RFID-Enabled Dynamic Value Stream Mapping for Smart Real-Time Lean-Based Manufacturing System

Von der Fakultät für Ingenieurwissenschaften,
Abteilung Maschinenbau und Verfahrenstechnik der
Universität Duisburg-Essen
zur Erlangung des akademischen Grades

eines

Doktors der Ingenieurwissenschaften

Dr.-Ing.

genehmigte Dissertation

von

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Tag der mündlichen Prüfung: 29. Februar 2016

Abstract

Lean Manufacturing has become the most popular and dominant management strategy in the pursuit of perfection and in strengthening the competitive edges of manufacturers to face the challenges in the global markets. However, today's global markets drive manufacturers to create highly customer-oriented job-shop manufacturing systems characterized by high dynamic behavior, uncertainty and high variability, in contradiction to lean being originally designed for high repetitive-production systems with a high-volume low-mix work environment with stable demand and a low degree of customization. Moreover, since the product is the changing agent, another challenging aspect that faces the effectiveness of lean is that the product life cycle is rapidly decreasing; and thus some of the lean initiatives often die after the product life cycle ends.

In this regard, in order to constantly cope with the resulting rapid changes and adapt new process designs while reviving lean initiatives and keeping them alive; an effective real-time lean-based IT system should be developed, since lean without a real-time IT system has become impracticable and unthinkable in today's high-customized manufacturing environments. In this context, due to the special characteristics and superior capabilities of Radio Frequency Identification technology (RFID), it could be the major enabler to support such a real-time IT system with real-time production data. However, RFID remains questionable and doubtable and manufacturers are still quite hesitant to adopt it in their manufacturing systems.

This thesis introduces a solid basis for a standard framework of a digitalized smart real-time lean-based system. This framework describes the best practice of RFID technology through the integration of real-time production data captured via RFID with lean manufacturing initiatives in manufacturing systems, in order to overcome today's lean manufacturing challenges.

The introduced framework represents a new kind of smart real-time monitoring and controlling lean-based IT mechanism for the next-generation of manufacturing systems with dynamic and intelligent aspects concerning lean targets. The idea of this mechanism has been derived from the main concepts of traditional value stream mapping (VSM), where the time-based flow is greatly emphasized and considered as the most critical success factor of lean. The proposed mechanism is known as Dynamic

Value Stream Mapping (DVSM), a computerized event-driven lean-based IT system that runs in real-time according to lean principles that cover all manufacturing aspects through a diversity of powerful practices and tools that are mutually supportive and synergize well together to effectively reduce wastes and maximize value. Therefore, DVSM represents an intelligent, comprehensive, integrated, and holistic real-time lean-based manufacturing system.

The DVSM is proposed to contain different types of engines of which the most important engine is the "Lean Practices and Tools Engine" (LPTE) due to its involvement with several lean modules that guarantees the comprehensiveness of the real-time lean system. Each of these modules is specified to control a specific lean tool that is equipped with suitable real-time monitoring and controlling rules called "Real-Time Lean Control Rules" (RT-LCRs), which are expressed using "Complex Event Processing" (CEP) method. The RT-LCRs enable DVSM to smartly detect any production interruptions or incidents and accordingly trigger real-time re/actions to reduce wastes and achieve a smart real-time lean environment. Practically, the basis of this introduced framework in this dissertation is derived based on a highly customized job-shop manufacturing environment of an international switchgear manufacturer in Germany.

The contributions of this dissertation are represented as follows: building the main framework of the DVSM starting with a systematic RFID deployment scheme on the production shop floor; introducing the main components of the DVSM (i.e. Event Extractor-engine, AVSM-engine, VVSM-engine, Real-time Rules-engine, and LPTE); demonstrating the feasibility of the DVSM concerning lean targets through developing a number of Lean Practices and Tools Modules that are supplied with RT-LCRs (e.g. Real-time Manufacturing Lead-time Analysis, Smart Real-time Waste Analysis, Real-time Dispatching Priority Generator (RT-DPG), Real-time Smart Production Control (RT-SPC), Smart-5S, Smart Standardized Work, Smart Poka-Yoke, Real-time Manufacturing Cost Tracking (RT-MCT), etc.); verifying the effectiveness of RT-LCRs in RT-DPG and RT-MCT modules through building simulation models using ProModel simulation software and finally proposing a framework of the tools "Smart-5S, Smart Standardized Work, Smart Poka-Yoke" to be implemented in the switchgear manufacturing environment.

„RFID-gestützte dynamische Wertstromanalyse für intelligente, echtzeitbasierte Lean–Fertigungssysteme“

Zusammenfassung

Lean Manufacturing hat sich zur weitest verbreiteten und dominantesten Management-Strategie im Streben nach Perfektion und dem Ausbau kompetitiver Marktvorteile von Herstellern im Angesicht der Herausforderungen des globalen Marktes entwickelt. Allerdings sind die Hersteller durch die heutigen globalen Märkte dazu gezwungen, hoch kundenorientierte Fertigungssysteme, welche durch ein hoch dynamisches Verhalten, Unsicherheit und hohe Variabilität charakterisiert sind, zu schaffen. Dies steht im Gegensatz zum ursprünglichen Design des Leans, welches für Systeme mit großen Wiederholungsraten, einer hohen Stückzahl bei niedriger Flexibilität, geringer Kundenspezifität und stabiler Nachfrage ausgelegt ist. Des weiteren wird die Effektivität einer solchen Herangehensweise an Lean Manufacturing durch die stark verkürzte Lebensdauer des Produkts, an welche oft auch Lean-Initiativen gebunden sind, in Frage gestellt.

Unter gegebenen Voraussetzungen ist es notwendig, ein effektives „Echtzeit Lean–basiertes IT-System“ zu entwickeln, um die konstant resultierenden rapiden Veränderungen und neue Prozessentwürfe handhaben zu können, während Lean-Initiativen erneuert und beibehalten werden. Es ist wichtig, ein effektives „Echtzeit Lean-basiertes IT-System“ zu entwickeln, da Lean ohne ein Echtzeit-basiertes IT-System bei der heutigen Anforderung an kundenspezifische Herstellung unpraktikabel sowie undenkbar wäre. In diesem Zusammenhang könnte Radio Frequency Identification (RFID) aufgrund spezieller Charakteristika und überlegenen Möglichkeiten maßgeblich dazu beitragen, ein solches „Echtzeit IT-System“ mit Hilfe von Echtzeit-Daten der Produktion zu realisieren. Dennoch bleibt RFID für viele Hersteller fragwürdig. Das führt dazu, dass die Hersteller bei dessen Eingliederung in ihre Produktionssysteme zögern.

Diese Dissertation führt eine solide Basis als Standardumgebung für ein digitalisiertes „Smart Echtzeit Lean–basiertes System“ ein. Die Rahmenstruktur beschreibt die beste

Nutzung der RFID-Technologie durch Integration der Echtzeitdaten, welche vom RFID-System mit Lean Manufacturing-Initiativen im Produktionssystem erfasst werden. Dadurch werden die heutigen Herausforderungen von Lean Manufacturing gemeistert.

Die eingeführte Rahmenstruktur repräsentiert eine neue Art von „intelligenter Echtzeit-Überwachung und -Steuerung von einem Lean-basierten IT-Mechanismus“ für die nächste Generation von Produktionssystemen, mit dynamischer und intelligenter Herangehensweise an Lean-Methoden. Diese Idee der Herangehensweise wurde vom Konzept des traditionellen Value Stream Mapping (VSM) abgeleitet, welches den zeitbasierten Verlauf stark betont und als Hauptfaktor für den Erfolg der Lean-Prinzipien betrachtet werden kann. Die vorgeschlagene Herangehensweise ist bekannt als Dynamic Value Stream Mapping (DVSM), ein digitalisiertes Event-Driven Lean-Based IT-System, welches in Echtzeit alle Aspekte des Lean Manufacturing abdeckt, um mit Hilfe einer Vielzahl von Tools, welche sich gegenseitig unterstützen, effektiv das Auftreten von Verschwendung zu minimieren und den geschaffenen Wert zu maximieren. Somit stellt DVSM ein intelligentes, umfassendes, integriertes und ganzheitliches Echtzeit Lean-basiertes Fertigungssystem dar.

DVSM soll verschiedenste Typen an Engines beinhalten, von welchen die „Lean Practices and Tools Engine“ (LPTE) aufgrund ihres Mitwirkens an mehreren verschiedenen Lean-Modulen, welche den Umfang des Echtzeit Lean-Systems gewährleisten, als wichtigste anzusehen ist. Jedes dieser Module ist auf die Kontrolle eines Lean-Tools spezifiziert, welches mit Echtzeitüberwachung und Kontrollregeln und sogenannten, durch “Complex Event Processing“ ausgedrückten, “Real-Time Lean Control Rules” (RT-LCRs) ausgestattet ist. Die RT-LCRs ermöglichen dem DVSM, auf intelligente Weise jede Störung der Produktion zu entdecken und angemessene Aktionen beziehungsweise Reaktionen auszulösen, welche Verschwendung reduzieren und eine Smart Echtzeit Lean-Umgebung schaffen. Die Basis des vorgestellten Rahmens in dieser Dissertation stellt einen hochspezialisierten, internationalen Einzelanfertigungsbetrieb für Schaltanlagen aus Deutschland dar.

Die Beiträge dieser Dissertation werden wie folgt dargestellt: Erstellen eines Hauptrahmens des DVSM, angefangen mit einem systematischen RFID-Entwicklungsschema auf Höhe einer Werkstattfertigung, Vorstellen der Hauptkomponenten des DVSM (d.h. Event Extractor-Engine, AVSM-Engine, VVSM-Engine, Real-time Rules-Engine und LPTE), Demonstration der Durchführbarkeit von

DVSM in Bezug auf die Ziele des Leans durch Entwicklung verschiedener Lean-Practices und Tool-Modules, welche durch RT-LCRs unterstützt werden (z.B. Real-time Manufacturing Lead-time Analysis, Smart Real-time Waste Analysis, Real-time Dispatching Priority Generator (RT-DPG), Real-time Smart Production Control (RT-SPC), Smart-5S, Smart Standardized Work, Smart Poka-Yoke, Real-time Manufacturing Cost Tracking (RT-MCT), etc.), Verifizierung der Effektivität von RT-LCRs in RT-DPG- und RT-MCT-Modulen durch eine, mit der Software ProModel erstellte, Simulation. Abschließend: Vorschlag einer Rahmenstruktur der Lean Tools "Smart-5S, Smart Standardized Work, Smart Poka-Yoke", zur Implementierung in die Umgebung der Schaltwerkproduktion.

ACKNOWLEDGEMENTS

In the name of Allah, the Most Gracious, the Most Merciful

First and foremost, all praise and thanks are due to The Almighty Allah for his endless blessings for completing this dissertation, and peace and blessings be upon His beloved Messenger “Mohammed” (SAAW).

I would like to express my heartfelt gratitude to my supervisor Prof. Dr.-Ing. Bernd Noche for his appreciated support and guidance during the thesis period that kept me working on the right track. I am also thankful to co-supervisor Prof. Dr.-Ing. habil. Gerd Witt for his sincere support and valuable remarks. I am grateful also to Prof. Dr.-Ing. Rüdiger Deike and Professor Dr. Rainer Leisten for being my intern examiners and for their constructive remarks.

I would like to direct my thanks to all my colleagues in TUL, special thanks go to Mohammed Ruzayqat, Bashir Salah, Abdelrahim Alsoussi, Mohammed Alnahhal, and Batin Latif Aylak for the friendly atmosphere. I would like also to thank Mr. Hassan Al Maimani for his technical assistance in proofreading my doctoral dissertation.

I would like also thank Konrad Adenauer Stiftung [KAS] for their financial support to pursue my Master and PhD degree in Germany.

A special thank is dedicated to my Parents and Brothers for their endless sincere prayers and moral support over these years. I am truly indebted to their support, encouragement, prayers and unconditional love.

Finally, yet most importantly, I would like to express my heartiest thanks and deepest appreciation to my wonderful wife, ISRAA and my sons, OMAR and LAYANA for being a steadfast source of encouragement and inspiration to me. Thank you for being a wonderful family and going through the difficulties of having a student husband and father.

Muawia Ramadan
Duisburg, 29.02.2016

Table of Contents

List of Figures

List of Tables

List of Acronyms

- **5S**	Workplace Organization
- **ABC**	Activity-Based Costing
- **AO**	Assembly Operator
- **AVSM**	Actual Value Stream Mapping
- **CEP**	Complex Event Processing
- **CIF**	Customer Importance Factor
- **CM**	Cellular Manufacturing
- **CR**	Critical Ratio Scheduling
- **CRM**	Customer Relationship Management
- **CTP**	Cost-Time Profile
- **DCS**	Distributed Control System
- **DPV**	Dispatching Priority Value
- **DRs**	Dispatching Rules
- **DSO**	Dynamic Smart-Objects
- **DVSM**	Dynamic Value Stream Mapping
- **DVSM-DB**	Dynamic Value Stream Mapping-Database
- **EDD**	Earliest Duet Date
- **EEE**	Event Extractor Engine
- **EPC**	Electronic Product Code
- **ERP**	Enterprise Resource Planning
- **FGs**	Finished Products
- **FIFO**	First-In-First-Out
- **GUI**	Graphical User Interface
- **HMI**	Human Machine Interaction
- **IB/OB**	Input/output Buffer
- **IO**	Inspection Operators
- **IrDA**	Infrared Data Transmission
- **IT**	Information Technology
- **JIS**	Job of Identical Setup
- **JIT**	Just-In-Time
- **KC**	Key-Condition
- **LEI**	Lean Enterprise Institute
- **LNRO**	Largest Number of Remaining Operations

LO	Logistic Operators
LPT	Longest Processing Time
LPTE	Lean Practices and Tools-Engine
LPTs	Lean Practices and Tools
MES	Manufacturing Execution System
MIT	Massachusetts Institute of Technology
MLT	Manufacturing Lead Time
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
NVA	Non Value Added
NVAT	Non-Value Added Time
ORFPM	On-Line RFID-Based Facility Performance Monitoring
PAC	Production Activity Control
PC	Penalty Cost
PDAs	Personal Digital Assistant
PLC	Programmable Logic Controllers
PO	Production Operators
POLCA	Paired-Cell Overlapping Loops of Cards with Authorization
PSF	Production Shop-Floor
QRM	Quick Response Manufacturing
RFADP	RFID-Based and Agent-Oriented Distributed Production
RFID	Radio Frequency Identification System
RMs	Raw Materials
ROI	Return of Investment
RT-CEP	Real-time Complex Event Processing
RT-CTP	Real-time Cost-time Profile
RT-DPG	Real-time Dispatching Priority Generator
RT-DSG	Real-time Dynamic Scheduling Generator
RT-KM	Real-time Knowledge Management
RT-LCR	Real-Time Lean Control Rules
RTLS	Real-Time Location System
RT-MCT	Real-time Manufacturing Costs Tracking Module
RT-MES	RFID-Enabled Real-time Manufacturing Execution System
RT-RE	Real-Time Rules-Engine

- **RT-REB**	Real-Time Rules Expression Builder
- **RT-SM**	Real-Time Scheduling Model
- **RT-SPC**	Real-time Smart Production Control
- **RT-SWA**	Smart Real-Time Wastes Analysis
- **RTU**	Remote Terminal Unit
- **RT-VE**	Real-time Visualization Engine
- **SCADA**	Supervisory Control and Data Acquisition
- **SCM**	Supply Chain Management
- **SME**	Society of Manufacturing Engineers
- **SMED**	Single Minute Exchange of Die
- **SNRO**	Smallest Number of Remaining Operations
- **SO**	Smart-Objects
- **SOA**	Service-Oriented Architectures
- **SPT**	Shortest Processing Time
- $\mathbf{SR}_i$	Sub-Rules
- **SSO**	Static Smart-Objects
- **SUP**	Supermarket
- **TEI**	Tree of Event Instances
- **TPM**	Total Productive Maintenance
- **TUI**	Touch User Interface
- **VA**	Value Added Activity
- **VSC**	Value Stream Costing
- **VSM**	Value Stream Mapping
- **VVSM**	Virtual Value Stream Mapping
- **WfMS**	Workflow Management System
- **WIP**	Working-In-Process or (Work-In-Progress)
- **WMS**	Warehouse Management System
- **WS**	Workstation

CHAPTER 1
Introduction

This chapter introduces a short overview about the research area i.e. lean manufacturing, and describes the lean problems and challenges as the main motives behind this research. It also explains the main research objectives and contributions. Finally, an outline of the thesis framework is provided.

