IDl_c$ ): It is the amount of money that labor costs per unit-time (e.g. minute, or second) which is based on the payroll. The labor cost-rate will be directly incurred on the tracked product cost pool without distinction between who was assigned directly to work in the value stream or indirectly (i.e. partially or shared like logistic operators who serve several workstations) to support it. For instance, the cost of the direct labor cost-rate ( $Dl_c$ ) is estimated according to the individual labor cost per shift (e.g. 100\$ per daily shift = 8 hours with one hours break = 7 hours.) This means that the  $Dl_c = 23.8$  ct/minute. the indirect labor cost ( $IDl_c$ ) can be estimated similarly.
- Machine/equipment cost-rate: This cost-rate includes all machine/equipment-related costs like depreciation-cost, maintenance-cost that include spare parts and repair costs, energy/fuel consumption cost, and others. For example, the depreciation cost  $De_c$  depends on the consumption ratio of a machine/equipment and its initial purchased price as well as the salvage value. The calculation of the depreciation cost-rate is presented in Equation [5.8]:

$$De_c = \frac{\text{Price of eqiupmet} - \text{salvage value}}{\text{Life span in TimeUnit (e.g.minute)}} \quad [5.8]$$

For instance, if the cost of a shipping truck is 15000 \$ and its average lifespan is 20000 working hours where the salvage value is 1500 \$. The depreciation cost-rate which should be allocated to the product without looking at the economic factors is equal to 0.675 ct/minute. To accurately estimate the shipping-state duration using the truck, it is proposed to use the truck real-time data beside IoT-event data. To estimate the truck cost-rate, it is important to use

some truck related data such as initial price, expected lifespan in minutes, fuel consumption rate, maintenance data, etc.

- Facility/space cost-rate: This cost consists of the all facility-relevant costs such as depreciation, repairs, and maintenance, rent or interest expense if owned. Facility cost-rate is incurred in products of a SC value stream based on the space used by it with respect to time. To do that, Baggaley [132] divided all facility costs by the total square footage of the facility to get the cost-rate per square foot. To incur this cost on individual products, the time spent by a product at a specific space is multiplied by the facility cost-rate.

After defining and determining the individual cost-rate of the cost-driver, the next step is to determine which cost-drivers are consumed during each product-state; this is known from the event-data set as mentioned above. For example, the cost of the receiving-state at an Entity<sub>i</sub> ( $R_{c-Entity_i}$ ) equals to 1 \$/minute. This cost is composed of several cost-drivers' cost-rate such as direct and indirect labor cost ( $DI_c + IDI_c$ ), energy cost ( $E_c$ ), equipment cost ( $E_c$ ), depreciation cost ( $De_c$ ), etc. The receiving-state cost-rate is presented in Equation [5.9]:

$$R_{c-Entity_i} = DI_c + IDI_c + E_c + E_c + De_c + \text{etc.} \quad [5.9]$$

Note that the indirect labor cost-rate is incurred in percentage which represents the cost of the actual labor time directed to this workstation as discussed below. In some special cases, we have to incur the individual cost-rate of each cost-driver separately if not all of them are consumed equally along the product-state time. Thus, during the execution run, the RT-SCCT displays on the RT-CTP how much money product "X" costs so far.

Since specific resources (e.g., material handling equipment, logistic labors, etc.) may be shared among different product activities, the shared resources' cost-rate is allocated on the value stream cost pool of

a product according to the actual benefit being received by this resource. For example, if a logistic operator cost-rate is 20 ct/minute, and he works on different activities using a forklift, there are many ways to incur his cost-rate directly on the product; one of these methods is to include his cost-rate in the total transport cost-rate to be incurred on the activities for each product equally.

The same fashion is also applied to convert, for example, the conventional manufacturing overhead costs pertained to the manufacturing operations (e.g., Material handlers, set up operators, maintenance operators, repair parts, inspectors, etc.) into direct cost-rates to be allocated in real-time to each product value stream cost pool. It is clear that to develop the exact cost-rate for each cost-driver, the technical experience and detailed process-cost studies and creativity must be employed.

Finally, it important to note that the cost-drivers vary from business to business. Thus the nature of the SC and its entities operations environment determines which methodology should be followed to track each cost-driver along the SC value stream. The pre-determined individual cost-rates of the cost-drivers must be re-estimated and adjusted from time to time to consider any changes corresponding to the operations parameter and conditions or functions. In material usage-driven operations costs, the costs of consumed materials along the value stream are similarly incurred on individual products as shown in the next section.

### **5.2.5 Material Usage-driven Manufacturing Costs**

The second main cost-driver beside time-driven costs is the material consumption along the SC value stream. The product value stream of material costs is calculated based on the direct and indirect material



consumed by the product along the SC value stream. The real-time SC cost tracking process starts with incurring the cost of the direct material used at the first stage. After that and during the workflow, material-cost is incurred once a material (e.g., component or sub-assembly) is added to the product until the final production stage. Therefore, the cost of the used material is presented as vertical line segments in the RT-CTP. In this case, the used materials are divided into direct and indirect materials. Direct materials are tangible items used over the SC value stream including individual products or components and sub-assemblies; whereas, the indirect materials are the consumable materials used during manufacturing operations that do not become an integral part of the product (i.e., baking material, lubricant, etc.). However, both direct and indirect materials will be converted into the direct cost. Accordingly, the material cost which is incurred on individual products over the SC value stream processes  $T_{mc}$  is defined as:

$$T_{mc} = \sum_{j=1}^m [MP_j + DM_j + IM_j] * C_{BOM_j} \quad [5.10]$$

Where:

$T_{mc}$ : Material usage-driven costs accumulated along the overall SC value stream, “m” represents the material accumulation’s occurrence times where  $j = 1, 2, 3, \dots, m$ .

$MP_j$ : The main product or raw material used at the first stage in the product SC value stream.

$DM_j$ : The components and sub-assemblies usage over the product SC value stream.

$IM_j$ : The indirect material used in activities.

$C_{BOM_j}$ : The cost of the material/components as defined in the bill of

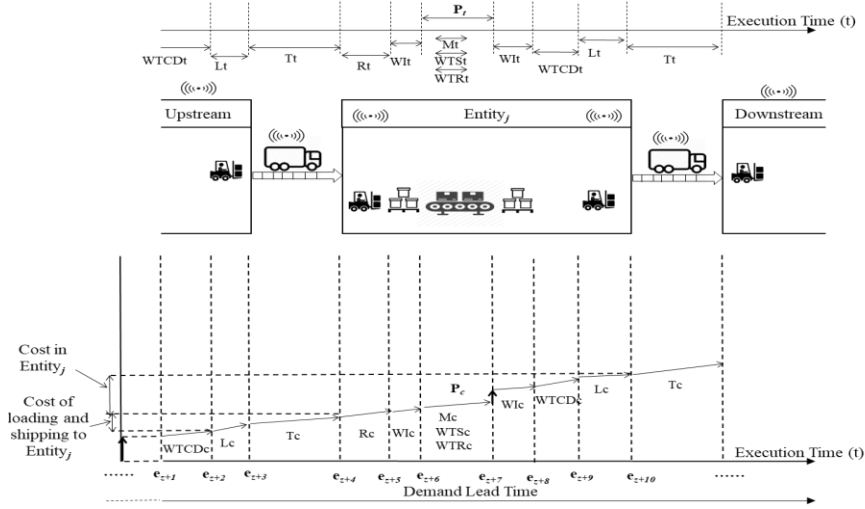
material (BOM) in VVSM.

Normally (IM) is shared through several products. Therefore, its cost is allocated to individual products according to the worth-ratio absorbed through each product. Technical experience and historical data help to define its cost-rate. For an effective, accurate and easier real-time costing method, it is proposed to incur the material cost in addition to the cost of the activities applied to it so far (e.g., replenishment cost, holding cost, transporting cost, etc.). In this case, the cost of the components and sub-assemblies will be updated on a relevant database in DSCPM (or on their RFID-tag if it is an active tag) after each state; this cost will be incurred on the semi-finished or finished product's cost once it is mounted with it.