1.1. Overview

Lean Manufacturing has become the most widely known and prominent approach in the pursuit of perfection and in strengthening the competitive edge in today's global markets. Lean manufacturing encompasses a wide range of tools that have the ability to maximize profit and at the same time, minimize waste in manufacturing processes, when practiced and applied in the day-to-day activities of an enterprise [HT00] [BSW+11]. Of all the available lean tools, Value Stream Mapping (VSM) comes across as one of the most powerful lean tools for lean transformation. VSM plays a crucial role in the journey towards lean- a never-ending journey, in which one continuously strives for a leaner production environment, in which waste is non-existent. The journey begins once a "value" has been defined based on the needs of the customer. The "value stream" can be analyzed through mapping the product and the corresponding information flow along a manufacturing system. Through thorough analysis of the value stream, the main criticalities or wasteful activities as well as their root sources can be identified, in order to apply the most suitable lean tools and techniques which fuel the elimination of waste, leading to a leaner production environment [BCZ06][LS07]. However, today's global markets drive manufacturers to create more complex job-shop manufacturing 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, specification, quantities, wide variety of components, smaller-lot size, etc.)[LV02][GKK08][KS09][Vel12][RNI+13]. Therefore, it has become increasingly difficult to address or represent this situation with simple and traditional methods like VSM. Since VSM is actually a paper-based data collection method, several factors contribute to its ineffectiveness and incapability as a solution to the ever-increasing demands of today's manufacturing systems, including: prone to data errors, time-consuming, and labor intensive, etc. These factors lead to incomplete, inaccurate, misleading, as well as untimely information and results, which then severely affect the lean decision-making process as a whole [HZD+09][VPR09]. Moreover, VSM, with its static nature, has limited ability to dynamically capture the complexity and the continuously changing behavior of such manufacturing systems. In other words, traditional VSM has become incapable of reflecting the real situation of complex manufacturing systems, as a VSM which is built from time averages (i.e. time average-based VSM) will only display the general condition of the value stream. Thus, traditional VSM is insufficient to represent an accurate picture of real-time situations, leading to an ineffective lean transformation [Che06]. Even after lean transformation, VSM still remains an ineffective tool when it comes to the interaction with rapid changes in production environments in terms of products and processes, since VSM information becomes outdated over time. The inability of manufacturers to adapt to the "continuous changes", prevents manufacturers from staying lean in the long term and the achievement of lean targets will be hindered. Thus, to solve these problems, the efficiency of VSM needs to be improved for better lean practicing, where new methods and technologies can be utilized [LV02].

In this context, there has been growing interest in the use of RFID (Radio-Frequency Identification) technology in manufacturing, to digitalize manufacturing information and improve the overall production performance. As a real-time production data capturing system, RFID plays a vital role in providing companies with immediate, accurate, and detailed information regarding the current production system [BR05]. With this technology, any object on the Production Shop-Floor (PSF) could be turned into a "smart-object" and thus, becomes identifiable in real-time to the existing information system. However, RFID adoption did not spread as rapidly as initially expected, due to many reasons. One reason is that manufacturers have not fully realized or understood the potentials of this technology in practice. To this day, no methodologies describe clear steps on how to utilize the captured real-time production data to bring more benefits and to obtain a return of investment (ROI) [FSG08][LCC14]. Besides that, the integration of RFID through the current Information Technology (IT) systems remains a big challenge [GKK08], providing further evidence that RFID technology has not yet reached its mature point for companies to adopt this technology [LLG+08]. In this context, [PN11] have indicated that an integration of RFID within the area of lean approach may bring revolutionary improvement for conventional lean practices and push companies into leadership positions within their industries. Furthermore, the recent advancement in using IT systems and wireless technologies may facilitate the integration between RFID and lean approach to develop a real-time intelligent lean manufacturing system. However, the current IT systems are push-oriented systems, which make them incompatible with lean principles that advocate pull production principles, which are based on customer demand [CA06].

For rapid RFID maturity and success, this research addresses the integration of real-time data capturing technologies, mainly RFID with VSM concepts to develop a computerized real-time lean-oriented IT system, known as “Dynamic Value Stream Mapping” (DVSM). It is built around the idea that, RFID and other supportive real-time data capturing systems are able to track the status of any smart-object on the PSF in the form of value streams and automatically map the value stream of the individual products with all relevant-production information. Thus, DVSM is able to keep up with the highly dynamic behavior of the manufacturing system by bridging the time-gaps between physical events i.e. flows of products and the generated corresponding interaction events between smart-objects on the PSF, from one side and the associated information flow on the operational and higher enterprise level from the other side; in order to enhance, support, reinforce, and sustain lean principles by keeping them alive for a leaner manufacturing environment in the long-term.

1.2. Problem Statement and Motivation

The complexity in today’s manufacturing systems driven by rapid changes in global markets based on customer requirements e.g. highly customized and low product life cycles with high quality and shorter lead times, makes practicing lean more difficult and inefficient [Vel12][ZDQ+13]. The lack of real-time visibility and monitoring systems complicates the situation even more as the dynamic behavior of production systems is not captured [MKM+12]. Apart from that, a shorter product life cycle leads to continuous changes in terms of manufacturing processes, causing lean initiatives in such manufacturing systems to die over time, due to the lack of continuous care and supervision [Ver04]. Another reason for the low success rate of lean in such environments is that lean has been designed for repetitive and stable production systems with a high-volume and low-mix work environment with stable demand and a low degree of customization which is in contrast to the needs of today’s global markets [Ver04][Vel12][Cho12]. Therefore, it is a matter of lean transformation and survival in complex and dynamic manufacturing systems without the support of any real-time lean-based dynamic mechanism [Ami13].

Practically, the lean challenges begin with the building of the VSM, which can only build one process flow at a time. As mentioned before, its static nature makes it hard to reflect the dynamic behavior of production systems and adapt to the continuous changes. Another barrier to a successful and effective lean implementation in dynamic-behaving systems is that the VSM is only capable of displaying information based on a one-time observation [CCC12].

Recently, in order to address these new challenges, there has been an increase in studies conducted by lean researchers such as [BCZ06][SKC$^+$06][SBG09][GK11][VSV11][KA13][PB14], who were content with conventionally refining lean methods to extend their abilities to adapt to the new situation. For instance, [SBG09] has investigated how lean production control principles can be used in a high-variety and low-volume job shop, [BCZ06] proposed an approach based on seven iterative steps to enhance lean implementation in complex manufacturing systems, while [AAW09][SG09][RNI$^+$13] have developed a dynamic VSM model through the integration of VSM and the simulation model to apply lean concepts. Despite all the significant work that has been carried out within the scope of VSM-simulation integration, the dynamic VSM still only represents one snapshot, which means that the simulation cannot provide real-time decisions for the actual performance along the value stream because the VSM cannot dynamically interact with the current situation on the PSF in real-time, as it works in offline-mode. Other researches go beyond lean, for instance [KS09] developed an approach known as "Quick Response Manufacturing" (QRM) with a method called "Paired-Cell Overlapping Loops of Cards with Authorization" (POLCA) which may be more effective than kanban control to address the complexity associated with multiple job routings.

However, these new approaches still have limited abilities to tackle the dynamic behavior and complexity of manufacturing systems that require what-if analysis and a higher predictability level based on lean concepts [Vel12]. The lack of an efficient dynamic lean transformation and sustainability tool for real-time monitoring and controlling supported by timely, accurate, and comprehensive real-time manufacturing operations data; further intensifies today's lean challenges which leads to lean failure in dynamic environments [MKM$^+$12][CS13]. Thus, lean faces a high chance of failing in today's manufacturing environments, as most companies fail to sustain the lean improvements that have been applied at the early implementation stages, as confirmed by the Society of Manufacturing Engineers (SME) [Sch09]. In other words, there has not been any groundbreaking and distinguished development of Lean Practices and Tools (LPTs) since 1934 that supports lean companies to cope with today's manufacturing challenges [KS09].

As a result of this, there is a need for a dynamic lean-based tool that constantly monitors the manufacturing process to not only effectively support and enhance the implementation of LPTs, but more importantly, to prevent them from becoming obsolete over time and to keep these principles alive and effective in the long-term in environments with high complexity, uncertainty, variability and dynamical behavior. This leads to the question of "how can manufacturers support LPTs in today's manufacturing environments?"

With the recent advancement of IT systems and wireless technologies, there has been growing interest in the manufacturing world to adopt RFID in order to digitalize the manufacturing information and automate the manufacturing processes [LCK09]. In context of RFID applications, several researches [Att07][GKK08][SV08][CXZ09][SPL09][VPR09][Rey11] have been conducted concerning RFID adoption in logistics, supply chains, manufacturing and other fields. These papers explore several benefits of RFID; 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 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 will not significantly benefit a manufacturing enterprise if they simply use it for tracking the location of products and do not use it beyond this point.

Although significant work has been carried out in the field of RFID adoption, the use of RFID is still controversial, questionable, doubtable, and did not spread as rapidly as initially expected, because manufacturers are still quite hesitant to adopt RFID. According to the survey conducted by RFID-Roadmap Project CERP in 2006 about RFID implementation obstacles, the results indicated that the lack of implementation standards and knowledge about best practices to gain more benefits, and the difficulties of integrating RFID with the current Enterprise Resource planning (ERP) systems are the most prominent obstacles hindering RFID adoption. This means, that the full potential of this technology has not yet been realized in practice. As a result, the success of RFID depends on the ways of utilizing the captured real-time data [LLG+08][Cho12].

To overcome these challenges, there has been a trend to integrate RFID with other manufacturing approaches. A few studies have investigated the possibility of combining RFID with lean approaches. For instance,[BR05][PN11] explore the relationship between lean and RFID in eKanban. [ZJH08] proposed a Just-In-Time (JIT) wireless manufacturing framework that is based on RFID to support the functionality of smart-kanban. [SMH+09][JFZ10] also proposed an RFID-based Kanban framework in lean environments. [BRM10][CS13] have investigated the importance of shop floor real-time visibility through accurate RFID automated captured data in reducing the wastes and improving lean performance. Empirically, [CCC12] have integrated the VSM concept with RFID to automatically generate a real-time VSM which is to be used as an online facility performance monitoring system.

Despite the significant scientific contribution of these studies, they are only considered as kanban-oriented approaches, since these studies limit their scope on improving the ability of a kanban system. In this case, kanban may not work effectively without reinforcement from other LPTs, since LPTs are mutually supportive. Similarly, the scope of other studies has only been limited to a specific lean tool targeted by manufacturers. Moreover, they unsystematically use RFID as a tool for detecting incidents or for mistake-proofing, which is not compatible with VSM concepts as a systematic lean waste analysis tool. Some studies on the other hand, compare RFID with barcodes, specifically its role in reducing time consumption in the data capturing process. As a result, there is almost no study that has been conducted to investigate the integration of powerful abilities of RFID to support lean tools and techniques within lean boundaries, where lean is a comprehensive, integrated, and holistic manufacturing approach that covers all manufacturing aspects, through a diversity of powerful tools and techniques working in conjunction with each other to effectively reduce wastes and maximize value.

Another key challenge in RFID integration is the vertical integration across current and pre-existing IT systems, which play an increasingly important role for manufacturers [GKK08]. Therefore, each manufacturer has to develop a solution from scratch, without the foundation of a design framework [Iva08]. Although such integration can be developed, the current IT systems are incompatible with lean manufacturing principles which will lead to a mismatch between improvements based on lean principles and the current production control applications, since lean advocates a pull production system on the shop-floor level, while traditional IT systems support push production systems and pay little to no attention to flow efficiency and individual lean techniques [CA06]

[CVS+11][PS12]. As a result, efficient lean manufacturing in today's production systems without the support of real-time lean-oriented IT systems becomes inconceivable and unachievable.

In light of the aforementioned multi-dimensional challenges, this research is driven by the fact that while several researchers have widely investigated RFID adoption in supply chains, logistics, and other manufacturing areas in different industries, almost no study has systematically investigated how to integrate RFID with a lean approach to pave the way to build a computerized real-time lean-based system for intelligent lean manufacturing implementation in the next-generation manufacturing systems.

1.3. Research Objectives

This research addresses a two-dimensional problem; firstly, the challenges and limitations of lean manufacturing in today's manufacturing systems, where lean has become inefficient and difficult to be practiced; and secondly, the adoption of RFID in manufacturing, which remains questionable and doubtable, as manufacturers are still quite hesitant to adopt it in their manufacturing systems.

The main objective of this thesis is to structure a solid basis for a standard framework of a digitalized smart real-time lean-based system that is able to overcome today's lean manufacturing challenges and to describe the best practice of RFID technology in manufacturing systems. This framework presents the integration of real-time production data captured via RFID with lean manufacturing initiatives in manufacturing systems, in order to achieve an intelligent, comprehensive, integrated, and holistic real-time lean-based manufacturing system. This system works automatically according to lean concepts that cover all manufacturing aspects, through a diversity of powerful tools and techniques working in conjunction with each other to effectively reduce wastes and maximize value.

Based on the concepts of traditional VSM, where the time-based flow is greatly emphasized and considered as the most critical success factor of lean; the initial step of this study starts with building the main concepts of the framework for a digitalized VSM that integrates RFID technology with lean manufacturing initiatives. The proposed framework that will be presented in this thesis is known as Dynamic Value Stream Mapping (DVSM), a computerized event-driven lean-based IT system that contains different real-time modules to enhance and sustain LPTs in production systems. DVSM is proposed to be used at an intermediate operational level, where the administration level i.e. ERP and the PSF level will be combined to achieve an integrated real-time lean enterprise.

The framework will also illustrate how DVSM, as a lean IT system, can intelligently monitor and control lean operational issues on the PSF. Thus, the DVSM is proposed to contain several real-time lean-based operational modules concerning LPTs (e.g. JIT, 5S, Poka-yoke, line balancing, SMED, Takt-time controller, etc.), where each module is equipped with suitable algorithms or mathematical models which are translated into what is known as Real-Time Lean Control Rules (RT-LCRs), that are based on the Complex Event Processing (CEP) mechanism. The thesis provides a systematic explanation on how RFID captured real-time data can be effectively utilized to support the functionality of LPTs-Modules that continuously provide supervision on the practicing of LPTs as well as to systematically detect unwanted incidents and unforeseen disruptions that have occurred and smartly generate the appropriate real-time re-(actions). In this regard, a dedicated module has been developed to automatically detect the root causes of wastes along the value stream in term of time. Besides that, with the proposed DVSM, the sudden operational changes such as rush orders, specification changes, prioritizing and planning activities, etc. can be tackled in order to achieve lean goals. Figure 1.1 below, summarizes the function of DVSM in manufacturing environments as an enabler to achieve a real-time closed-loop lean manufacturing system. AVSM stands for Actual Value Stream Mapping that represents the current situation on the PSF, whereas VVSM stands for Virtual Value Stream Mapping that represents the ideal or the planned situation on the PSF. As the workers play an important role in lean transformation and sustainability, they are included in the DVSM-modules, and thus they become a part of the live interaction with real situations.