#### **5.2.6 Working Logic of RT-SCCT in DSCPM and the RT-CTP Construction.**

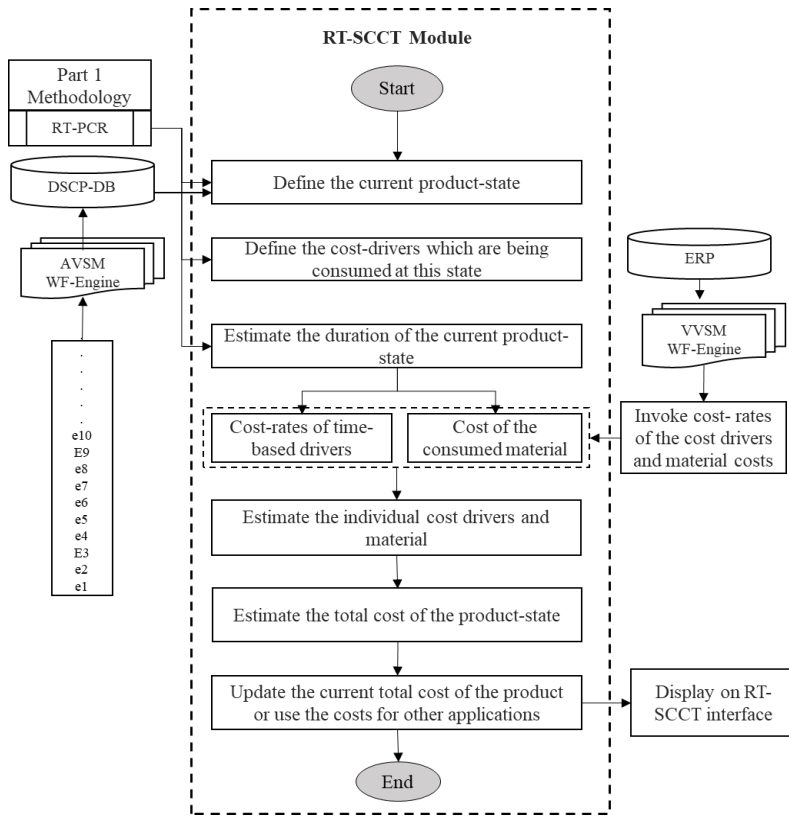
This section discusses the working principles of real-time allocation of the costs to individual products going along the SC value stream based on time-unit (i.e., second, minute) and material usage rate. The real-time information of process progress is one of the important key functional factors of RT-SCCT. While the activities are executed and the products pass through their value stream on the execution-level, the resources and materials are being consumed where the cost is growing. Meanwhile, IoT tracks all operations and activities on execution level and maps their information to the DSCPM using RT-CEP system, and then the cost-relevant information is mapped to the corresponding real-time costing rules in RT-SCCT module. RT-SCCT recognizes the current product-state during the flow and simultaneously incurs the pre-determined product-state's cost-rate into product value stream cost pool to estimate the total cost of the entire SC value stream of each product.

The time and material usage-driven costs, which contribute to the gradual cost development during the flow of products along the SC single entity value stream, are shown in Figure 5.8. It is seen that the time-driven costs are represented in the CTP as line segments with a positive slope while materials are presented in the CTP as vertical line segments.



**Figure 5.8: Real-time Product Cost-time Development.**

As product value stream consists of sub-streams in the overall SC, then the costs of these sub-streams (i.e., individual SC entity value stream) are estimated identically to that in the above-mentioned single entity value stream. The costs belonging to these sub-streams must be incurred on the product cost pool. Figure 5.9 describes the working logic of the real-time SC cost tracking module in the DSCPM and how the cost-time development in Figure 5.8 can be constructed as we described in the previous sections.



**Figure 5.9: The Working Logic Flow of the RT-SCCT Module in DSCPM.**

### 5.2.7 Part 2 Conclusion

As today's global markets force the SCs to work in a high customization production environment, the cost tracking of the individual product becomes a very important key element of SC performance measurements. This part has discussed the concept of the real-time SC cost tracking system. The framework addressed how the IoT data is used to track the cost development of individual products in real-time during the progress of the workflow along the SC.

As a result, RT-SCCT adds a new powerful feature to the DSCPM by bridging the operational and financial views in one pool. The potential benefits of this module are listed below:

- It Monitors the costs of individual processes/product and the entire activities included in the value stream as well as identifying and distinguishing between the VA and NVA costs.
- It transforms (as much as possible) the product indirect costs into direct costs.
- It helps in better estimating what was hard to estimate (carrying costs, ordering costs, shortage costs, etc.).
- It enhances daily operational decisions depending on the cost-benefit analysis.
- It monitors the financial consequences due to any necessary adjustments or changes in the execution-level either technical or operational.
- It determines labor costs, which are hidden in the overhead costs.
- It Identifies the most costly activities as well as the most wasteful NVA activities, which are targeted by the highest priority to be corrected or eliminated.
- It gives the opportunity to realize the power of time and its impact on the total cost.
- For strategic and competitive goals, RT-SCCT helps the companies to precisely split the product total cost in terms of individual operations, processes, materials, components, labor, tooling, and other drivers. This will help in building more accurate decisions regarding inventory policies, distribution networks, and many other strategic issues.
- It helps to estimate the ratio of materials-usage cost to time-driven cost along the SC value stream.

# **Chapter 6. Managing Perishability in Dairy Supply Chain using DSCPM Framework (a case study scenario)**

## **6.1 Introduction**

To establish a profitable and sustainable position in the market, SCs are required to operate at low cost while providing high product availability especially at the last outlet (retailers) [141]. Achieving high product availability, inventory accuracy is one of the main factors to be considered. Inventory inaccuracy negatively impacts many other SC functions such as forecasting, ordering, replenishment, etc. [95].

To resolve these problems, companies, such as Wal-Mart, start moving to use RFID technology. Hardgrave et al. [95], in their study on Wal-Mart state that, “RFID is making a difference.” However, such studies only considered tracking the paying-demand products using RFID and adjusting the inventory records without considering any other causes of inventory discrepancies. Discrepancies in inventory result from many causes such as non-paying demand (e.g., shrinkage and thefts), damage to products, expiration, misplacement, etc. [96]. Resolving such discrepancies required not only tracking the physical products at selling points, but also tracking its information (e.g. outdating or expiration date). Which enables managing these products value streams along the overall supply chain, and maintains accurate and suitable inventory levels that can achieve the targeted profitability and service levels.

In this chapter, we develop a simulation model for a three-echelon dairy supply chain system to show the impacts of using DSCPM

framework on supply chain performance. DSCPM will be used to develop a new module in PPAE to track and monitor perishable products information (i.e., outdating due date). The model will also show the effects of the real-time decision-making, which enabled by DSCPM-IoT functionalities, on the SC performance measures being tracked.

## **6.2 Assumptions and Notation**

### **6.2.1 Model Assumptions**

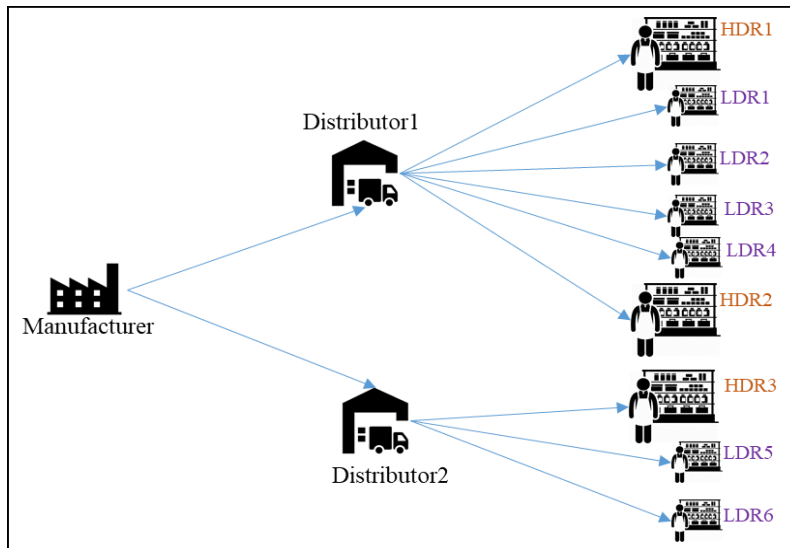
To compare dairy SC performance and to show the impacts of real-time decision-making before and after employing IoT functionalities, we used a multi-agent mixed with a discrete event simulation model to simulate the processes of three-echelon supply chain system of a perishable product.

The timing of events during a day in the model can be described as following: After opening the store, inventory decreases due to customers demand events, which follows the normal distribution. By closing the stores, outdated inventory is removed, remaining inventory is counted, performance measures such as the outdating percentage and fill rate are calculated, and the orders are placed. Goods arrive with a replenishment lead-time delay consists of two parts, loading/unloading time, and shipping time between SC members. We used the following assumptions and notation:

- The dairy SC consists of a manufacturer, two distributors; each of them serves two type of retailers. Distributor 1 serves two high demand retailer (HDR), and six low demand retailers (LDR); while distributor 2 serves one HDR and three LDR. The goods flow along the supply chain as illustrated in Figure 6.1. We assume a

cooperative relationship between all members, i.e., all of them seeking the overall strategic fit. Therefore, the simulation model will iterate to find the best member inventory system parameters that give the best profitability for the overall system and maintain the best fill rate with lowest expiration rate simultaneously. The output of the simulation will be used again to simulate the model after activating IoT functionalities to show the impact on the system performance.

- The model assumes a single perishable product, which is a 1.8 litter milk gallon, with a fixed lifetime of 11 days. The lifetime is defined here as the remaining shelf life for the product since it produced at manufacturer plant, this parameter is called as the Remaining Time Before Expiration (RTBE).
- Demand is probabilistic with a time-varying pattern during the day. The daily demand events at HDR has mean and variance 600, 120 respectively, while the daily demand events at LDR has mean and variance 80, 16 respectively.



**Figure 6.1: Proposed SC's Goods Flow.**



- Customers withdraw items with positive remaining shelf life from retailer shelves, depending on their demand and preference regarding remaining shelf life. For each demand withdrawal, the customer picks a quantity according to a predetermined probability distribution illustrated in Table 6.1.

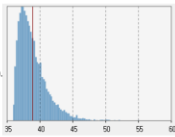
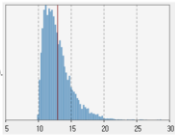
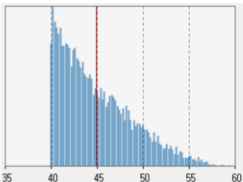
**Table 6.1: Distribution of Demand Withdrawal Event at Retailers.**

<b>Retailer</b>	<b>Demand withdrawal quantity (pcs)</b>	<b>Probability</b>
<b>HDR</b>	1	0.60
	2	0.30
	3	0.10
<b>LDR</b>	1	0.95
	2	0.05

- As the system follows customer demand, the manufacturer capacity assumed to be infinity. When the manufacturer produces distributor orders quantities, each product attached with RFID tag which includes its unique ID and RTBE value. This tag can be seen everywhere along the supply chain value stream. We assumed RTBE = 11 days according to Korean market standards.
- In this model, for all SC members, we use inventory system and control policies similar to what has been used at wholesalers in Kanchanasuntorn and Techanitisawad [146], i.e. (R, s, S) policy. The unsatisfied demand at retailers is considered lost sales, while it is back ordered at distributors and manufacturer, due to the observed nature of the dairy industry. All members follow the same review interval,  $R = 1$ , with reorder point “s” and desired maximum inventory level “S”. For each outlet, order quantity equal to the difference between its maximum inventory level and the current inventory position. The procurement order from the upstream chain is generated when the inventory position of the members is less than reordering point s at the daily closing time (assumed 8:00 pm).

- At the close time, any product, whose age reaches the end of its lifetime, is perished and consequently, the on-hand inventory level decremented. In other words, the inventory position is first corrected for the estimated amount of outdated and an order is placed if this revised inventory position drops below the reorder level “s”.
- Replenishment orders arrive with a lead-time consist of two parts, loading and unloading lead-time, which follows beta distribution and shipping lead-time, which follows the gamma distribution. Table 6.2 illustrates these distributions parameters values for all SC members.

**Table 6.2: Model Lead-Time Distribution Parameters.**

	Manufacturer to Distributor	Distributor to Retailer
Shipping Lead-time Distribution	<p>Alpha: <input type="text" value="2"/> - the shape parameter &gt; 0.  beta: <input type="text" value="1.5"/> - the scale parameter &gt; 0.  min: <input type="text" value="36"/> - the minimum x value(hours).</p> 	<p>Alpha: <input type="text" value="2"/> - the shape parameter &gt; 0.  beta: <input type="text" value="1.5"/> - the scale parameter &gt; 0.  min: <input type="text" value="36"/> - the minimum x value(hours).</p> 
Loading/Unloading Lead-time Distribution	<p>p: <input type="text" value="2"/> - the lower shape parameter &gt; 0.  q: <input type="text" value="3"/> - the upper shape parameter &gt; 0.  min: <input type="text" value="40"/> - the minimum x value(minutes).  max: <input type="text" value="60"/> - the maximum x value(minutes).</p> 	

## 6.2.2 IoT Functionality Assumptions

Assuming that IoT technology, represented by DSCPM as a real-time SC performance monitoring mechanism, is well deployed in the dairy SC under study. Therefore, it is possible to collect and monitor all of the spatial and timely data related to all of the products' information, and costs along the SC value stream. This information also can be tracked in real-time; for instance, RTBE.

To help managing product perishability while maintaining the

planned expiration and service levels, we develop a PPA-module using DSCPM framework. The module includes two types of IoT functionalities (i.e., RT-PCRs) to be employed in this simulation experiments. Java code has been used to build the functionalities in AnyLogic software. We describe these functionalities as below:

- *RTBE-based distribution*: this functionality enabled at distributors. We assumed that distributors can monitor the daily inventory movements of his retailers. Therefore, he can decide in almost daily bases which products (i.e., according to their RTBE) to send to each retailer in the downstream chain. This type of decisions required seeing what exactly available in the distributor and his retailers stock, what is in transit, and what orders available in real-time. This information and other costs information become available and enabled by IoT, and the decisions can be made according to it. It is worth also to note that such functionality operational costs are very low as it is only required to invest in the IoT systems.
- *RTBE-based products movement between retailers*: this functionality enabled between LDR and HDR and conducted/monitored by distributors. Assuming all products information can be seen at all retailers' stores, it is possible to make decisions to move the products with low RTBE (e.g., products with  $RTBE < 3$  days) from LDR to HRD with a discounted price. To do that, we need to automatically and timely inform distributors about the available quantities to be moved from each LDR, and where it should be sent (according to the receiver's real-time inventory conditions). In addition, we need to decide whether it is worthy to do that by comparing the transportation costs with the expected expiration costs. All of these decisions can be enabled by developing an RT-PCR in DSCPM modules. Such functionality

required additional operational costs, such as the transportation costs and discount costs. These costs will be considered in the experiments.

### 6.3 Simulation Experiments

According to Kanchanasuntorn and Techanitisawad [146], the product lifetime or perishability and lost sales policy are the main factors that significantly and interactively degrades the system performance, i.e., reduces the service level and the net profit while increasing the total cost. Such findings corroborate the need, which essentially motivated us, to investigate the impacts of employing IoT technologies to handle such problems.

According to Chapter 3, there are mainly, two attributes of SC performance measures to be monitored: cost or profit and customer responsiveness. As recommended by many literatures [76, 146], we use a mixture of metrics. These metrics are system net profit, system total cost, service level in terms of fill, and expiration rate. Thus, in order to compare the performance of the system before and after employing IoT functionality, these metrics long-term averages have been measured and monitored. The profits incurred during daily operational run given by the following equation:

$$Profit = \sum_{i=1}^n (S_i \times p_i - ((SC_i + Q_i \times v_i) + \bar{H}_i \times hc_i + Sh_i \times shc_i + Ex_i \times exc_i))$$

Where:

Index i: SC member,  $i = 1, 2, \dots, n$ .

$S_i$ : Daily sales quantity in member i.

$Q_i$ : Daily ordered or manufactured quantity by member i.

$\bar{H}_i$ : Daily average inventory in member i.

$Sh_i$ : Daily shortage quantity in member i.

$Ex_i$ : Daily outdated or expired products in member i.

$SC_i$ : Ordering or manufacturing setup cost in member i.

$p_i$ : Selling price per product in member i.

$v_i$ : Purchasing/manufacturing cost per product in member i.

$hc_i$ : Daily holding cost per item in member i.

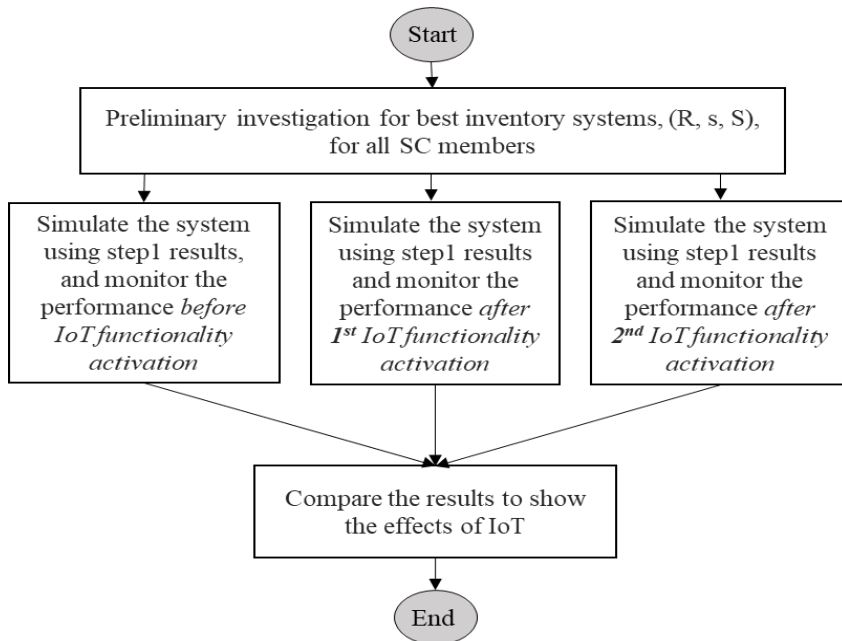
$shc_i$ : Shortage cost per item in retailers and per item per day in distributors and manufacturer.

$exc_i$ : Expiring or outdated cost per item in member i.

The costs of the system can be simply extracted from the above profit equation by taking the costs part before deducting it from the revenue part. The fill rate, which represents the level of customer responsiveness, is monitored by counting the number of product demands that could not be satisfied from retailer's stores because of products shortages (i.e. lost sales) and finding its proportion from the total occurred demand and then deducting that value from one. Finally, expiration rate is monitored by counting the expired products at all SC members and finding its proportion from the total products flow through the system.

Accordingly, to show the expected roles and effects of IoT functionality on products perishability management, we conduct simulation experiments. The experiment procedure illustrated in figure 6.2. The used parameters values are shown in Table 6.3. Part of these values have been collected and validated by applying site visits to some Korean retailers and malls such as CU-chain, e-Mart-chain, Trader (e.g., product price, moving costs, discounts). Other values have been approximated after consulting some experts in the field (e.g., setup, holding, shortage costs). In this experiment, the model was solved for its best inventory system parameters (i.e. (1, s, S)) for each member. AnyLogic optimization engine has been used to do that. The simulated

time was 365 operational periods. The system iterated 500 times with 5 repetitions each. The results from the first step have been used to simulate the model on its long run to monitor the performance and collect the data to be used as a base-model data. Then, using the same parameters the model has been simulated for the same period, but after activating the first IoT functionality. Finally, the model simulated again after activating the second IoT functionality. All of the results have been collected and analyzed. We will demonstrate the analysis in the next section.