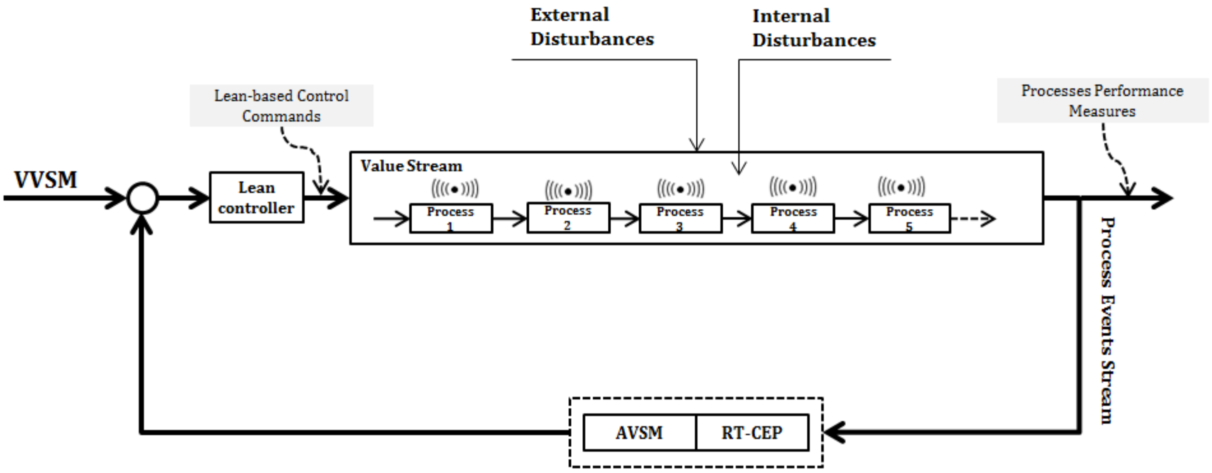


Figure 1.1. An Overview of a Real-time Intelligent Lean Control System.

Another addressed aspect in this research is the financial aspects of production, as the traditional VSM does not pay attention to the cost along a value stream. A real-time manufacturing cost tracking and monitoring model has been developed as a part of DVSM-modules. This module allows manufacturers to evaluate the benefits of lean improvements-and establish root cause analysis with regards to costs, to pinpoint the sources and locations of the most costly wastes, so that lean improvement efforts can be prioritized to eliminate the most costly wastes.

As a result, this thesis aims to fill the gap of knowledge regarding the use of RFID technology and tries to remove the ongoing doubts and ambiguity about RFID adoption in manufacturing areas. It shows that more RFID benefits can be harvested through Lean-RFID integration and in parallel; an alternative solution for lean practitioners instead of a paper-based lean implementation will be introduced. This will convince manufacturers to adopt RFID in their manufacturing systems and consequently achieve a short-term ROI as well as contribute to solve today's lean challenges.

1.4. Thesis Outline

In order to achieve the research objectives, figure 1.2 shows the research methodology used within this doctoral research. This thesis is organized as follows:

➔ **Chapter 2** provides a general introduction to the research topic, which is necessary to understand the contribution of this work. It provides on one side a review about lean manufacturing practices and tools, the common types of waste in lean environments, and the challenges of lean implementation in today's manufacturing systems. On the other side, it reviews the role of automatic real-time data capturing technologies, namely RFID, which has special characteristics and superior capabilities, in different manufacturing areas.

➔ **Chapter 3** introduces a framework of a new kind of smart real-time monitoring and controlling lean-based IT mechanism for the next-generation of manufacturing systems with dynamic and intelligent aspects concerning lean targets. The proposed mechanism is known as Dynamic Value Stream Mapping (DVSM), a computerized event-driven lean-based IT system that runs in real-time according to lean principles that cover all manufacturing aspects through a diversity of powerful practices and tools to effectively reduce wastes and maximize value. Therefore, DVSM represents an intelligent, comprehensive, integrated, and holistic real-time lean-based manufacturing mechanism. This chapter is considered as the core of this dissertation.

➔ **Chapter 4** introduces a real-time time analysis framework to track the manufacturing lead time (MLT) of an individual product along the value stream in real-time, in order to identify its time-components, and accordingly measure the leanness of the production environment in terms of time. In this context, the wastes in a manufacturing environment are converted into time and hence, lead to longer MLT. Here, the traditional VSM lean tool is not able to understand the dynamic interactions, and thus, it is incapable of uncovering the potential wastes which are inherent within the processes or identify their root-causes. Therefore, this chapter also introduces a smart real-time waste analysis mechanism based on the time-segments of the MLT to pinpoint the most wasteful activities, and thus the most critical product-state that influences the duration of the MLT. This kind of mechanism is proposed to make the hidden root-causes of wastes immediately visible through real-time waste analysis, so that they can be avoided or treated directly.

➔ **Chapter 5** addresses the significant role of RFID in smart lean manufacturing environments or lean-based digital factories. This chapter systematically discusses the utilization of RFID systems beyond tracking purposes to include intelligent real-time monitoring and controlling of production operations concerning lean targets. Therefore, this chapter introduces the best practice of RFID technology to smartly support LPTs during daily production runs to keep lean system alive and effective.

➔ **Chapter 6** introduces an innovative real-time costing framework incorporating lean manufacturing and RFID for bridging the gap between lean operational aspects and financial costs together in real-time. The developed framework is called Real-time Manufacturing Cost Tracking System (RT-MCT) module, which is executed in real-time by DVSM-LPTE. The need for such a costing method is vital in identifying the root causes of redundant costs and pinpointing the most costly root causes and their locations, so they are targeted with the highest priority to be eliminated. Furthermore, this costing method mirrors the monetary impacts of implementing lean improvements at various value stream stages in today's mass-customization production environments. The system presented is validated through ProModel simulation software along with extensive calculations, moreover, a demo software using java has been developed.

➔ The thesis will conclude with a brief conclusion.

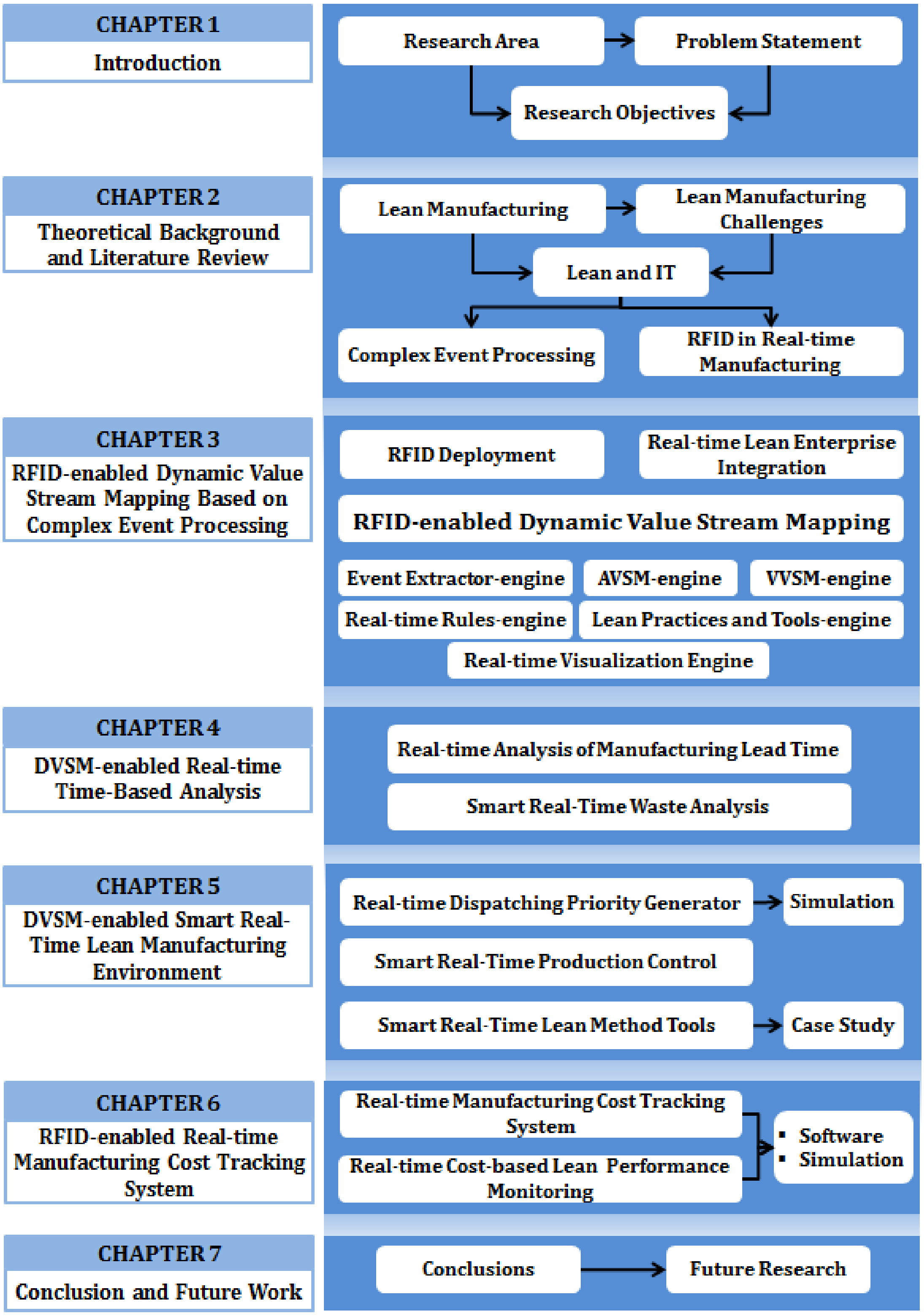


Figure 1.2. The Research Methodology of this Dissertation.

CHAPTER 2
Theoretical Background and Literature Review

This chapter provides a general introduction to the research topic, which is necessary to understand the contribution of this work. This part of the research provides on one side a review about lean manufacturing practices and tools, the common types of waste in lean environments, and the challenges of lean implementation in today's manufacturing systems. On the other side, it reviews the role of automatic real-time data capturing technologies, namely RFID, which has special characteristics and superior capabilities, in different manufacturing areas.

2.1. Introduction

Lean manufacturing is a production philosophy that encompasses different tools and practices to systematically identify and eliminate different forms of waste. The implementation of lean concepts has shown significant impacts on various industries. Numerous conducted studies have tried to develop lean tools and techniques to tackle the challenges of today's manufacturing systems, in order to eliminate waste and achieve perfection. However, despite the advancement of using real-time IT systems in manufacturing, not much attention has been given to combine lean with IT to enhance and ensure a leaner environment as well as to reach lean targets [BRM10]. Furthermore, the traditional IT systems, such as ERP and MES are incompatible with lean manufacturing principles, since they are push-oriented IT systems [CA06][CVS+11].

In this context, today's lean challenges in manufacturing systems demand a revolutionary improvement to keep lean tools and practices effective and prevent them from becoming obsolete, especially since the development of LPTs in 1934, there has not been any groundbreaking improvements [KS09]. As mentioned, one solution to support and enhance the extent of LPTs is an integration of lean concepts with real-time IT systems. In other words, a real-time IT system can improve the quality of information (i.e. accuracy and timeliness) and consequently facilitate the adoption of lean practices.

In context of real-time visibility, RFID technology can be considered as the major enabler to support a lean-oriented IT system with real-time production data. To enhance its functionality, RFID can be supported by other data capturing systems (e.g. sensors, digital cameras, data-entry systems, etc.) to reach about 100% PSF visibility [CS13].

RFID technology is an emerging technology in manufacturing due to its ability to record products, materials, equipment, and personnel information at an item-level in a way that is fully automatic, instantaneous, and touch-free [Qin11]. RFID could be used to achieve a leaner environment through a better and effective usage of real-time production data to support lean practices and tools, leading to waste elimination and an overall improvement in competitive strategy. Subsequently, the efficiency and effectiveness of operations can be improved constantly, leading to higher levels of customer service and lower costs.

2.2. Lean Manufacturing

Due to fierce competition in today's global markets and to strengthen competitive edge over competitors, many manufacturers have adopted lean manufacturing; one of the most prominent practices, that has been proven effective [WA10][GLB$^+$13]. The term "lean" refers to a system that utilizes less of everything during production – less labor, less manufacturing space, less equipment, less inventory, and less engineering inputs during development and processing; to create the same outputs as those created by a traditional mass production system [Pan98][Rus09]. Lean manufacturing is a comprehensive set of practices, tools, and techniques; that aims to eliminate wastes and improve the effectiveness and performance of a production system [Wil09]. The basic idea behind lean manufacturing is the identification of waste (or "muda", the Japanese word for waste) which has to be eliminated, in order to achieve the fundamental goal of any company including reducing costs, increasing productivity, increase flexibility, and focus on the activities that add value from the customer's perspective [Ōno88][MK07]. From the customer's perspective, value is equivalent to anything that the customer is willing to pay for in a product or the service that follows [Abd03]. To reach these goals, lean manufacturing focuses mainly on material flow; from the moment the material enters the process to the moment when a product is ready for the customer [WJR08].

2.2.1. Type of Wastes

Waste can be defined as unproductive manufacturing practices and activities that absorb resources, thus adding costs to products but creating no value [WJ10]. Waste has different forms; the most common types are the seven wastes categorized by [Ōno88]. The seven cardinal wastes and their potential causes are discussed below:

1. Overproduction: Producing more, producing earlier and/or faster than required by the next process are some examples of overproduction.
2. Waiting: This refers to the idle state of objects waiting for other resources as labors, materials, machinery, measurement or information.

3. Transportation: This includes any unnecessary movement of people or products between workstations across the PSF.
4. Motion: This includes unnecessary motion of labor, WIPs, tooling and equipment that does not add value to the product or service" within a workstation.
5. Over-processing: Extra efforts which add no value from customer perspectives.
6. Excess inventory: Excessive raw materials (RM) and work-in-process (WIP) inventories waiting to be processed.
7. Defects and Reworks: Defects are non-conforming products which do not fulfill customer requirements.

Nearly every waste in the production process can fit into at least one of these categories, though many researchers have extended the list of manufacturing wastes to encompass many other wastes (e.g. space utilization, energy consumption, and underutilizing people and resources) [WJ10]. The sources of waste causes a vicious circle; and the worst type among the seven wastes is overproduction because it leads to all kinds of wastes (i.e. it leads to excess inventories, extra space, extra handling which require extra labor and equipment, and bins, extra quality problems, etc.)[RS99].

However, in today's manufacturing systems, almost no research has discussed the possibility of developing a real-time smart mechanism which is able to detect the sources of waste in real-time and automatically generate re-(actions) without human intervention, such as exceeding inventory threshold, wrong assembly or transport and misplaced tools.

2.2.2. Lean Manufacturing Practices and Tools- LPTs

Over the years, different lean tools, practices, concepts, and techniques have been developed and evolved for different production improvements and waste elimination [RT99][GD01]. These tools may exist with different names; some of them may even have an application scope that overlaps with other tools [PGJ03]. Some of these tools can be successfully used on their own, while others require support and reinforcement from other tools to achieve an effective and holistic lean system. In different words, lean tools should work in conjunction with each other, since they are mutually supportive.

Based on several references [RT99][Fel02][AR07], the most important and common lean tools are briefly described in this section. According to [AR07], lean tools can be classified into three main groups: (1) Quality Tools, (2) Production Process Tools or Just-In-Time (JIT) Systems, and (3) Lean Methods Tools. These three groups are the pillars of the "House of Lean Manufacturing", as seen in figure 2.1.

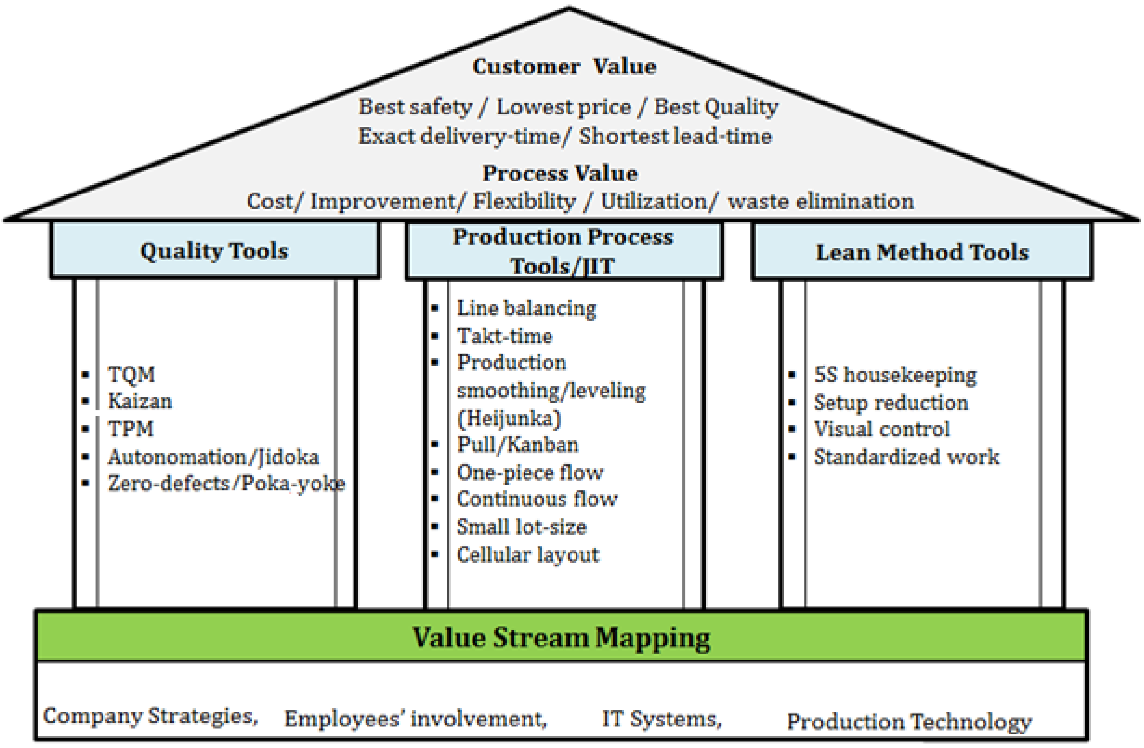


Figure 2.1. The "House of Lean Manufacturing" [Pow12].

The base on which these three pillars stand on is "Value Stream Mapping" (VSM), which was originally developed and published in the book "Learning to See" by Mike Rother and John Shook [RS99] and it has become one of the most powerful tools for lean implementation [WF08][AAW09]. In principle, VSM is a simple paper and pencil tool used to map and visualize the time-based information of the material flow within the manufacturing processes as well as the corresponding resources usage.

The main pillar "Production Process Tools" encompasses effective tools in the area of production processes. The most important is JIT which consists of three elements: JIT-production, JIT-distribution, and JIT-purchasing. JIT-production is the backbone of lean manufacturing, which is limiting the quantity of RM, WIP, and final goods (FG) to the required amount for one-piece flow operations [Mon98]. The "kanban system" acts as the nervous system of JIT-production by directing materials just-in-time to workstations. In this context, "Takt-time" is used to synchronize the pace of production with the pace of demand (e.g. producing one piece every 71 seconds). By producing according to Takt-time and utilizing the kanban for JIT, smaller lot sizes, timely coordination and synchronize WIP movements, huge inventory reductions, the prevention of over-production can be achieved, since every process is producing at a pace that is not higher than the demand. Thus, RM, WIPs, sub-assemblies, and FG inventories are kept at minimum level as one of the key performance measure of lean. Other practices can be used for JIT objectives, such as “continuous flow” that refers to producing one piece at a time and passing it immediately from one process step to the next without stagnation in between. The “line balancing” lean concept guarantees “continuous flow”, by ensuring that each workstation is producing in a synchronized manner. However, for the interrupted flow, a “supermarket” can be used to handle WIPs when continuous flow is not possible [RS99]. Another tool to achieve an effective JIT is “production smoothing” or in Japanese, “Heijunka”, it’s called also “load-leveling box”. The core of Heijunka is “leveling the production volume and production mix” to keep the production level as constant as possible during daily production runs. Besides that, in terms of production smoothing, manufacturers have to be committed to reduce the lot-size to the optimal quantity to maintain the Takt-image [RS99]. Reducing lot-sizes should be followed by the lean method of “set-up time reduction” or “Single Minute Exchange of Die” (SMED).

Because layout design also plays a critical role in lean manufacturing environments, “cellular manufacturing” (CM) should be applied. CM is an application of group technology (GT), where a portion of the manufacturing system should be converted into cells (e.g. U-shape).

Once a production system has continuous flow, small-lot sizes, and applies CM concepts, a fundamental element of lean known as “one-piece flow” will be achieved.

In Lean Method Tools, “5S-housekeeping process control” practice is one of the most effective tools for continuous improvement and it is used to eliminate wastes that are caused by a poorly organized work area (e.g. wasting time looking for a tool). 5S stands for five effective Japanese housekeeping concepts: “Sort” (Seiri): eliminate all unnecessary tools, parts, and instructions; “Set in Order/ Straighten” (Seiton): assigning the right sorted object to the right workplace. “Shine” (Seiso): deals with the cleanliness of the workplace, which should look organized, clean, and ready for use for the next shift; “Standardize” (Seiketsu): standardize housekeeping rules through the systematic practicing of housekeeping rules to prevent reverting back to the old ways of working; and Sustain (Shitsuke): the reinforcement of the importance of housekeeping by ensuring that workers have "self-discipline" without being told [Fel02].

Another important lean methods tool is “work-standardization”. Manufacturers achieve standardized work, by finding the best practice to produce each item according to Takt-time and document it. The Lean Methods Tool, “visual control” encompasses the concept of line-of-sight management. One application of visual control is the “Andon” device that indicates the “status” of a machine, line, or process.

The third group of lean tools is the Lean Quality Tools; TPM is the cornerstone of support JIT and lean manufacturing sustainability [Fel02]. There are three main aspects of a TPM system: preventative maintenance, corrective maintenance, and maintenance prevention.

Kaizen refers to the philosophy of continuous and ongoing improvements of manufacturing, engineering, business management processes, etc. and it involves everyone - top management, managers and workers. It is like a never ending journey.

Another key element in successful lean manufacturing implementation from a quality perspective is the autonomation/Jidoka tool. These tools have the capability to automatically stop the production line, either by machines or by humans, if defects or abnormalities (e.g. quality problem, wrong sub-assemblies) are detected using supervisory functions or techniques.

One well-known kaizen event is Poka-yoke or the practice of mistake-proofing, which is also considered as one of the autonomation/Jidoka techniques to achieve a production system with “Zero-defects”.

In this section, the most common lean tools are briefly discussed. In this context, several waste reduction tools can be involved in lean initiatives, which is necessary to achieve an effective lean manufacturing environment. Essentially, lean tools need to work in conjunction with each other and the failure in one of them will impact others, and thus the overall lean environment.

2.3. Lean Manufacturing Challenges in Today’s Manufacturing Systems

In recent times, there have been challenges in the deployment and implementation of lean tools in manufacturing systems, preventing manufacturing organizations that have deployed lean manufacturing initiatives from successfully achieving lean goals. Many research papers [GD01][PGJ03][Ver04][Ami13] have investigated lean implantation in manufacturing systems, however due to rapid changes in products and technologies, lean initiatives simply diminish in the long run.

From value stream perspectives, the success of lean transformation can be hindered by external and internal challenges or obstacles. External challenges arise due to external causes and include: 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.

[WF08]. It their turn, the external challenges will create several internal challenges including: high product variety-low volume manufacturing environment, product complexity and large number of needed components in assembly lines, similarities between components and subassemblies, production variability, quality issues, variance in the cycle times for each process, different routings, turbulences in schedule due dates, priorities, etc. This implies that an accurate and timely flow analysis of such complex and dynamic manufacturing environments become fairly difficult and impact the success of lean transformation. Therefore, lean transformation and sustainability in such environment becomes more complicated and has an even lower chance of succeeding, since lean is designed for repetitive-production systems with a high volume and a low mix work environment with stable demand and a low degree of customization [Ver04] [Cho12][Vel12].

The Lean Enterprise Institute (LEI) has published some of the most common obstacles for lean implementation and sustainability [Cho12],including: Backsliding to old ways of working; the lack of know-how implementation; the lack of a crisis to create a sense of urgency; the cost system does not recognize the financial impact of lean of improvements; resistance by middle management, regarding lean as the "flavor-of-the-month" i.e. temporary initiative; failing to remove "anchor draggers" who oppose change; the lack of employee involvement; resistance by employees; resistance by supervisors; and failure of past lean projects. The LEI claims that more than 60 % of lean failures are a matter of sustaining problems in lean transformation where the employees are not committed to lean practices.

As a result of the above challenges, VSM arises as a major key challenge in the journey towards perfection [CGG+07]. Since the aforementioned circumstances in today's manufacturing environments cannot accurately be modeled or represented by the current generation VSM. VSM is unable to mimic the real-time behavior of the manufacturing environments nor adapt to the rapid changes in products and manufacturing processes which is considered more important than flow mapping itself [CGG+07]. The next section discusses the main limitations and drawbacks of traditional VSM in today's manufacturing environment.

2.4. Limitations of the Traditional VSM

Although VSM is considered the best industry practice to achieve lean in many manufacturing environments, unfortunately, VSM has several drawbacks that make it incapable of achieving lean strategies in today's complex and dynamic manufacturing systems. This section explores the major limitations and weaknesses inherent in the current generation of VSM that hinders an effective lean transformation and sustainability in rapidly changing global markets. Based on the reviewed literatures [LV02][BCY06][Che06][Riv06][HS08][AAW09][CCC12], the main limitations of VSM in today's manufacturing environments are summarized as follows:

- VSM is a manual and paper-based technique with limited level of detail, number of different versions, and accuracy.
- Creating the VSM is a time-consuming technique, where a team should conduct several walks in the facility and spend more time for analysis; this time will increase dramatically in today's high mix-low volume environments.
- VSM is just a snapshot for a specific period of time, thus the static nature of the current generation VSM cannot accurately see, map and model the actual performance of the highly dynamic behavior of today's PSF.
- The power and effectiveness of VSM is reduced, where collecting the average values of the aggregated data to create the VSM deceives the real conditions and misleads the decision makers. Moreover, the lost information in highly dynamic manufacturing systems may contain clues of waste causes or potential improvements.
- VSM is unable to encrypt time dependencies related to product flows, controls, process instants and time dependent causal effects.
- VSM is unable to map multiple products flow and analyze the movement of products using shared process resources.
- VSM has no mechanism to diagnose and explore the root causes of the most wasteful activities in the value stream.
- VSM lacks the ability to ensure the feasibility of lean transformation and lean sustainability after implementation.
- The VSM has no standard definition of the value added and non-value added (VA/NVA) activities to be used for diagnosing the value stream times.
- VSM is unable to track the actual transportation and queuing delays and the changes in transfer batch sizes, since it is a snapshot.
- VSM is unable to track the actual process parameters (e.g. processing-state) and the performance measures (e.g. Utilization, Takt time) of the manufacturing system.
- VSM is unable to track and map the accumulation of manufacturing costs during the manufacturing process.

- VSM is unable to draw the spatial structure of the PSF-layout to monitor the performance of intra-logistics and material handling activities.
- VSM is unable to track and present current status of the used resources as well as the WIP-inventory level in front of each process.
- VSM lacks the "what-if" analysis required to optimize the production processes.

In order to overcome the above drawbacks, there is a need to digitalize VSM concepts and combine it with the current IT systems in order to generate an accurate real-time VSM for different products simultaneously with all relevant production data, where the captured data can be utilized for real-time lean-based decision-making processes, which automatically generate the appropriate re-(actions) on the user's behalf to avoid wastes and add values.

2.5. Lean and IT

As mentioned, Lean approach depends mainly on manual efforts, using pencil and paper [RS99][CVS+11], this method works well in case of single-flow manufacturing systems [AAW09]. However, using this method for today's complex manufacturing systems will lead to inefficient lean implementation with unsatisfactory results [Dug12]. In this context, [GP11] concluded that the companies have to develop new strategies of implementing lean practices with the support from IT systems to be able to deal with today's manufacturing challenges and survive in the market. [Bel05] describes that lean and IT are interdependent and complementary. The results of [WZ06] research have provided several insights on the relationship between IT integration and lean practices; this integration contributes significantly to reduce MLT.

As a result, an efficient lean manufacturing environment without IT software support has become unachievable, impracticable and unthinkable in today's manufacturing systems [CVS+11]. In addition, the available IT systems and softwares are moderately supporting LPTs, since they are unaligned with lean objectives, for example MES provides some useful information that are necessary to support the lean journey, but it is still undedicated to constantly support LPTs' functions [CVS+11].

Moreover, since over a decade, the available IT systems and manufacturing application softwares are monolithic and cannot provide the manufacturers enough flexibility to handle their rapidly changing business processes [GKK08]. Therefore, to keep pace with today's highly dynamic manufacturing systems and to benefit from the recent advancements in IT such as Service-Oriented Architectures (SOA) [PKD+06], and the real-time data-capturing technologies, namely RFID; the manufacturers have to develop a new generation of IT systems and manufacturing application softwares that provide much more flexible, dynamic, and efficient data processing and manufacturing intelligent mechanisms.

In this regard, several researches, e.g. [Bel05][CVS+11][Pow12], have discussed the integration between Lean and the current IT systems like ERP, MES. But almost no research on this topic has been found that discusses an RFID-enabled Lean IT system that smartly reinforces the daily practicing of LPTs during production runs. In the next section, the recent adoption of RFID in different manufacturing areas is reviewed.

2.6. RFID in Real-Time Manufacturing

In recent times, auto-ID technology tools, especially Radio Frequency Identification (RFID) technology has become a promising technology, that has the ability to help enterprises to achieve their aims in terms of real-time information from manufacturing operations i.e. increasing the real-time visibility at the PSF. RFID is a technology that allows objects to be 'tagged' with a small chip and become smart-objects, which can then be tracked and read electronically [Had11]. Compared to other auto-ID technologies, RFID technology has superior features and for this very reason, has become a key enabler to support information sharing activities in enterprises and among heterogeneous application systems. Nevertheless, in order to reach 100% visibility, other data capturing technologies can be used to reinforce RFID functionality such as sensors, digital cameras, etc.