**Figure 6.2: Simulation Experiment Procedure.**

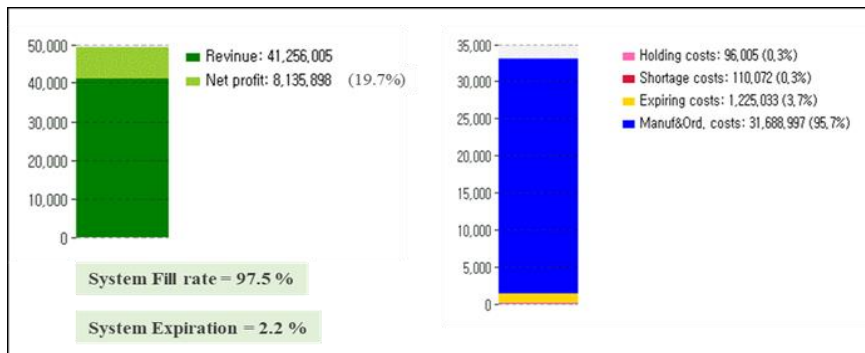
**Table 6.3: Parameters in Experimental Simulation Model**

Parameter	Unit	SC Member (i)			
		HDR	LDR	Distributor	Factory
$p_i$	\$	5	5	4	2.5
$SC_i$	\$	20	20	20	100
$v_i$	\$	4	4	2.5	2
$hc_i$	\$	0.006	0.006	0.005	0.003
$shc_i$	\$	1	1	5	3
$exc_i$	\$	5	5	4	2.5
Transportation Cost Between Retailers/move	\$	30	30		
Discount for Closed Outdating Goods	%	10	10		

## 6.4 Results and Discussion

### 6.4.1 Performance Analysis of Original Model before IoT (base-model)

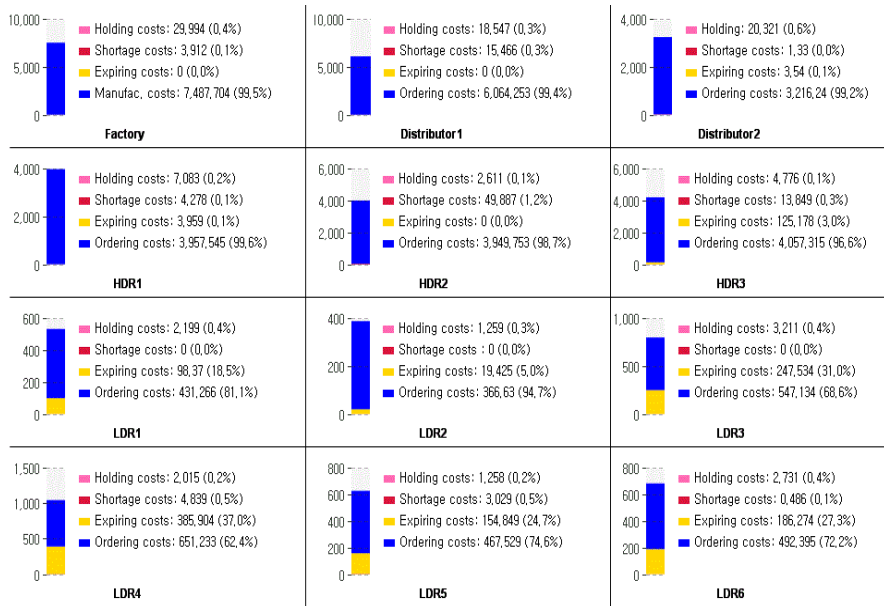
As mentioned before, the results of the best inventory system parameters for all supply chain members, Table 6.4, have been used to monitor the long run performance. The model has been simulated for 1, 2, 3, and 4 years (365 operational periods for each year), and the performance data have been collected. Approximately similar averages have resulted from the four experiments. Figure 6.3 summarized the overall system daily profit, costs, fill-rate, and expiration rate, while Figure 6.4 and Figure 6.5 shows the profits and costs of each individual SC members.



**Figure 6.3: System's Daily Performance before IoT.**

**Table 6.4: Best Values for SC Members Inventory Parameters.**

SC Member	IS Parameters	Best Value	SC Member	IS Parameters	Best Value
Factory	s	9998	LDR1	s	452
	S	9998		S	464
Distr.1	s	6032	LDR2	s	278
	S	6032		S	296
Distr.2	s	4214	LDR3	s	584
	S	5306		S	674
HDR1	s	2210	LDR4	s	304
	S	2210		S	520
HDR2	s	1460	LDR5	s	206
	S	1460		S	344
HDR3	s	1748	LDR6	s	450
	S	1832		S	620



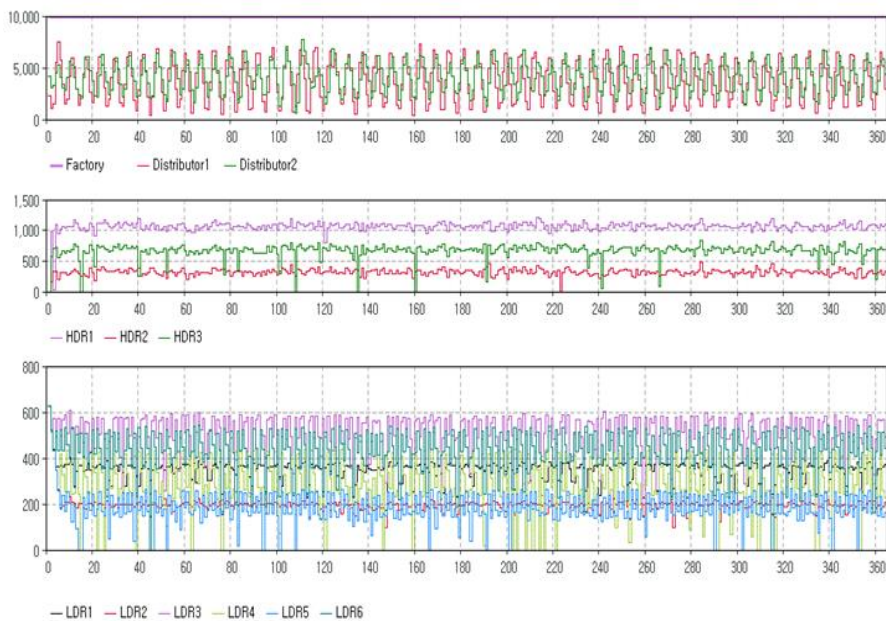
**Figure 6.4: Individual SC Member's Daily Costs before IoT.**

System inventory levels are shown in Figure 6.6, while accumulated expired products are shown in Figure 6.7.

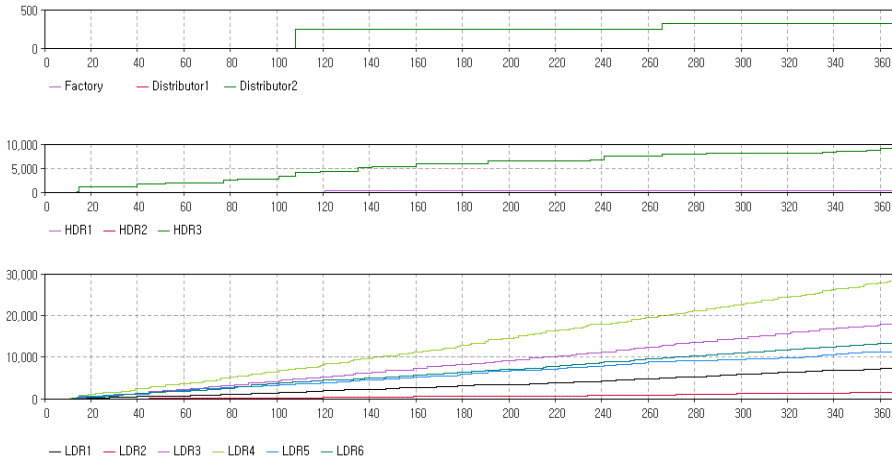




**Figure 6.5: Individual SC Member's Daily Profit before IoT.**



**Figure 6.6: System's Inventory Levels before IoT.**



**Figure 6.7: System's Accumulated Expired Products before IoT.**

According to the above results, it is clear that the system's 2.2% expiration rate obviously concentrated at the low demand retailers. That because they receive products with random RTBE. Thus, many products expired before customers demand it. Accordingly, in the next sections, we will show the impacts of using DSCPM framework on monitoring the performance in real-time and the role IoT functionality to reduce the expiration percentage while maintaining the fill rate approximately at the same level.

#### 6.4.2 Performance Analysis of Original Model after IoT

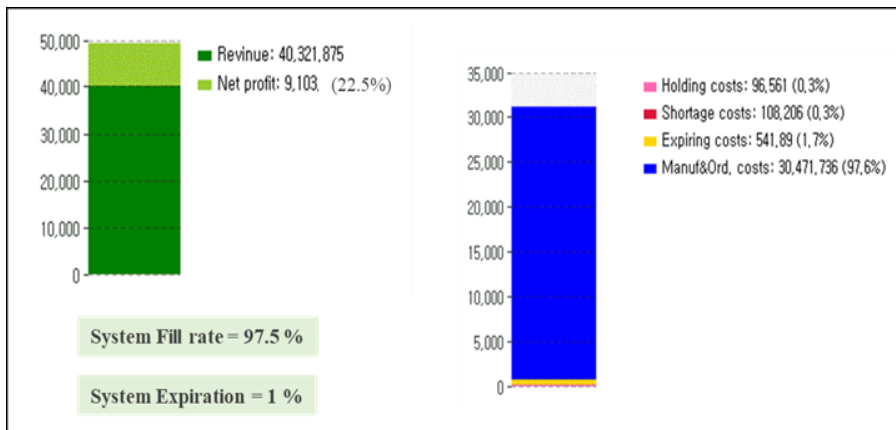
By enabling real-time performance monitoring along the dairy SC value stream and activating the above-mentioned IoT functionalities. It becomes possible to manage products perishability through timely decisions at the right place. We show the impacts of activating IoT functionality in two stages as below:

##### Stage 1: Activating RTBE-based distribution functionality

In this stage, the model has been simulated again, but after activating the "RTBE-based distribution" IoT functionality. The decision that been activated through this functionality is to decide

which products, according to their RTBE parameter, to be sent to which retailer (For instance, the decision could be: according to  $LDR_i$  current performance and inventory data, for his current order, send products with  $RTBE \geq x$  days).