2.6.1. RFID System Components and Infrastructure

RFID allows manufacturers to track objects throughout their production and subsequent life cycle, spanning enterprise boundaries as well as spatial and temporal limits [GKK08]. According to [Asi05][ZJH08], RFID can be described as:

"RFID is a generic term for technologies that use radio waves to automatically track and identify objects. The method starts with the storing of a unique serial code in a microchip; an antenna is attached to the chip so that the identification code can be transmitted. The chip and its antenna together are called a RFID transponder or a RFID tag. To enable the data exchange (i.e. receive and send back the information from/to tags); RFID reader is required to communicate with the RFID tags. The RFID reader converts the radio waves reflected back from the RFID tag into digital information and passes them to the information system"

Based on several literatures [Asi05][MD06][AA07][Mot07][GKK08][Fri09][KSP09][AI10][Kla10][SAD10][Rey11][YY11]; this sub-section describes the basic components of an RFID system. An RFID system consists of several components such as readers (interrogators, transceivers), tags (transponder), software/middleware, the antenna, and the controller for data processing. An RFID tag consists of two essential elements: an integrated circuit chip and an antenna. The integrated circuit chip stores information of the tagged object and the antenna is used to communicate with the RFID reader. It receives instructions and transmits data to the reader [AA07]. RFID tag is attached to physical objects which are to be tracked such as containers, machines, tools, spare parts, or even on individual products [Asi05][Kla10]. An RFID-chip is used as an electronic data carrier that can write and read different information such as shipping history; completed processes so far, serial numbers, etc. [AI10]. There are three types of RFID tags: passive (no battery), active (with battery), and semi-passive according to their power supply [KSP09]. RFID-readers read or interrogate moving or stationary RFID-tags. The fixed readers are usually connected to a remote antenna; some readers may work with multiple antennas and use a device multiplexer [Asi05][Mot07]. The reader then sends the collected information to the RFID-middleware or controllers [Kla10]. Some readers can also write to the tags, this ability is useful in a dynamic production environment where the customer's needs, business processes, and standards may change at any time [Asi05]. The antenna is a separate device that is connected to the reader by a cable [Asi05][Rey11] and provides communication among the tags and the readers [YY11]. RFID middleware on the other hand, is a type of software that bridges the RFID system and enterprise IT applications. It runs centrally on a single server or is distributed over different machines. RFID middleware helps data gathering and management for any RFID deployment as well as the filtering, aggregation, and routing of RFID data [GKK08][SAD10]. RFID middleware interfaces with other back-end systems such as Enterprise Resource Planning (ERP), Supply Chain Management System (SCM), Manufacturing Execution System (MES), and Warehouse Management System (WMS) [MD06][Fri09]. Finally, the RFID controller is a machine (e.g. computers, servers, workstations, etc.) that supports the database or application software.

2.6.2. RFID versus other Technologies

RFID technology has gained significant interest in many industrial areas due to its special characteristics and superior capabilities over other ID technologies, especially barcode technology, which is currently the dominant data capturing technology. Many papers have addressed this topic, including [Shi92][Abd03][Asi05][MT07][SV08][ZJH08][LCC09][XL09][Qin11][Wan12][PS12][Has13].

The capabilities and advantages of RFID over barcode and other Auto-ID tools show that RFID technology allows for better integration with lean manufacturing practices and tools. The advantages of RFID include: data can be captured automatically and continuously with minimal human intervention; no direct line-of-sight operability is required; multiple RFID tags can be read instantaneously and simultaneously; faster reading rate; higher data storage capacity; higher reliability in very harsh working environments; tags can be embedded inside tracked objects if necessary; uniquely identified- and item-based-tagging; ease of programmability and reusability; wider reading distance; higher reading accuracy; supports counterfeiting and better security; supports detailed information (i.e. product information, such as arrival, departure, etc.); longer Lifespan; and finally, the possibility of real-time management (i.e. dynamic data exchange).

In terms of lean manufacturing, bad visibility due to barcode misreading or huge scanning efforts leads to significant wastes in production. For example, BOSCH enterprise calculated that producing in smaller lot-sizes would create the need for 12 million additional scans each year, for which it would need to employ 50 workers [Wes07]. RFID technology on the other hand, can guarantee a successful JIT environment through the elimination of unnecessary wastage, as well as human errors in scanning processes [RHB+08].It is clear from these advantages, that RFID has more opportunity to improve business performance in manufacturing operations in comparison to barcodes [HPP07]. The RFID use the Electronic Product Code (EPC) Standard which has been designed and introduced by the Auto-ID Centre at MIT [WW91][Asi05][HPP07][ZJH08][VPR09].

2.6.3. Literature Review about RFID Technology

Radio Frequency Identification (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 [HPP07][GKK08][Bla09] [Cho12].

Several researches about RFID adoption in logistics, supply chains, manufacturing and other fields have been reviewed, including [Att07][MT07][SV08][CXZ09][SPL09] [Rey11]. 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 [WWY10]. 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.

A survey was conducted by [FSG08] among 114 German companies that have adopted RFID-technology, in order to determine the percentage of improvements after the deployment of RFID in their production facilities. The results shows 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. A similar survey was also conducted by Aberdeen Group 2007 to measure the influence of RFID on the performance of 150 manufacturing companies. The primary objective from using RFID for 34% of the surveyed companies was asset tracking, with 24% for production efficiency, and 19% for supply chain visibility [Dor07].

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) [MT07][SZ08], bullwhip effect [MT07][BMV10] [Zhi12], inventory accuracy [FT05][BGO+07][ALÖ09][HAG09], and replenishment policies [CL04][SAD10][CTF12]. It can be concluded that RFID technology ensures the accuracy of inventories through the solving of problems that cause transaction errors, shipment errors, delivery errors, scanning errors, incorrect identification, shrinkage errors, theft, unavailable for sale, vendor fraud, administrative errors, inaccessible inventory, misplacement, and supply errors. Hence, companies can improve the relevant operations performance.

Based on these reviewed literatures, 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. Other academic papers including [ZGP04][BR05][LZN+05][BT06][CP07] [HZJ07] [GKK08] [HC08] [IZ08] [MRP+08] [HZD+09] [LCC09] [SPL09] [TLC+09] [VPR09] [JFZ10][ZJH+10][ZHQ+10][DED11][HMW+11][ZHD+11][ZPP+12][Wan12][ZHD+12][ZDQ+13] have expanded the realized capabilities of RFID in supply chain applications to the core of manufacturing applications and operations, in order to enhance the overall manufacturing shop-floor performance.

Moreover, Intermec Technologies Corporation (2007) introduced RFID technology because of its significant capabilities, which allows it to replace barcodes in manufacturing operations. Many benefits have been realized, such as an increase in productivity; the elimination of time-consumption and costly steps; a decrease in human error; an increase in inventory accuracy; a reduction in inventory levels; improvement in customer satisfaction and on-time delivery; an increase in flexibility; and several other benefits [Int07].

In mass-customization manufacturing, [TLC+09] proposed a distributed multi-agent system framework for mass customization manufacturing called “RFID-based and agent-oriented distributed production” (RFADP) system. The RFADP system greatly reduces the complexities of managing dynamic production flows in mass customization. It also improves the traceability and visibility of WIP, as well as reduces inventory in manufacturing environments. Meanwhile, real time production planning and scheduling in mass customization production can be enhanced with an RFID-enabled real-time manufacturing execution system (RT-MES) framework as presented by [ZDQ+13]. The RT-MES visualizes and manages a dynamic PSF in real-time, where the WIP items can be quickly and easily identified and controlled to avoid any types of disturbances in production as well as making production planning and decision scheduling activities more practical and precise.

In [ZHD+12], a holistic data mining approach for excavating practical standard operation times and generating dispatching rules depending on RFID- real-time shop-floor production data, have been presented. A real-time job dispatching algorithm was built to set the best dispatching rule for the sequence of jobs in real-time. Furthermore, new concepts to convert enormous RFID data into valuable pieces of information for better shop-floor management were discussed.

Recently, [Jou98] reported that several automotive industries like (BMW, Ford, Daimler Chrysler, Bosh, and VW) have begun applying RFID technology in their production shop floor to help in different manufacturing operation activities, especially in the management of the kanban system, in order to gain more competitive advantages.

For manufacturing applications, [PS12][VPR09] examine several empirical RFID applications such as Production Activity Control (PAC), which includes planning, implementation, and control, quality control, reducing manufacturing waste and facilitating lean manufacturing, inventory and WIP control, closed-loop supply chain management for quality improvement, maintenance activities, and new product development.

RFID has also been used in other manufacturing operations like maintenance. For example, Boeing improved its maintenance system through RFID adoption. A real-time location system (RTLS) was used to locate and accurately identify equipment, tools, and critical components, in order to track their performance history and to ensure the correct item is serviced and maintained [Bla09]. Besides that, [AZY10] has developed an RFID-based real time maintenance system, to achieve a better maintenance system in the mining industry. Furthermore, an RFID-based maintenance system sensor has also been developed to reduce the downtime due to the shortage of spare parts and cutting tools of CNC machines which often leads to excessive downtime costs [CP07]. The tools or spare parts usage time can be automatically updated by an IT system, which eliminates potential data entry errors and lost data. Accordingly, a purchase order can be created in advance to avoid shortages of cutting tools and spare parts, thus reducing downtime.

In terms of 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 [SJ07]. For instance, in [HYL10] 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 [GKK08], there was a focus on constructing a modern IT architecture that integrates sensor/radio frequency identification data systems with MES and ERP to increase scalability and to facilitate the interaction between all three layers. In [ZJH+10], 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 [ZJH+10].

In order to increase data granularity and the effectiveness of the real-time data capturing system, several studies [ZGP04][RHB+08][BRM10][JFZ10] have investigated the integration of sensors with an RFID system. A sensor enabled-RFID tag (sensor-tag) is an RFID tag which contains a sensor to monitor physical parameters (e.g. temperature, humidity, velocity, vibration, force), besides having the same functionality of a normal RFID tag. Integrating an RFID system with a sensor and measuring network, makes it possible to collect WIP timestamp-related data, equipment-related data, and geometrical-and-physical-parameter-related data in real-time, as well as data regarding measuring tools (i.e. digital calipers, measuring templates, etc.). This allows for the collection of work piece-related quality data or equipment-related maintenance data, which are obtained during multistage machining processes in the job-shop manufacturing environment.

Based on research papers regarding RFID-manufacturing, there is an increasing trend towards the implementation of RFID technology in manufacturing, due to the distinguished characteristics and capabilities of RFID in manufacturing and operations applications. However, only a few studies and research papers including [BR05][ZJH08][SMH+09][BRM10][PN11][CCC12][Cho12][PS12][Wan12]have discussed the integration and utilization of RFID technology with other adopted business initiatives such as lean manufacturing. In these studies, the possibility to integrate the capabilities of RFID technology with lean practices and tools to achieve lean targets and increase the leanness of manufacturing environment have been discussed, providing the opportunity for companies who apply this concept to take the lead within their respective industries. In other words, the usage of RFID can burst conventional lean paradigms and push companies into leadership positions within their industries [PN11].

For instance, [Cho12] investigates whether more accurate information captured through RFID can help to achieve the goals of lean initiatives in a manufacturing environment. A discrete-event simulation demonstrated the hypothesis that implementing RFID technology for lean manufacturing initiatives improves all aspects of lean manufacturing operations and can reduce some wastes.

A framework in [BRM10] specified how RFID could be used to reduce the seven wastes. Several case studies were presented to demonstrate how RFID can bring value through automated data collection to achieve leaner manufacturing environments. To enhance kanban systems, [ZJH08][SMH+09] developed an approaches to digitalize kanban systems by capturing real-time information using RFID, in order to enhance JIT systems in discrete manufacturing workshops. The study showed that RFID technology brings more accurate and timely data to the management information system and can largely improve the circulation velocity of the kanban system with a smaller error rate, in comparison to the traditional kanban system. In this field, it was stated in [BR05] that by attaching an RFID tag to containers or circulated cards, an e-kanban system can be improved with RFID technology. Once the RFID reader detects the arrival of containers, a pull signal can be automatically generated in the system. The study found that an RFID-based e-kanban is more up to date compared to the traditional e-kanban system.

In addition to that, a simple real-time VSM combining an “On-line RFID-based Facility Performance Monitoring” (ORFPM) system with RFID technology and wireless internet to track material movements, has also been developed [CCC12]. The study simulated the ORFPM system through two sets of laboratory layouts; one being a job shop and the other being a cellular layout. The results indicate that the system is able to successfully transmit data via wireless Internet, develop a database for transportation time and lead time, as well as automatically generate a real-time VSM. The system used RFID technology to track the material flow in production systems, automatically generating and providing VSM to users with real time data, and then allowing users to remotely manage the performance of their production facility. In [PN11], the relationship between RFID and lean manufacturing is investigated and the compatibility with one another is checked by examining if RFID can be used to identify and eliminate the various forms of waste in three applications (item identification, electronic kanbans, and real-time-locator systems (RTLS)). The study concludes that RFID can coexist with lean and help with lean implementations. The supporting role of RFID technology in the context of lean thinking was evaluated in [PS12]. It was demonstrated in two case studies that RFID is an important tool in the development of an extended lean enterprise.

In order to bridge the gap between the physical flow of materials on the shop floor and manufacturing information and execution systems, [BÇT+07] proposed an RFID-based manufacturing monitoring and analyzing system, which is able to collect and update valuable information related to the WIP flow across PSF. Thus, process flow and time analysis can be performed to effectively control the right parts, at the right time, to the right workstations and labors. The study listed some collected information like: Arrival time of parts at a workstation, activity start time, activity end time, departure time from workstation, and critical operation parameters related with the workstation such as temperature, speed, power, etc.

The deployment of RFID introduces new challenges in terms of processing the enormous amounts of RFID captured event-instances and data, generated in real-time (measured in seconds or milliseconds) during a daily production operation run by different resources located along the value stream on the PSF. In this regard, few studies [ZF07] [WLL09][FHQ+11] 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.

2.7. Complex Event Processing – [CEP]

CEP is a kind of technology and method that is used to obtain meaningful and useful information from huge amount of events, as well as to control event-driven information systems [LF98]. In the scope of lean manufacturing, we define an event as a "change of smart-object state", e.g. product arrives; process starts at machine, machine setup started, etc. Generally, events are categorized into primitive events and complex events. Both of these events have their own distinct properties and a relationship exists between primitive and complex events in terms of goals and uses [ZF07].

- 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 [JFZ10].
- A complex event (E_i) is an aggregation of primitive events over a period of time at specific location(s) [Luc02]. A complex event is aggregated according to predefined rules which contain event operators to find the relation between primitive event and/or complex events [WLL09].

In this thesis, event types and instances are generally represented by upper and lower case letters respectively, such as (E and e). Take "start-processing state" for a machine as an example. The machine is ready to start processing (E_{sp}); if the following combined events have occurred: "machine setup ends-event" E_S, "labor available-state" E_L, "material arrival event" E_{M_a}, and "sub-assembly arrival event" E_{S_a}. The events in this example can be expressed as: $E_{sp} = E_S \wedge E_L \wedge E_{M_a} \wedge E_{S_a}$, 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 [FHQ+11].However, since the introduction of RFID technology in the field of manufacturing, 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 [WLL09]. Furthermore, there has been almost no research addressing the application of CEP mechanism to smartly support and enhance the practicing of lean manufacturing in real-time in daily production runs.

2.8. Discussion and Conclusion

This chapter provided brief information about lean manufacturing as well as the implementation of RFID technology within manufacturing organizations. It can be concluded that RFID 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 on the PSF. In other words, RFID and other real-time data capturing technologies like sensors 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 data in real-time (i.e. in seconds or milliseconds).

However, despite the fact that RFID is seen by many researchers as a revolutionary enabler of automated real-time data capturing system, there still remains confusion as to how manufacturing organizations can use the huge amount of data in a more effective manner to bring more benefits. Therefore, many enterprises have not achieved their intended targets, since these organizations have not realized how to utilize RFID effectively to reach their objectives and gain more benefits. Moreover, the majority of

RFID researches are limited to supply chains and logistics applications, where the main focus was on inventory management, objects/assets tracking and tracing, and locating.

In the field of manufacturing, only a few studies have discussed the possibility of combining RFID technology with lean manufacturing principles. However, these studies only limit their scope on improving the ability of a kanban system, which is an example of a lean practice that does not work effectively without reinforcement from other lean practices and tools like TPM, 5S, Line balancing, Poka-yoke, etc. Consequently, the idea of a comprehensive integration between lean and RFID is still not very well understood and not mature enough for lean and RFID practitioners. This issue still remains one of the top concerns in the manufacturing field.

Based on the reviewed literature, the following gaps and limitations have been identified in the RFID implementations in manufacturing towards designing a dynamic production control system based on lean manufacturing principles:

- There is almost no comprehensive, standard, clear, and effective lean-RFID-IT integration frameworks that have been developed to consolidate, enhance, and smartly support LPTs in real-time.
- In terms of lean practicing on a daily basis, there is no work that discusses how to use the RFID real-time production captured information to support the individual LPTs, in order to enhance, support, reinforce, and sustain lean principles and keep them alive in the long-term.
- Despite the abundance of researches claiming the potential of RFID in manufacturing, there is a lack of real-time data analysis/mining frameworks that help lean practitioners to achieve a leaner environment.
- The in-depth real-time visibility provided by RFID needs to develop new concepts for the next-generation of software that is dynamic and flexible enough with the appropriate level of intelligence to deal with the next-generation of manufacturing systems that generate enormous amount of events in order to smartly support LPTs in real-time.

In summary, due to the lack of studies that address RFID-lean manufacturing integration in a manufacturing environment, there is a need to develop a clear, detailed, and comprehensive framework to guide lean practitioners towards the effective usage of RFID-technology to enhance and support lean tools, techniques, and practices to achieve a leaner manufacturing environment.

This study aims to revolutionize the lean paradigm by utilizing RFID benefits to create an extended real-time lean enterprise. This can be achieved by developing a real-time data driven IT system or platform based on lean principles which advocates lean practices and tools in the short- and long-term. This would be extremely useful to create a real-time intelligent lean manufacturing system.

CHAPTER 3
RFID-enabled Dynamic Value Stream Mapping based on Complex Event Processing

This chapter is considered as the core of this dissertation. The basis of this chapter is to introduce a framework of a new kind of smart real-time monitoring and controlling lean-based IT mechanism for the next-generation of manufacturing systems with dynamic and intelligent aspects concerning lean targets. Such a mechanism is realized through utilizing RFID technology in a corporation with VSM concepts to address the dynamic aspects of the manufacturing environment in real-time, where the time-based flow is greatly emphasized. The proposed mechanism is known as Dynamic Value Stream Mapping (DVSM), a computerized event-driven lean-based IT system that runs in real-time according to lean principles that cover all manufacturing aspects through a diversity of powerful practices and tools to effectively reduce wastes and maximize value. Therefore, DVSM represents an intelligent, comprehensive, integrated, and holistic real-time lean-based manufacturing mechanism.

3.1. Introduction

The most popular tool for implementing lean initiatives in manufacturing enterprises is value stream mapping [CCC12]. However, today's manufacturing systems are 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.) [LV02][GKK08][KS09][Vel12][RNI+13] . Therefore, it has become obviously difficult to address or represent such circumstances with a simple and static mapping technique like VSM.

As a result of this and based on VSM concepts, there is a need for a dynamic computer-based lean tool that is able to automatically map the flow and continuously monitor the manufacturing processes to not only effectively support and enhance the implementation of LPTs, but more importantly, to sustain LPTs. Furthermore, keep them alive and effective in the long-term in today's manufacturing environments with high complexity, uncertainty, variability and dynamical behavior.

In this context, the recent advances in automatic data capturing technologies i.e. RFID, computers and IT systems have made it easy to digitalize manufacturing information.

However, since over a decade, the available IT systems and application software are still monolithic and cannot provide the manufacturers with enough flexibility to handle their rapidly changing business processes [Wan12].

Therefore, for next generation lean manufacturing information systems; there is a need to develop a lean-oriented IT system which should be dynamic and flexible enough to keep pace with today's highly dynamic manufacturing environments and to quickly adapt the rapid changes in products and processes from lean perspectives.

Such lean IT systems should be able to create a smart real-time lean manufacturing environment, through involving smart real-time mechanisms that prevent wastes in real-time during production runs and keep LPTs alive for the long-term, such as hindering the backsliding to old ways of working, monitoring and controlling 5S, poka yoke, TPM, Takt-time, work standards, Andon, smart priorities and flow controlling, etc.

Accordingly, this chapter introduces a framework that describes the integration of real-time data capturing technologies, mainly RFID, with VSM concepts to develop a computerized real-time lean-oriented IT system, known as "Dynamic Value Stream Mapping" (DVSM). DVSM is an event-driven system that uses complex event processing (CEP) concepts to handle the enormous amount of triggered events at a manufacturing execution level as well as higher enterprise levels.

Through the utilization of CEP concepts to process RFID data and to support LPTs, the overall performance at the PSF can be improved and enhanced. Furthermore, manufacturing wastes, which lead to losses in companies, can be avoided and eliminated in real-time. This framework also allows for more flexibility, allowing lean specialist to express and create RT-LCRs for monitoring and controlling lean implementation during a production run.

To validate the DVSM framework and demonstrate how RFID data can support smart lean environments ; the subsequent chapters discuss a number of DVSM-modules based on CEP to smartly support different LPTs (e.g. lead-time analysis, real-time costing, real-time waste detection, 5S,TPM, SMED, Takt-time, Line balancing, dispatching, etc.). In order to verify the feasibility of the constructed RT-LCRs, the simulation software ProModel has been used to validate some of these rules.

3.2. Systematic Deployment of RFID for DVSM

To achieve the intended purposes of DVSM, RFID real-time traceability systems should ensure 100% PSF production data capturing with high accuracy. This will reinforce the effectiveness of DVSM functionality, minimize the potential loss of data and eliminate the risks of human intervention in data capturing.

Based on the literature review, this section presents a step by step systematic method to create a smart or an intelligent environment on the PSF in order to effectively capture manufacturing information in real-time, which can be used through DVSM-modules to serve for achieving lean's goals and targets. The deployment steps of RFID system are shown in figure 3.1, and explained as follows:

➔ First Step

RFID-readers Deployment, the typical manufacturing layout spaces and locations, buffers, passages and routes, doors and gates, and working centers are equipped with high frequency RFID- readers, since these objects or facilities are the major parts of the value stream where the products pass through, and hence can be tracked as well [ZDQ+13]. For effective tracking, RFID-readers can also be attached to vehicles that are used for moving WIPs and containers or pallets [Wan12]. This step guarantees a full cover of PSF's layout to track all PSF's objects and supply the DVSM with all information about the current status of the PSF.

➔ Second Step

RFID-tags Deployment, convert the typical manufacturing assets into smart objects. The type of RFID-tag (i.e. passive or active) is used based on a particular criteria such as object criticality or necessity for RT-LCRs, for example some objects need to update their status during the production, such as updating the remaining life of the cutting tools or spare parts based on the actual processing time. In addition to that, the assets 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 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 WIPs is considered as the events stimulant, since if there are no WIP-flow events, then there are no events at all. The volumes of data and process duration play an important role in this part of this step.

Once these objects are attached with RFID-tags, they become smart objects, and thus identifiable trackable, and traceable in real-time with the all information about their statuses and movements, this enables them to be able to interact live with all smart-objects through RT-LCRs to create an intelligent lean environment on the PSF. The operators, supervisors, and mangers have the ability to interact live with the PSF's objects through DVSM user interface. In this case, for movable operators like LOs, they are supplied with wireless Personal Digital Assistant (PDAs) to remain informed on the latest developments or changes taking place on the ground.

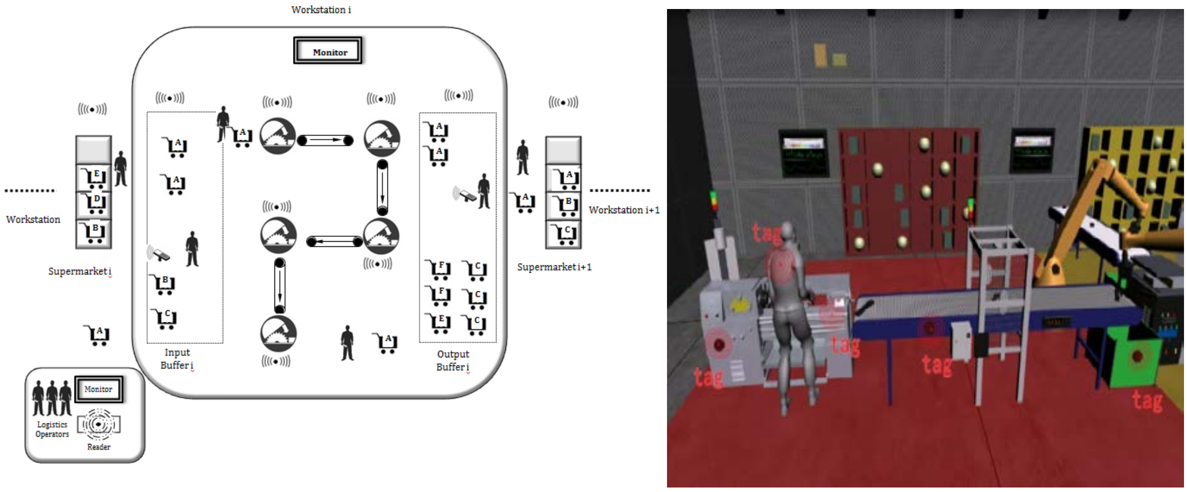


Figure 3.1. RFID deployment in a workstation.

➔ Third Step

Wireless-communication network deployment, according to different criteria (e.g. cost, speed, beneficial result, energy-saving and cost-reducing, etc.) the suitable wireless network can be installed. There are many different forms of building wireless network, such as : GPRS, Bluetooth, Wi-Fi, infrared data transmission (IrDA) and 433MHz wireless communication, and short range wireless technical standards like ZigBee, WiMedia, dedicated wireless system, etc. each of these wireless communication form have unique characteristics and need special requirements for transmission speed, distance and power consumption, etc. [DLJ^{+}08].

➔ Forth Step

RFID-supportive real-time data capturing technologies, in order to guarantee 100% of PSF real-time visibility; additional technologies can be applied to support RFID in data collection. Based on [ZGP04][RHB^{+}08][BRM10][JFZ10], the following technologies and methods could be employed:

i. Digital cameras can be utilized to monitor specific events and process parameters.
ii. 2D-barcodes can be applied under particular circumstances in which RFID cannot be applied.

iii. Extract and exchange production events through some PSF systems like various Automation Devices, Programmable Logic Controllers (PLC), Distributed Control System (DCS), Remote Terminal Unit (RTU), Real-Time Location System (RTLS), and Supervisory Control and Data Acquisition (SCADA) systems.

iv. RFID-sensor integration can be configured, like velocity sensors, force sensors, vibration sensors, displacement sensors, etc., to collect equipment-related data, and measuring tools, like digital calipers, measuring templates, etc., to collect work piece-related quality data [ZGP04][Lva08][RHB+08][BRM10][JFZ10]. Here, sensor data is creating an unprecedented opportunity to reach almost 100% real-time visibilities to enable the functionality of DVSM.

v. When the event cannot be captured by RFID or any other supportive data capturing technologies, workers are still able to interact with the current situation through DVSM's touch user interface (TUI), he/she can enter an event-related data (e.g. Individual process tasks starts and ends, machine breakdown event, repair completion events, setup events start and finish, etc.) in the easiest way, or through Human-Machine Interfaces (HMI).

For example, the CNC machine cutting tool is attached with a RFID-tag to record tool's preset data (e.g. projection, edge radius, and effective diameter), operation data (e.g. speeds, feeds and depth of cut) and the usage time (e.g. events of start-time and end-time). once the tool is attached to the spindle, the RFID reader on the CNC machine is configured to read the data from the RFID-tags. This avoids most common sources of potential data entry errors, tool-offsetting errors and possible tool crashes. After the operation ends, the RFID encoder update the usage time and the remaining life cycle of the tool onto the RFID-tag, this information can be invoked or queried by different operational departments for different operational issues such as triggering a purchase order, capacity planning, costing, maintenance, etc. [CP07].

3.3. Data Volumes of RFID on the PSF

Before starting the tagging of RFID-tags as described in the second step in the previous section, it is critical to know the depth, scope and granularity of the required product-related data. Therefore, this section discusses briefly the identification level of the products and materials to become smart objects, especially the current trends that are shifting the focus to track the individual items and the averages used in VSM only display a general condition, which is not enough for an accurate production control method. Thus, 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 controlling. As seen in figure 3.2, based on [IGM+09] the object-level of tracking can be classified as follows:

i. Pallet-level: In pallet level tagging, a 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.

ii. Case-level: In addition to pallet level tagging, a RFID-tag is applied to every case unit.

iii. Item-level: In addition to the both mentioned levels, a RFID-tag is applied also to every single item, including RWs, WIPs, subassemblies, and components.

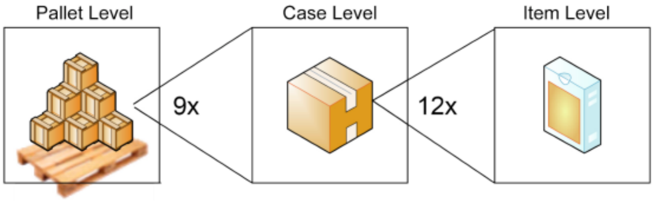


Figure 3.2. Products and Material Traceability Level [IGM+09].

In some smart real-time manufacturing cases, another important aspect should be considered; the speed at which a real-time decision is made, this depends upon some manufacturing parameters such as the processing time of each object-level (i.e. pallet, case, and item levels) as well as the flexibility of the manufacturing system. If processing time is on the order of an hour, a response in 5 minutes may pass for real-time; if processing time is on the order of a few minutes real-time responses are probably needed in less than 1 minute [Qin11].

3.4. Real-time Lean Enterprise Integration

One of the main challenges facing lean enterprises in today's dynamic production systems is the inability to make quick decisions against sudden changes, which is caused due to the time-gaps or asynchrony between manufacturing events, i.e. products flow and the associated events on the PSF, from one side and the associated information flow on the operational and higher enterprise level from the other side, as seen in figure3.3a. 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 PSF. In this context, besides being lean, the enterprises have to be increasingly agile to rapidly respond against such challenges. Therefore, it is important to bridge this time-gap through real-time integration of all enterprise levels together using real-time lean-oriented IT systems, as figure 3.3b illustrates.

The envisaged DVSM is proposed to bridge this time-gap and guarantee an overall real-time integration along the horizontal and vertical direction based on lean principles. The vertical integration of information and knowledge between the PSF and top floor is required to bridge the time-gap vertically between enterprise management levels; where the horizontal integration is required for integrating information between the resources i.e. smart-objects at a particular enterprise level [GSM+11].