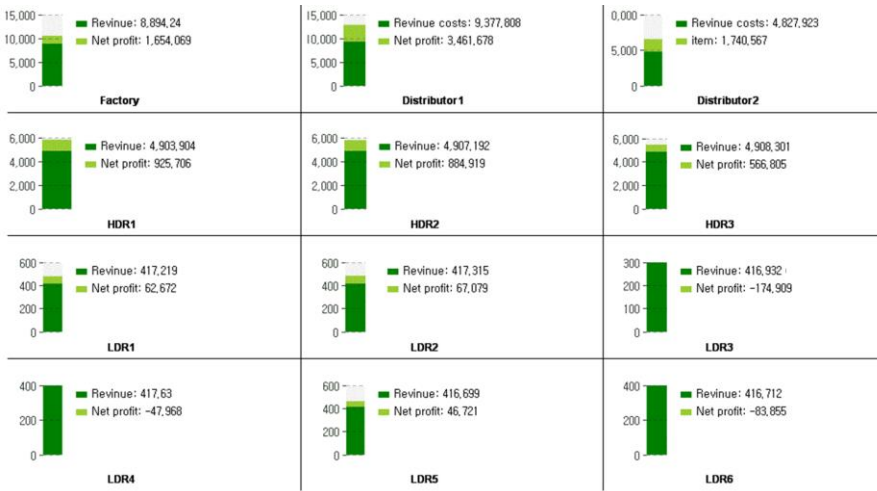
For simplicity, we use a simple search procedure to find the best decisions parameter “x”. We assume the same decision being applied for all of the LDR and HDR (e.g., for any order, if the retailer is LDR send products with  $RTBE \geq x$ , and if it is a HDR send products with  $RTBE < x$ ). The best performance has been achieved using  $x = 8$  days. Accordingly, the performance results for the overall system and for individual SC members illustrated in Figure 6.8 and Figure 6.9 respectively. The system accumulated expired products is shown in Figure 6.10.



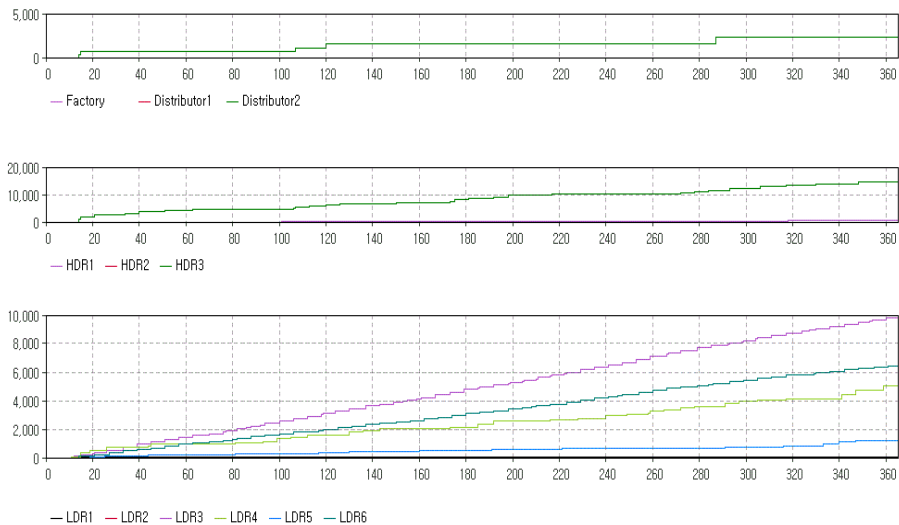
**Figure 6.8: System's Daily Performance after IoT Functionality 1.**

According to these results, it is clear that the overall profit has been increased by not less than 2.5%, and the expired product percentage decreased by 1.2% while maintaining the same customer service level (fill rate). That means, for the same inventory systems it is possible to enhance the system performance by managing products perishability using IoT functionality. In addition, Figure 6.9 shows that such functionality moved some retailers from losing to profit conditions (e.g.,

LDR1, LDR5) by decreasing their products expiration rate, see Figure 6.10.



**Figure 6.9: Individual SC Member's Daily Profit after IoT Functionality 1.**



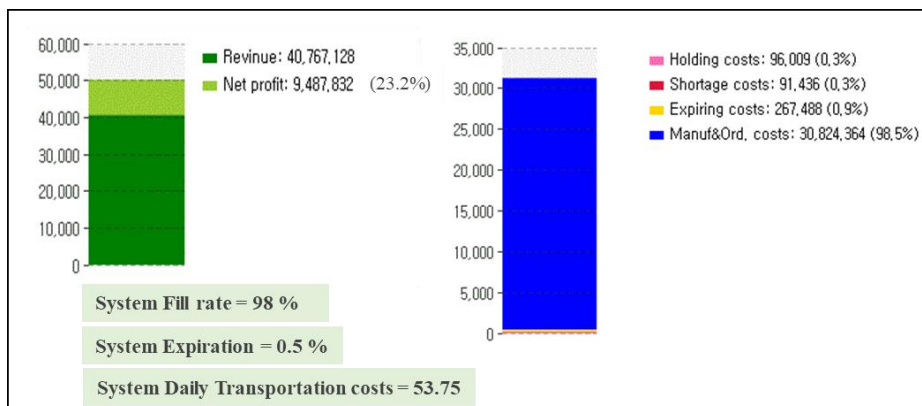
**Figure 6.10: System's Accumulated Expired Products after IoT Functionality 1.**

## Stage 2: Activating RTBE-based products movements between retailers functionality

In this stage, the model has been simulated again, but after activating the “RTBE-based products movements between retailers” IoT functionality. The decision that been activated through this

functionality is to decide which RTBE parameter-limit to be considered to trigger products movements from LDR to HDR in order to avoid product expiration at LDR stocks. For instance, the decision could be: according to  $LDR_i$  and  $HDR_j$  current performance and inventory data, send any product with  $RTBE \leq y$  days from  $LDR_i$  to  $HDR_j$  and apply a discount for that products.

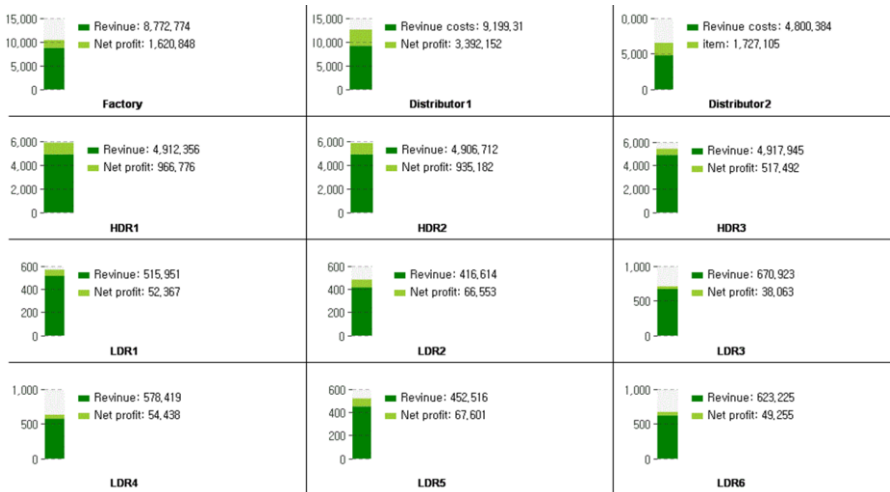
Similar to stage 1, and for simplicity, we use a simple search procedure to find the best dictions parameter “y”. We assume the same decision being applied for all of the LDR, (e.g., at the end of the day, if any LDR retailer have products with  $RTBE \leq y$ , and if the quantity of those products is worth to be moved, then: send a signal to the distributor fleet to move them to a predetermined HDR in the beginning of the next day). The best performance has been achieved using  $y = 2$  days. Accordingly, the performance of the overall system and at each individual SC member illustrated in Figure 6.11 and Figure 6.12 respectively. The system accumulated expired products shown in Figure 6.13.



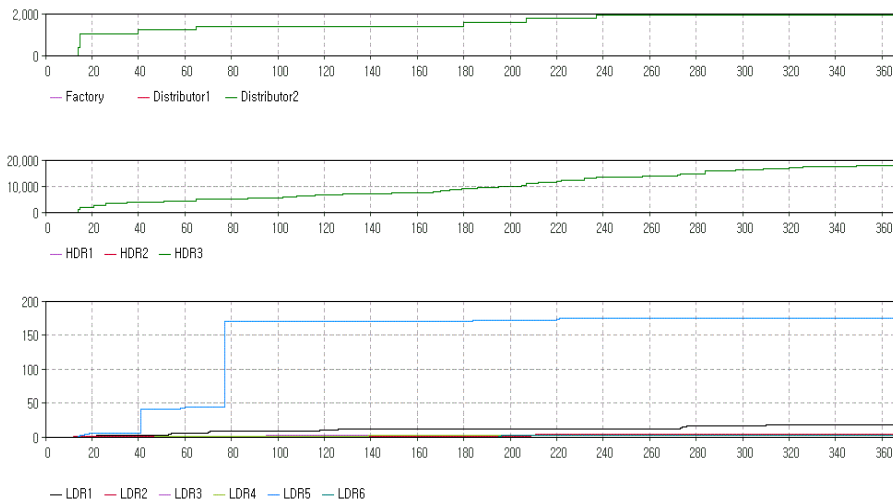
**Figure 6.11: System's Daily Performance after IoT Functionality 2.**

According to these results, adding the second IoT functionality decreased the expiration rate by around 80% compared to the original system. That directly reflected in the system total profit, which has

been increased by 0.7% after deducting the new additional daily operational costs “transportation costs”. Moreover, this functionality significantly affects individual retailer’s profitability as shown in Figure 6.12.



**Figure 6.12: Individual SC Member’s Daily Profit after IoT Functionality 2.**



**Figure 6.13: System’s Accumulated Expired Products after IoT Functionality 2.**

## 6.5 A New Approach, for Designing and Managing Perishable Products Inventory System

Conventionally, SC members use an Automated Store Ordering system (ASO) for the non-perishable products, which does not take into

account detailed information about the age of the inventory. Sometimes they use this ASO system also for perishable product categories, and they would like to know the improvement potential if they would extend the logic of this ASO system using the information on the age of the inventory [147]. On the other hand, retailers who want to make their ASO system for non-perishable items applicable to perishable items will have to take into account that not only additional information on the age of the inventory is needed. Due to the outdating costs for perishable items, the retailer may aim for a lower service level, i.e., decreasing inventory levels, for perishables compared to nonperishables, resulting in a larger percentage of demand that is not registered due to out-of-stock situations [147, 148].

In this section, we propose a new approach for designing and managing perishable products inventory systems. This approach adapts DSCPM mechanism and employs the IoT functionalities to enable a new solution for this problem. The next subsections illustrate the idea, apply it to the dairy SC model, and compare its performance with the previous models.

### **6.5.1 New Approach Idea**

Designing perishable products inventory systems required solving and controlling two conflicted performance indicators:

- Fill rate: which requires a relatively high inventory levels to avoid out-of-stock situations. For maintaining a high-level fill-rate, it is required to have a mechanism to dynamically review the inventory and make real-time decisions to adjust and control its levels.
- Expiration rate: which requires low inventory levels to avoid outdating situations. For maintaining low-level expiration rate, it is required to have a mechanism to dynamically monitor the inventory

ages and locations and make real-time decisions to save and control its expiration wastes.

Accordingly, to resolve such conflicts, we propose a two-stage solution as below:

**Stage1:** Designing SC members inventory systems as a nonperishable product, i.e., without considering the expiration costs in the objective function.

$$Profit = \sum_{i=1}^n (S_i \times p_i - ((SC_i + Q_i \times v_i) + \bar{H}_i \times hc_i + Sh_i \times shc_i))$$

This will lead to higher inventory levels and therefore:

- a) Higher fill rate
- b) Higher expiration

**Stage 2:** Manage the inventory and expiration using DSCPM framework IoT functionalities.

## 6.5.2 Performance Analysis Using the New Approach

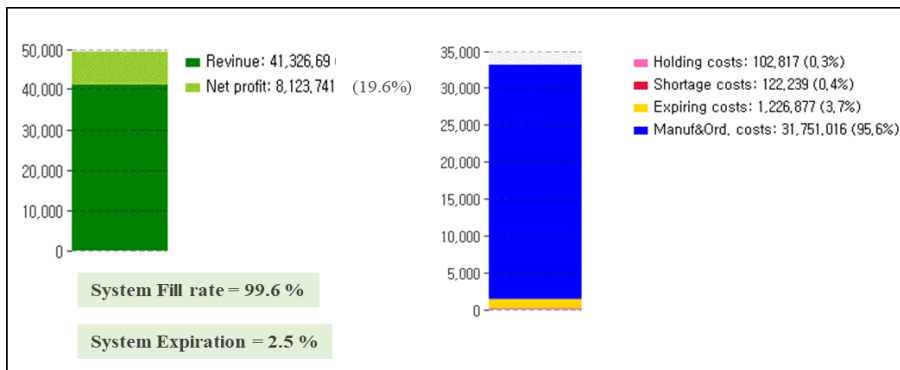
Using same simulation parameters as in base-model, the best inventory parameters for all supply chain members shown in Table 6.5. As expected, compared to the old approach base-model the system average inventory level increased by 3%. That positively affects the system fill-rate by increasing it to 99.6% which is higher than the base-model by 2.1%, while the expiration rate affected negatively and increased by 14%, see Figure 6.14 and Table 6.6. However, after applying IoT functionalities using this approach, the overall system performance significantly developed as shown in Figure 6.15 and Table 6.6. For instance, system daily profit increased by more than 3.6% compared with 2.2% in the original approach model, fill rate increased by 1.63% than the original model, while the expiration rate decreased by 80%. These results prove the superiority of the new approach in



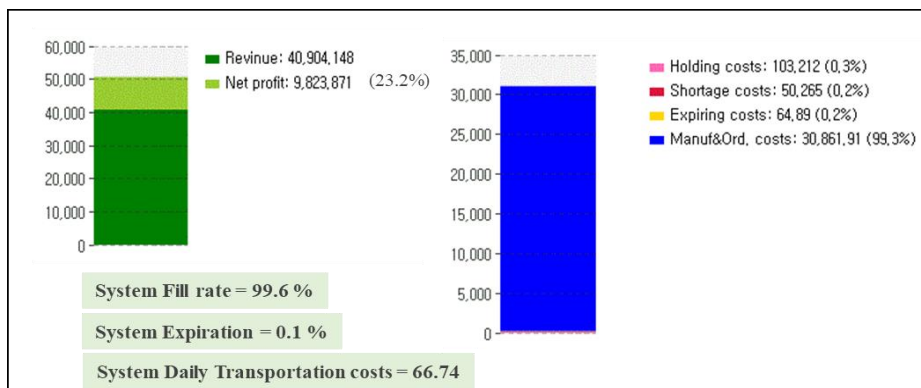
which the perishable products treated as nonperishable and IoT deployed to monitor the dairy supply chain performance and enable real-time decisions to manage its perishability.

**Table 6.5: Best Values for SC Members Inventory Parameters Using New Approach.**

SC Member	IS Parameters	Best Value	SC Member	IS Parameters	Best Value
Factory	s	9998	LDR1	s	7574
	S	9998		S	9447
Distr.1	s	6032	LDR2	s	7058
	S	6032		S	7058
Distr.2	s	4214	LDR3	s	3638
	S	5306		S	3662
HDR1	s	2210	LDR4	s	3236
	S	2210		S	3248
HDR2	s	1460	LDR5	s	1910
	S	1460		S	1910
HDR3	s	1748	LDR6	s	1940
	S	1832		S	1940



**Figure 6.14: System's Daily Performance before IoT Using New Approach.**



**Figure 6.15: System's Daily Performance after IoT Using New Approach.**

**Table 6.6: System Performance Comparison between Old and New Approaches.**

		Overall Costs	Revenue	Net Profit	Expiration %	Fill Rate
Old Approach	Befor IoT	33120.11	41256.01	8135.90	0.02	0.98
	After IoT	31333.05	40767.13	9434.08	0.01	0.98
	Improve after using IoT			15.96%	-77.27%	0.51%
New Approach	Befor IoT	33202.96	41326.69	812373.00%	2.50%	99.60%
	After IoT	31147.02	40904.15	975713.00%	0.10%	99.60%
	Improve after using IoT			20.11%	-96.00%	0.00%
Approaches Comparison	Befor IoT			-0.15%	13.64%	2.15%
	After IoT			3.42%	-80.00%	1.63%

## 6.6 Decisions Sensitivity Analysis

In order to show the sensitivity of the decisions enabled by IoT functionalities and the importance of its timely and special characteristics, a sensitivity analysis experiment have been conducted. Table 6.8 illustrates the results of nine combinations of the decisions made by IoT functionalities. These decisions control the parameter “x” for the first functionality and the parameter “y” for the second functionality. The experiment conducted on both old and new approaches. The results show that: changing decisions parameters significantly affect the overall system as long as individual members performance. Accordingly, the real-time performance monitoring and the SC visibility (i.e., information transparency, enabled by IoT functionalities) are essential and effective for enhancing the right and timely decisions. That leads to better performance and highlights for continuous development opportunities. It is also worthy to note that, these decisions can be made individually for each SC member. This could lead to better results; however, that requires a high-level computation system to simulate it. Therefore, we leave it for future research.