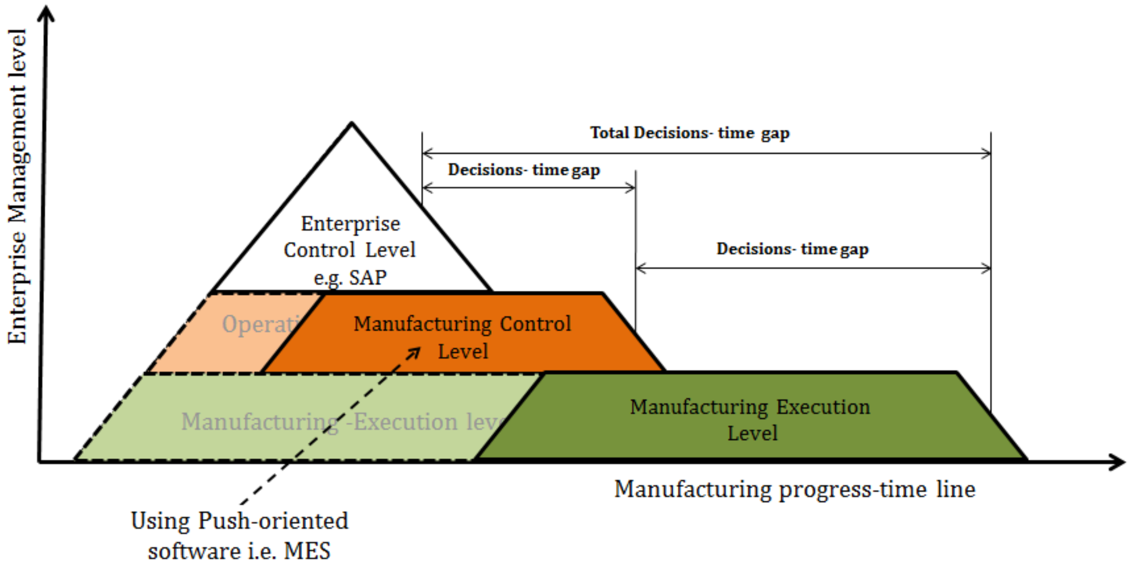


Figure 3.3a. The time-gap between information flow and physical activities through management levels in a manufacturing enterprise.

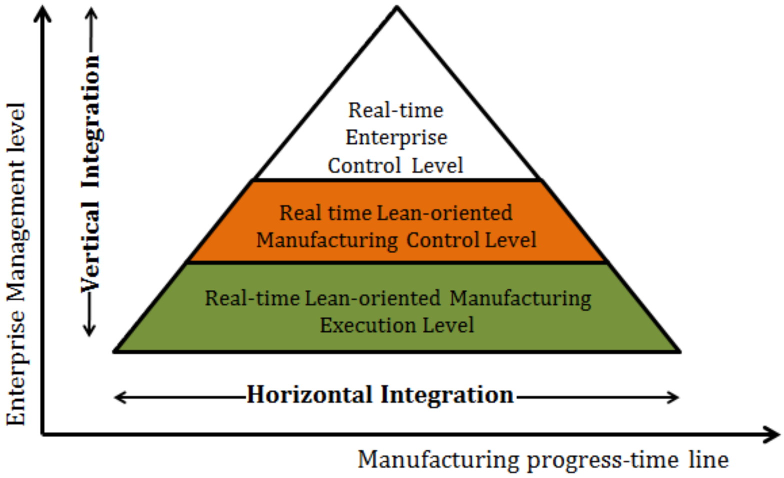


Figure 3.3b. Real-time Lean-based Enterprise Integration.

3.5. Integration of DVSM in the Real-time Lean Enterprise System

After the PSF is turned to a smart manufacturing environment; the event driven lean-oriented system DVSM should be integrated with the existing enterprise IT infrastructure. Therefore, this section briefly introduces the integration of the envisaged real-time lean-oriented system with the enterprise control systems, e.g. ERP, SCM, workflow management system (WfMS), etc., see figure 3.4. In this framework CEP is a great method to be integrated into the IT infrastructure to support and facilitate the functionality of DVSM, thus the Real-time Complex Event Processing (RT-CEP) level is the interface between RFID-system at the PSF, and the DVSM level, as well as with other enterprise levels, and RT-CEP can be considered as an RFID middleware software. For effective PSF integration with IT systems, the OPC/OPC-UA standards can be used to address the communication between the RFID middleware software and RFID readers and other PSF systems e.g. PLC, HMI, sensors, etc., which can be used in combination with RFID system [Lva08].

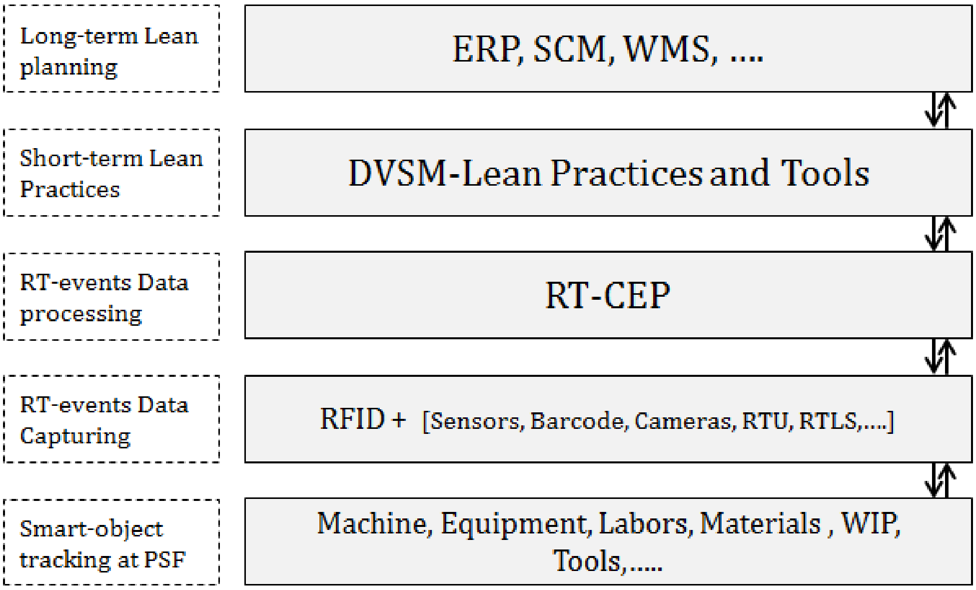


Figure 3.4. Integration of the DVSM within the Enterprise's IT system for Real-time Lean Enterprises.

At the RT-CEP level, the enormous amounts of generated events can be pre-processed and forwarded to the DVSM and higher levels in the enterprise's IT system, where DVSM has different engines for different functions, as seen in the next section.

3.6. Dynamic Value Stream Mapping Framework – [DVSM]

This section presents the core of this thesis that tackles the integration of an RFID data-capturing system with VSM principles to enhance a smart lean manufacturing environment. The integration framework, namely Dynamic Value Stream Mapping

(DVSM), is a computerized event-driven lean-based IT system that contains different smart lean control modules to enhance, sustain and achieve the aims of lean initiatives in a manufacturing environment.

Since this system deals with RFID captured event-instances; DVSM 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 to avoid wastes and add more values. An overview of the DVSM components is depicted in figure 3.5a. The DVSM framework is composed of five main engines:

➔ **First**: Event Extractor Engine-[EEE], it is a real-time production-related data collection engine; it is used to reflect and integrate the current state of the smart-objects (i.e. resources) on the PSF with the enterprise environment. Therefore, EEE serves as a linkage between the physical world (i.e. smart objects on the PSF) and virtual world (i.e. IT system).

➔ **Second**: Actual Value Stream Mapping Engine-[AVSM], it is the DVSM-interface with the PSF; it translates the products-related production data into flow in terms of time and location, (i.e. VSM-format).

➔ **Third**: Virtual Value Stream Mapping Engine-[VVSM], it is the DVSM-interface with the enterprise levels; it translates the standard lean-based production data that has been developed in the high enterprise's level into the context of event-instances (i.e. VSM-format). Before releasing the products for production, each product should have a VVSM that represents its standard lean-based data.

➔ **Fourth**: Real-time Rules Engine-[RT-RE], in this engine, the Real-Time Rules Expression Builder (RT-REB) module gives the lean specialists the ability to express or construct with the assistance of the "Rule Input Elements" (RIE) module (i.e. based on CEP concepts) the suitable rules for the other DVSM-Engines, such as rules for the EEE to extract the needed events, or create RT-LCRs for the Lean Practices and Tools-Engine (LPTE) to control production processes based on lean concepts, or supply the AVSM and VVSM-Engines with the needed rules to execute their functions, as seen in figure 3.5.

➔ **Fifth**: Lean Practices and Tools Engine-[LPTE], it is considered as the head of DVSM. This engine enables a smart real-time re-(action) mechanism without the need for supervisors or human intervention, since they are unable to monitor all production-related information in details and accordingly make quick decisions. It is proposed, that the RT-RE supplies this engine with different RT-LCRs, which in their turn utilize the event-instances in AVSM and DVSM-database (DVSM-DB) as well as VVSMs-data for smart real-time monitoring and controlling of the production processes on lean basis, where the Lean Practices and Tools (LPTs) can be enhanced in the small details of daily production runs. Thus, this engine bridges the gap between the standard lean-based environment represented by VVSM and the physical situation represented by AVSM.

➔ **Sixth:** Real-time Visualization Engine-[RT-VE], it displays mainly the AVSM of each product at the local TUI of workers and supervisors. The RT-VE is equipped with rules to invoke and process the current production data from AVSM, lean-based control data (i.e. reactions), and standard work instructions from VVSM to display them in VSM-format.

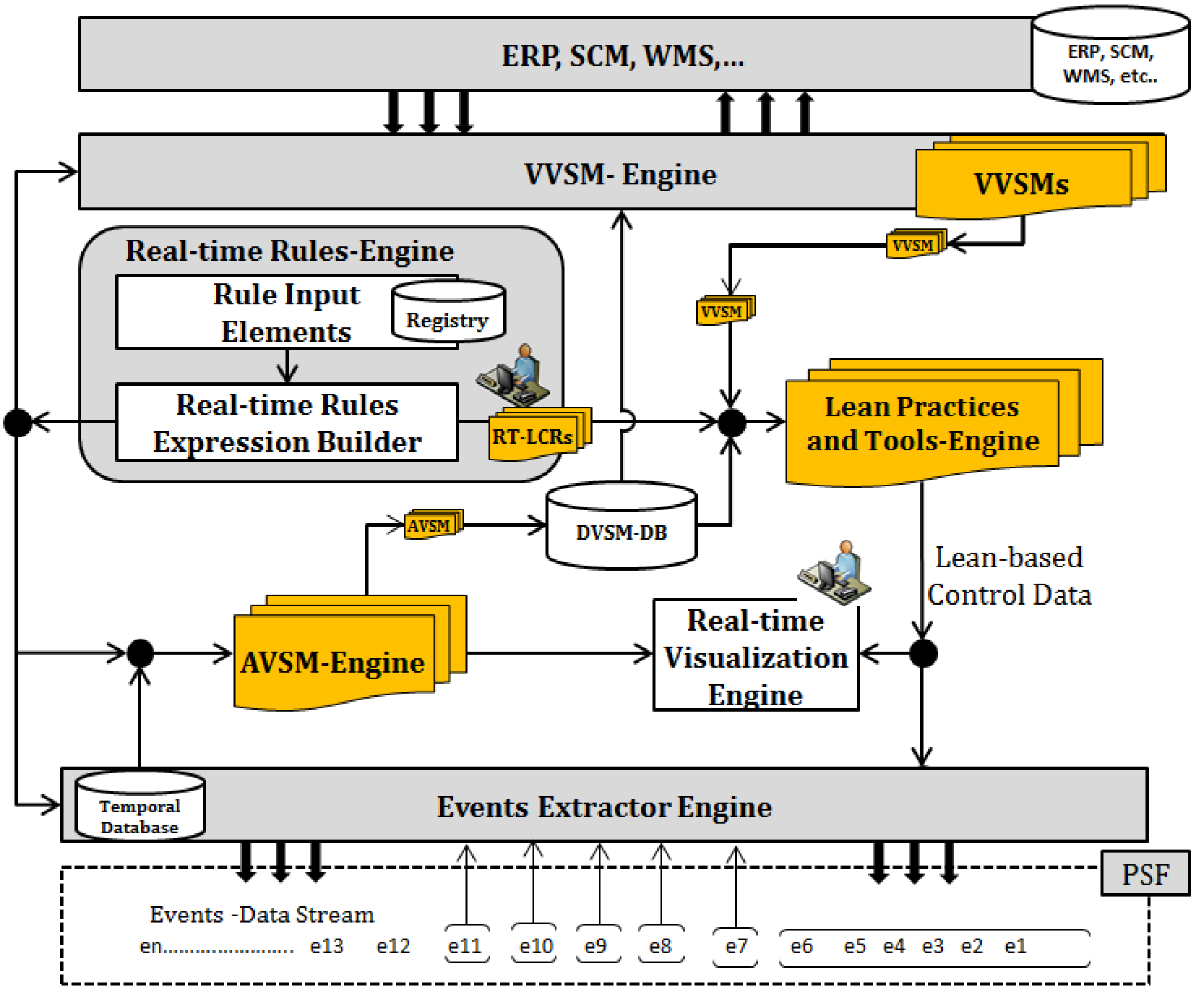


Figure 3.5a. An Overview of Components of the DVSM for Smart Lean Manufacturing.

In this context, after creating and saving a RT-LCR on a specific module in LPTE, it will be activated during the production run, in order to generate a quick re-(action) towards the unplanned and unexpected production incidents and disturbances that are the root causes of waste. Moreover, a certain RT-LCRs could represent a control algorithm of a specific lean tool such as TPM, 5S, poka-yoke, Takt-time and Kanban control, line balancing, etc. Other RT-LCRs could be used to study the behavior of the production system using specific patterns to predict and detect the interruptions and incidents in advance and accordingly generate real-time re-(action), in order to reduce the 7 type of wastes in a lean environment. In addition to that, these rules could also be expressed to detect the opportunity for further improvements (i.e. Kaizen-events). The working mechanism and the interaction between the DVSM-Engines are illustrated in figure 3.5b.

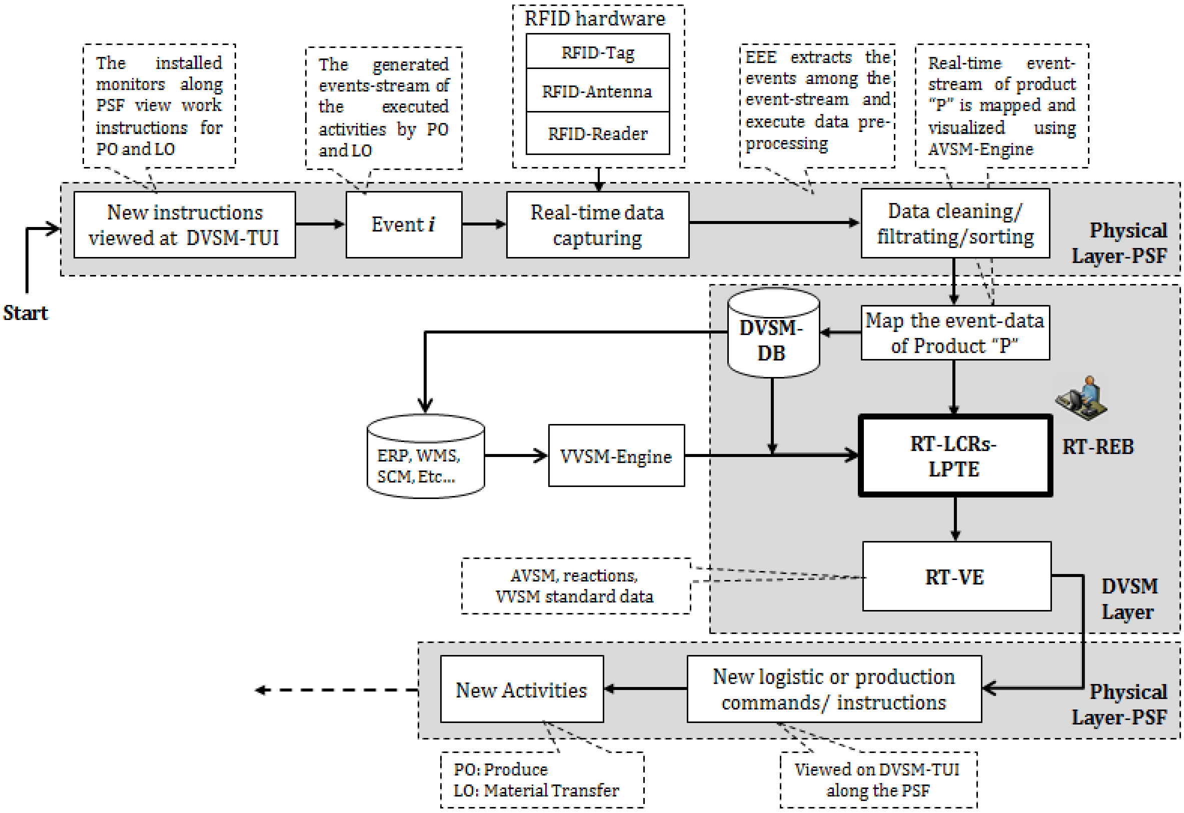


Figure 3.5b. The Working Mechanism of the DVSM.