## **6.7 IoT Costs-benefits Analysis**

Successful implementation of RFID through the whole supply chain under study requires a good understanding of the impact of RFID at all echelons. To understand the value of an RFID investment, we need to measure the elements of cost as well as the business and customer related benefits comprehensively [149]. Therefore, cost-benefit analysis is a key component of this investment decision. If an RFID deployment cannot be justified in term of its economic value to the SC, it is not likely to help it; and consequently, it is not likely to remain a viable deployment over the long term. Many factors play a role in determining RFID technology costs and benefits. For example, costs can be fixed, such as investment in new tools and processes to install and test tags, or recurring (variable), such as the cost of RFID tags or the cost associated by applying them on items, cases, or ballets and testing them. Expectations of RFID benefits, as discussed in previous sections, can be broken down into two parts: the first is cost reduction (e.g., inventory cost reduction, waste reduction, process automation, and therefore efficiency improvements), and the second is value creation (e.g., increase in revenue, increase in customer satisfaction due to responsiveness, and anti-counterfeiting, etc.).

Although it is difficult to calculate the true costs based on limited information from pilot projects and researches. The initial cost of an RFID deployment can be broken down into three key areas: hardware, software, and services. Hardware costs include the cost of readers, antenna, host computers, and network equipment (cables, routers, and so on). Software costs include the cost of creation of middleware and other applications (for example, ERP and SCM). Service costs include the cost of installation, tuning, integration of various components, training, and business process re-engineering (workflow) [150]. In

addition to the initial investment costs, there will be reoccurring costs (variable costs), namely cost of tags and maintenance [151]. Accordingly, this section provides a rough estimation of the RFID implementation costs to compare it with the estimated benefits from the previous section.

Despite that the total cost will vary depending on the size and type of the application; capital investment will be required to implement an RFID system. A manufacturing company, in our model, will need to purchase equipment that can write information to the tags. They will also need to locate RFID reading equipment and antennas in various locations. To make the system useful, a company may need to hire an integrating or engineering firm to develop the software that will configure the data from the tags into useful information. Equipment, installation, integration and computer system costs can add up quickly. In addition to initial equipment costs, we suppose that manufacturer is likely to purchase tags that are affixed to gallon or bottle caps (i.e., RFID bottle caps). According to RFID Journal and some E-business websites (e.g., Alibaba.com), the additional cost per cap can range between \$0.07 and \$0.17 depending on the type of used tag and volumes purchased. Ongoing maintenance costs for the equipment and software must also be considered when determining the total system cost. As RFID systems continue to increase in popularity, costs for equipment and tags will begin to decrease. Over the last few years, the cost of the RFID hardware has been declining steadily. According to RFID Journal, the costs have gone down steadily over the past years, and it is anticipated that these costs will continue to decline to reach the \$0.05 per tag. We also assumed that no need to add a new process to affix the tag on the bottles because it is already fixed inside the cap at caps supplier. In order to fully take advantage of an RFID system in the

proposed model, we assumed adding technology to the distributors and retailers side of the supply chain.

To fully understand the costs associated with implementing an RFID system, an analysis of the costs was performed for all the SC members. An estimation of the costs associated with installing this system can be seen in Table 6.7. The costs have been categorized into hardware, middleware, service, and other costs. The anticipated number of yearly-required tags is 1,200,000. Adding the tags cost, anticipated yearly maintenance expenses for the equipment and software applications, and initial installation costs, it is anticipated that this system annual costs are \$162,600.

To determine the proper ROI calculation Net Present Value (NPV) formula has been used as below.

$$NPV(i, N) = \sum_{t=0}^N \frac{R_t}{(1+i)^t}$$

Where

$t$  : The time period you want to evaluate (the life of the project)

$i$  : The interest rate that could be earned on an investment in the financial markets with similar risk.)

$R_t$ : The net cash flow i.e. cash inflow – cash outflow, at time.

Assuming that:

- The estimated yearly profit achieved after applying IoT is \$490,200 ( simulation model results).
- The market interest rate is projected to average 7% over the 5-year project life.
- And the total annual costs as shown in Table 6.7.

Then the calculation would be:

$$NPV = \frac{(\$490,200 - \$162,600) * 5}{(1 + 0.07)^5} = \$233,574$$

Thus, this project would have a positive benefit to the SC, saving

them \$233.574 over five years, and the payback period for install and operate such IoT system will be around one year.

**Table 6.7: Costs for Proposed IoT System to Manage Perishable Products.**

Installation Cost	Cost Type	Unit Cost	Quantity Required	Summation
<i>Hardware Costs</i>				
RFID reader with antenna*	Fixed	\$1,500	33	\$49,500
RFID bottle tags ( estimated per year)	Variable**	\$0.07	1,200,000	\$84,000
<i>Middleware Costs (variable)</i>				
Basic read/write software cost	Variable**	\$7,000	1	\$7,000
Web hosting	Variable**	\$100	1	\$100
<i>Service Costs</i>				
Mechanical installation (cost per day x number of readers)	Fixed	\$500	33	\$16,500
Electrical installation (cost per day x number of readers)	Fixed	\$500	33	\$16,500
Equipment vender services and support (cost per day x number of days)	Fixed	\$1,000	30	\$30,000
Computer Integrator-engineering service	Fixed	\$50,000	1	\$50,000
Computer Integrator-ERP update	Fixed	\$50,000	1	\$50,000
Computer equipment-network installation	Fixed	\$10,000	12	\$120,000
<i>Other costs</i>				
Ongoing maintenance costs	Variable**	\$5,000	1	\$5,000
<b>Annual fixed costs***</b>				\$66,500
<b>Annual variable costs</b>				\$96,100
<b>Annual costs</b>				\$162,600

\*Assume 2 riders for each distributor and manufacturer and 3 readers for each retailer

\*\*Annual variable costs

\*\*\* Assume the system fully depreciated evenly over five years.

Finally, it is worthy to note that, some literature has discussed how to share the tagging costs among the SC members. Ustundag et al. [149] has proposed two approaches. In the first approach, the tagging cost is shared equally between SC members while in the second approach the tagging cost is shared according to the expected benefit of each SC member using the tagging cost sharing factor.

## 6.8 Conclusions

With the advent of IoT technologies and using the proposed DSCPM mechanism to develop IoT functionalities for real-time decision-making, a new approach to practical solutions for managing products perishability becomes achievable. Such mechanisms not only enabled tracking products ages and manage them, but also it is opened a new gate for SC information integration. In the other hand, it enabled

a special and timely decision-making process. As shown in this chapter, such mechanism leads to find a new solution for the old problem. Therefore, it becomes possible to deal with perishable products as a nonperishable product using a new generation of ASO system supported and enabled by IoT technologies.

**Table 6.8: Decision-Making Sensitivity Analysis.**

	Decisions Parameter		Costs						Revenue	Performance		
	X	Y	Ordering	Holding	Shortage	Expiration	Moving	Overall Costs		Net Profit	Expiration Rate	Fill Rate
Old Approach	2	5	30824.36	96.01	91.44	267.49	53.75	31333.05	40767.13	9434.08	0.5%	98.0%
	2	6	31336.12	95.87	145.44	484.50	53.59	32115.52	41168.38	9052.86	0.9%	97.2%
	2	7	31487.96	95.63	128.45	386.65	66.82	32165.51	41361.44	9195.93	0.7%	97.7%
	3	5	32027.40	95.11	186.67	469.70	80.63	32859.51	41886.45	9026.94	0.9%	97.2%
	3	6	31969.38	94.36	321.87	459.21	66.16	32910.98	41866.73	8955.75	0.9%	93.2%
	3	7	32893.32	93.64	592.87	575.98	87.78	34243.59	42688.71	8445.12	1.1%	90.4%
	4	5	33149.71	94.75	141.23	528.32	96.49	34010.50	42970.92	8960.42	1.0%	96.7%
	4	6	32932.55	93.21	457.67	574.30	89.75	34147.48	42752.73	8605.25	1.1%	93.0%
	4	7	33631.59	95.52	214.10	594.00	86.88	34622.09	43458.56	8836.47	1.1%	96.8%
New Approach	2	5	30861.91	103.21	50.27	64.89	66.74	31147.02	40904.15	9757.13	0.1%	99.6%
	2	6	30644.45	103.25	49.61	123.36	56.96	30977.63	40632.96	9655.33	0.2%	99.6%
	2	7	31393.31	102.64	58.77	125.95	55.89	31736.56	41391.76	9655.20	0.2%	99.3%
	3	5	31727.93	102.31	72.93	146.90	68.22	32118.29	41747.64	9629.35	0.3%	98.9%
	3	6	32231.84	103.26	242.94	425.52	67.89	33071.45	42127.30	9055.85	0.8%	98.7%
	3	7	32304.49	103.06	81.14	487.75	67.64	33044.08	42200.97	9156.89	0.9%	99.1%
	4	5	33750.33	103.61	548.82	757.15	79.73	35239.64	43549.60	8309.96	1.4%	97.3%
	4	6	36002.85	115.13	1002.04	1873.89	79.81	39073.72	45280.65	6206.93	3.2%	97.8%
	4	7	36223.14	114.44	1165.45	1963.40	80.38	39546.81	45452.89	5906.08	3.4%	97.2%



# Chapter 7. Conclusions

This dissertation proposed concepts of a smart real-time performance-based IT mechanism for next-generation of supply chain management systems.

## 7.1 Conclusion

The thesis has introduced a systematic explanation on how IoT captured real-time data can be effectively utilized to digitalize SCs for continuously enhance and support the functionality of SCM practices and applications. Furthermore, keep them alive and effective in today's high customized working environments.

The dissertation starts with a short overview of SCPM and the major challenges that influence the success of performance measurement systems in a highly complex environment characterized by high dynamic behavior, uncertainty, and high variability. This work also reviewed the importance of real-time IT systems in performance measurement and concluded that an effective performance measurement environment without advanced IT software support has become unthinkable for today's supply chains. In this context, due to the special characteristics and superior capabilities of IoT, it has been suggested to be the major enabler to support such a real-time IT system with real-time operational data. However, it has been found that IoT remains questionable and doubtful and manufacturers are still quite hesitant to adopt it in their systems. Therefore, this research addressed a two-dimensional problem; firstly, the challenges and limitations of PMS in today's dispersed SCs, where it has become

inefficient and difficult to be implemented; and secondly, the adoption of IoT in SCs, since there is almost no standard study that comprehensively and systematically discusses the best practices of IoT in SCPMS.

The suggested idea to address this problem comes from the fact that performance measurement should be extended to cover all operational aspects of the SC multiple organizational functions and multiple firms and enable its orchestration. That through a diversity of powerful practices and tools that can work and synergize well together to effectively enable real-time decision-making, reduce wastes, and maximize value. Therefore, this thesis introduces a solid basis for a standard framework of a digitalized smart real-time performance-based mechanism in order to describe the best practices of IoT technology in SCM to achieve an intelligent, comprehensive, integrated, and holistic real-time performance-based working environment. The integration between IoT and SCPM has been derived from the main concepts of traditional business processes workflow, where the time-based flow is greatly emphasized and considered as the most critical success factor of achieving SC goals.

The introduced mechanism is known as Dynamic Supply Chain Performance Mapping, which represents a new kind of a smart real-time monitoring and controlling performance-based IT mechanism for the next-generation of SCM systems with dynamic and intelligent aspects concerning performance targets.

To describe the best practices of IoT technology within SCPM, several smart real-time performance-based modules concerning performance targets have been developed, including:

- ✚ Module 1: Real-Time Analysis of DLT tracks the demand lead time of an individual product along the SC value stream in real-time. That by identifying its time-components, and accordingly measure the performance of the work environment in term of time.
- ✚ Module 2: Real-Time Smart Decision-making Analysis (RT-SDA) identifies the hidden performance violations events, to find inefficient processes and their locations along the SC value stream. This kind of mechanism is proposed to make the hidden root-causes of performance violations immediately visible by analyzing the event-instances in real-time. Therefore, they can be avoided or treated directly by enhancing decision-making process or triggering automated reactions.
- ✚ Module 3: Real-time Supply Chain Cost Tracking System (RT-SCCT) runs through DSCPM in order to enable the SC members to monitor the real-time gradual development of the products associated manufacturing and operational costs during their flow along the SC value stream, as well as monitoring the operations performance in terms of cost.

All modules are running in real-time on DSCPM-PPAE, and they are equipped with the suitable RT-PCRs that describe how the IoT captured data can be utilized in the best manner to smartly support PPAs through their modules during daily working runs.

As aforementioned, the concepts of this thesis has been demonstrated by constructing several RT-PCRs algorithms based on CEP to prove how the IoT data can be utilized to support SCM practices. The feasibility of the constructed RT-PCRs of the modules has been validated by simulation models using AnyLogic. As a result, the DSCPM can bring revolutionary improvements in

traditional PMS to face the challenges in today's business environment. In this regard, the potential results of this work include the increase in flexibility and adaptability of event tracking-based performance monitoring for real-time supply chain management practices and applications.

## 7.2 Future research

This dissertation opens some new future research opportunities:

- ✚ This research opened a new gate for a further researched to deploy IoT technologies not only to track supply chain products but also to collect data from all processes and activities along the overall supply chain value stream, and use it for a new generation of SCM practices and applications. These applications could include new solutions for old problems similar to the perishability problem addressed in Chapter 6.
- ✚ This framework could be further enhanced, by standardizing the CEP-rule semantics for constructing the RT-PCRs that can be easily translated into any programming language code. A complex event compiler could be used to check the validity of a RT-PCRs code according to the information in the meta-data, as well as to conduct syntactical and lexical analysis and corrections of the RT-PCRs expression.
- ✚ Concerning the developed modules, this work introduced simple RT-PCRs to explain and clarify the concept of these modules. Therefore, more detailed and complex RT-PCRs should be addressed in this field, such as fully automated the decision-making process using machine learning algorithms, which could be another possible research direction in the area of SCPM.

- ✚ Another possible future research is the ability to tie the DSCPM with simulation software. Thus, the practitioners have the ability to investigate the likely consequences in advance to prevent causing serious disruptions as well as check the validity of critical decisions for the critical situations in advance.
- ✚ Another possible extension of this study is to develop further performance-based modules for another SCM practices and applications such as distribution fleet management, continuous development modules based on the real-time data.
- ✚ Further and more practical investigations might be done regarding the economical factor of deploying IoT for performance measurements.
- ✚ Another important topic to be deeply researched is for answering the question of “Who will own and control the developed systems and platforms?”

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# 초록

공급망 성과 측정 (SCPM) 은 현재 세계 시장에서의 심화되는 경쟁 속에서 경쟁력을 제고하여 비교우위를 점할 수 있도록 하는 중요한 경영전략 중 하나이다. 고객 맞춤형 주문보다는 밀어내기 방식으로 대변되는 소품종 대량생산을 통해 수요를 충족하던 전통적인 공급망 환경과는 달리, 현대의 시장 상황은 고객 요구의 다각화에 따라 불확실성이 증가하고, 동적 환경으로 변화하고 있으며 고객 중심의 운영을 요구하고 있다. 더군다나 제품의 수명주기의 길이가 급격하게 짧아지면서 공급망 운영에 있어 이러한 문제들에 대해 대응하는 데 어려움을 겪고 있다.

이러한 빠른 변화와 새로운 프로세스 설계의 적용에 지속적으로 대응하기 위해 효과적인 실시간 성과 기반 IT 시스템의 개발의 필요성이 증대되고 있다. 현대의 동적이며 개별적인 환경에서의 실시간 성과 측정은 IT 시스템 없이는 불가능하기 때문이다. 이러한 맥락에서 사물인터넷 기술은 그 특성과 기능을 활용하여 실시간 운영 데이터를 다루는 IT 시스템 구축을 도울 수 있다. 그러나 기술의 성숙도에 대한 의심은 기업 입장에서의 사물인터넷 도입을 꺼리게 하는 요인이다.

본 논문에서는 디지털화된 스마트 실시간 성과측정 기반 시스템의 표준 프레임워크를 소개하고자 한다. 제안한 프레임워크는 현대의 시장경쟁을 뛰어넘기 위해 실시간 운영 데이터를 사물인터넷 기술을 통해 통합 및 수집하고 성

과를 측정하는 모범 운영 사례를 제시한다. 본 논문에서 제안하는 프레임워크는 동적, 지능적 측면에서의 전략적 성과 목표달성을 목표로 하는 차세대 공급망 관리를 위한 성과 기반 스마트 실시간 모니터링 및 통제 IT 메커니즘이다. 이 메커니즘의 아이디어는 시간 기반 흐름이 성공적인 운영을 위한 가장 중요하게 여겨지는 전통적인 공급망 업무흐름 및 성과측정 시스템으로부터 도출되었다. 이 메커니즘은 공급망의 모든 측면들을 고려한 공급망관리 원칙에 따라 실시간으로 운영되는 컴퓨터화된 이벤트 기반 성과측정 IT 시스템으로 동적 공급망 성과 맵핑 (DSCPM: Dynamic Supply Chain Performance Mapping) 이라고 부를 수 있다. 이를 통해 가치 창출을 최대화하고 낭비를 최소화하는 적절한 의사결정을 실시간으로 내릴 수 있게 된다. 따라서 DSCPM은 지능적이고 포괄적이며 통합된 성과 기반 공급망 관리 지원 시스템이다.

DSCPM은 다양한 타입의 엔진들로 구성되어 있으며 이 중 다양한 모듈에 관여하여 실시간 모니터링 시스템의 포괄성을 보증하는 측면에서 가장 중요한 엔진은 Performance Practices and Applications Engine (PPAE) 이다. 각각의 모듈들은 특정한 공급망 어플리케이션을 통제할 수 있도록 한다. 이러한 통제는 complex event processing 방법론을 사용한 Real-Time Performance Control Rules (RT-PCRs) 이라는 실시간 모니터링 및 통제 규칙에 의해 이루어진다. RT-PCRs는 공급망 내 방해 요소를 탐지하고 이를 통제하기 위한 실시간 의사결정에 대한 주의를 주거나, 성과를 통제하기 위한 즉

각적인 반응을 할 수 있게끔 하여 궁극적으로 스마트 실시간 작업 환경을 조성하는 데 도움을 준다.

본 연구의 의의는 다음과 같다. (1) 사물인터넷 기술을 적용함으로써 생산 시스템의 모든 자원을 스마트 오브젝트화하여 디지털화된 공급망 구축의 프레임워크를 제시하여 동적 실시간 공급망 성과측정 및 관리를 가능케 한다. (2) Event Extractor 엔진, WF 엔진, 실시간 규칙 엔진, 및 PPAE를 포함한 DSCPM의 프레임워크를 구축한다. (3) RT-PCRs를 활용하여 실시간 수요 리드타임 분석, 실시간 스마트 의사결정 분석, 실시간 공급망 비용 추적 시스템 등의 툴을 개발하여 DSCPM의 실현 가능성을 분석한다. (4) AnyLogic 소프트웨어를 기반으로 시뮬레이션 모델을 구축하여 RT-PCRs의 효율성에 대해 검증한다.