Some of the modules of LPTE have been validated in industrial case studies as further discussed in the coming chapters. In the following subsections, the components of the DVSM framework are discussed and elaborated with emphasis on event-instances and CEP.

3.6.1. Event Extractor Engine -[EEE]

The EEE is used to extract and process the enormous volume of RFID captured production event-instances and their data in real-time (measured in seconds or milliseconds) during a daily production run. It is also called a Real-time Complex Event Processing Engine (RT-CEP) as seen in figure 3.4.

In this stage, several event processing operations must be applied to extract and process RFID captured production data with 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 [ZHD+12]. Several IT research papers have discussed several event extraction methodologies using CEP, e.g.[ZF07] [WLL09][FHQ+11]. After that, the pre-processed production data can be sorted into specific formats and saved as event-instances in a temporal database which become ready to be utilized by other DVSM-Engines. The utilization of the saved event-instances in the temporal database is done through subscribing them by different RT-LCRs in other DVSM-engines. Some correlation or aggregation operations between event-instances are done in LPTE-modules, in order to generate the optimal re-(actions) at the right time, at the right location, and for the right person. Each event type should be defined based on RIE, in order to be detected. Otherwise, it will be deleted during event-data filtration and sorting.

1.6.2. Real-time Rules Engine-[RT-RE]

3.6.2.1. Real-time Rule Input Elements-[RIE]

This part of the RT-RE contains pre-defined RIE. These elements can be viewed in a pop-up box to be used while creating or expressing the RT-LCRs to facilitate the construction of RT-LCRs. 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-LCRs. The proposed RIE is shown in figure 3.6.

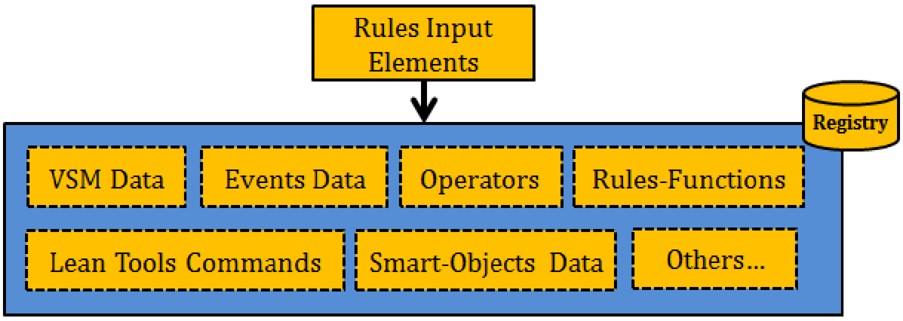


Figure 3.6. The RIE_of the RT-REB.

3.6.2.1.1. Operators

The operators are used to build a relationship between events in the body of the rules. In previous literature [Luc02][ZF07][WLL09][JFZ10][KMG+10], some operators for extracting and defining the relationship between events have been presented, these operators can be used in building the RT-LCRs. For more flexibility in the DVSM, 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 manufacturing system. Some operator types are discussed below:

- Logical-operators

Logical-operators are the most commonly used operators to construct the relations between event-instances [ZF07], examples of logical-operators include (i) OR (∨): Disjunction of two events, (ii) AND (∧): Conjunction of two events, (iii)NOT(¬) :Negation of an event E (¬ E), etc. In order to construct relations between the main parts of the RT-LCR, which consist of event relations; further logical operators can be defined in this engine.

- RFID-operators

Because the majority of events are captured from PSF using RFID, RFID-operators represent these events in the form of a smart-object ID-code using for example Electronic Product Code (EPC) method (e.g. WIP-ID, operator-ID, equipment-ID, material-ID, machine-ID, etc.); Timestamp “T”; and Location of event “L” [ZF07]. RFID-operators are used by the RT-LCRs for tracking, defining and mapping the AVSM of the actual product flow (i.e. the path or route) as well as to translate the standard production data into time-based flow through the VVSM-Engine. For example, a segment of the AVSM path’s event-data of product “P_A” at workstation "WS_i" is represented in the following path’s event-data vector:

$$\begin{aligned}\mathrm{AVSM_A} = \cdots &< \mathrm{P}_{A-EPC}, \mathrm{L_{B2}}, \mathrm{T_A} >; < \mathrm{P}_{A-EPC}, \mathrm{L_{B2}}, \mathrm{T_D} >; < \mathrm{P}_{A-EPC}, \mathrm{L_{M12}}, \mathrm{T_S} >;\\ &< \mathrm{P}_{A-EPC}, \mathrm{L_{M12}}, \mathrm{T_E} >; < \mathrm{P}_{A-EPC}, \mathrm{L_{M12}}, \mathrm{T_D} >; < \mathrm{P}_{A-EPC}, \mathrm{L_{B3}}, \mathrm{T_A} >;\\ &< \mathrm{P}_{A-EPC}, \mathrm{L_{B3}}, \mathrm{T_D} > \cdots\end{aligned}$$

This part of AVSM’s path event-data views the traveled path by P_A 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’s event-data can be graphically visualized in traditional VSM-format through the AVSM-engine with all associated production data. This facilitates the understanding of the actual interaction between resources on the PSF. Moreover, the path history of WIPs with all product-states can be accurately tracked or traced for further flow analysis.

The event-instance related data and key attributes are simultaneously recorded in the DVSM-DB, where the operational aspects of each product-state along the value stream are described. For example, the processing-state that lies between $< \mathrm{P_A}, \mathrm{L_{B2}}, \mathrm{T_A} >$ and $< \mathrm{P_A}, \mathrm{L_{B2}}, \mathrm{T_D} >$ is executed on product (P-ID) at machine (M-ID) from worker (L-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 DVSM-DB. In this state, more event data can be defined to be subscribed. These event-data can be recorded in the event-data set:

$d_{e_i} =< P_{ID}; M_{ID}; O_{ID}; E_{ID}; Mat._{ID}\ ; T_{ID}; \{Pa. 1, Pa. 2, Pa. 3, etc\}, etc \ldots >.$

This set of data can be invoked by RT-LCRs that already subscribed this event-instance in their CEP-code.

In other words, the timestamps in RFID-operators and the associated event-data sets can be utilized by different LPTE's modules simultaneously to support different LPTs in real-time. For instance, the processing-time at machines can be utilized by different LPTE's modules, such as:

i. TPM Module, automatic recording and updating the exact usage-time of a machine for preventive and corrective maintenance or Mean Time to Repair (MTTR) and Mean Time to Failure (MTTF) analysis.

ii. Real-time dynamic production 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 products (if it is within the acceptable limits or not). Another example, it can be used for RT-DPG module.

iii. JIT module (Just-in-Time (JIT) purchasing): automatically determining and updating the exact remaining life of a cutting tool, which has been used at this machine, or in the case of the life cycle of spare parts, a purchase request can be made at the right time based on the current data, to support Just-in-Time (JIT) purchasing to avoid tool shortages.

iv. Continuous improvements module (Kaizen-events): utilize this time for offline performance analysis (e.g. machine utilization, labor performance, time-based waste root causes) 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.

v. Real-time manufacturing 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 6.

The event-data set can also be extracted using other operators like time- and location-operators. Time-operators represent the event relations in terms of time. The events referred to here are the captured events from RFID rather than the events from enterprise information systems such as ERP and SCM. First of all, we need to define the time-based functions for the occurrence of an event, which will be needed for the rules expression:

- $e_{i,\mathrm{Start}}$: Starting time of an event instance, $e_i \in E_i$,
- $e_{i,\mathrm{End}}$: 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$D_{E_i} = e_i\mathrm{EndTime} - e_i\mathrm{StartTime}$.

- Time-operators

Time-operators are important for detecting the timestamps of each product-state along the value stream, examples of temporal complex event operators are:

- 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 production process isn’t overstepped by other process (ii) a machine setup-event must be applied before the processing event starts. Expression: (E_m) occurs if and only if (E_w) has already occurred. The proposed RT-LCR semantic: $(E_w; E_m)$ iff $(e_{w_s}, e_{w_e} \in E_w) \wedge (e_{m_s} \in E_m) \wedge e_{m_s} >= e_{w_e}$; where E_w: welding event and $e_{w_s}; e_{w_e}$ are the start and ends time primitive event. E_m : milling event; e_{m_s} is the start time of this event.
- Sequence of events SEQ-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 minutes) means e_2 occurs 10 minutes after the occurrence of e_1. For lean purposes we can use this operator to control the Takt-time which depends on the work time between two consecutive units, in order to meet customer demand and prevent overproduction wastes. RT-CEP semantic: $((e_{P_{S1}};\ e_{P_{S2}};\ \ldots.;\ e_{P_{Si}}),\ 10)$ iff $(e_{P_{S1}};\ e_{P_{S2}};\ ..;\ e_{P_{Si}} \in E_p)$.
- 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 $\exists e_1 \in E_1$ & $\exists e_2 \in E_2 \wedge (e_{1\mathrm{Start}} - e_{1\mathrm{End}})||(e_{2\mathrm{Start}} - e_{2\mathrm{End}})$. For external setup as a lean concept, 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 $(e_{S_s}, e_{S_e} \in E_S) \wedge e_{P_s} \leq e_{S_s} < e_{S_e} \leq e_{P_e}$.

In the above examples, a setup command is generated between processing start- and end-events: e_{P_s}; e_{P_e} , where e_{S_e} does not exceeds 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 manufacturing system. This feature distinguishes DVSM from other systems, thus making the real-time controllability of LPTs more flexible and adaptable with any kind of 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 (<>): 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 production process at a certain location while a 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 lean dimensions. For example, control the interaction between smart-objects to avoid time waste, control the implementation of 5S, and determine the cost-drivers being used in the processing-state of products to incur their cost-rate to the product cost pool.
- Remote Location constructor (><): The remote location operator determines whether two or more events occur at different locations.

Depending on manufacturing system requirements, other operators can be defined like the causality operator (→) to define the dependency between events.

3.6.2.1.2. Smart-object Data

This part of the RIE defines all types of resources that exist on the PSF that become a smart-object after being tagged with an RFID-tag, as presented in section 3.2. Smart-objects must be predefined in a registry to facilitate the expression of RT-LCRs. So any changes in the existing resources will be adapted and considered through RL-LCR.

In this work, we consider two types of tracked smart-objects, namely, Static Smart-Objects (SSO) and Dynamic Smart-Objects (DSO). Examples of SSO include machinery, tools, equipment, shelves, supermarkets, conveyers, as well as any other objects which are associated with a specific workstation and used within its vicinity. The status of SSOs changes in terms of time. On the other hand, DSOs include WIP-products, labors, containers, movable material handling equipment, 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 tools and spare parts).

It is important to predefine the characteristics, the attributes, and the features of each object to be considered in RT-LCRs. Normally, this information is saved in the ERP database and if needed they will be invoked through the RT-LCRs. 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 is able to 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 PSF, such as his impact on the average processing times at different machines or his learning curve. Another example would be machine features such as the maximum capacity of a machine or the capability to produce a certain product specification.

3.6.2.1.3. Event Data (Event Identification)

This part of the RIE systematically defines all types of event-instances, which are relevant to each smart-object at the PSF and needed in the RT-LCRs, see figure 3.7.

One of the effective methods to define all production events is to split the production activities along the value stream into primitive events. To do so, a simple step-by-step methodology as shown in figure 3.7 can be used in order to build the Tree of Event Instances (TEI); this is illustrated in figure 3.8. Firstly, all objects on the PSF (e.g. Milling Machine, movable equipment, logistics operators, etc.) should be identified and indexed in this format SO_i, where "i" is the index of object, i = 1, 2, 3,… n and n is the number of active smart-objects on the PSF. 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… m and m represents the number of working groups. Thirdly, all possible events which could be generated during daily production runs should be defined (i.e. $e_{SO_{i,j}}$). After the event type is defined; the event-data set (i.e. event-related data) that accompanies or coincides with the event-instance should also be defined as well. Finally, decide the needed events for each module in LPTE.

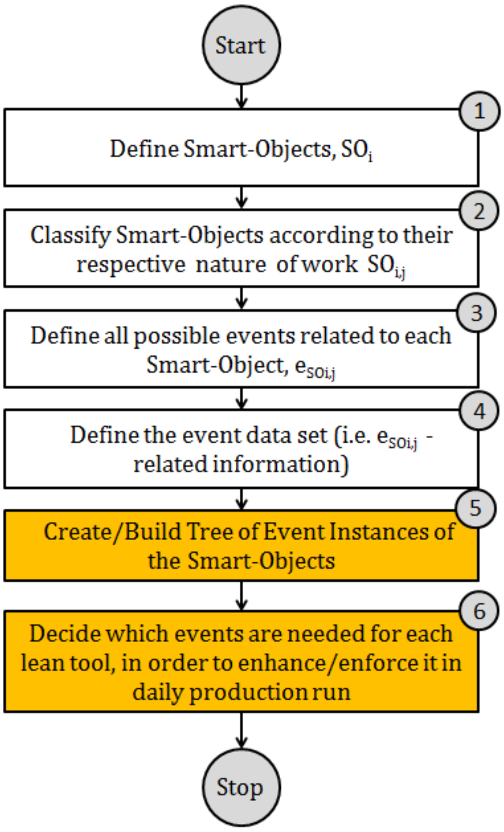


Figure 3.7. Methodology to Create Tree of Event Instances of the Smart-Objects.

For example, each EVENT type "E" represents a specific status and can be defined as: $E = [E_{ID}, L_{x,y}, T_S, T_E, C]$, with each EVENT type having its own unique ID. For example, $L_{x,y}$ 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; $C= \{e_1, e_2, \ldots e_n\}$, $n \geq 0$, 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. Other process attributes or parameters are also defined in the RFID-tag, such as the speed of the conveyer belt. $A= \{attr_1, attr_2, \ldots attr_n\}$ where $n \geq 0$, is a set of attributes, that characterizes the event type. For example, by using real-time poka-yoke rules to enhance quality at WS_i, once RFID has detected the "arrival-event" of product "P_i", the required temperature and pressure (i.e. process attributes that are considered for this particular process for "P_i" at WS_i) can be changed automatically without human intervention. Here, human error (e.g. forgetting to change the process attributes to new values or changing them to wrong values) can be avoided and thus, stoppage in the process that leads to long waiting time; quality problems, i.e. defects or reworks; and breakdowns can be avoided.

Figure 3.8 shows that lean practitioners are able to decide which smart-objects and the associated event data are required for the corresponding lean tool.

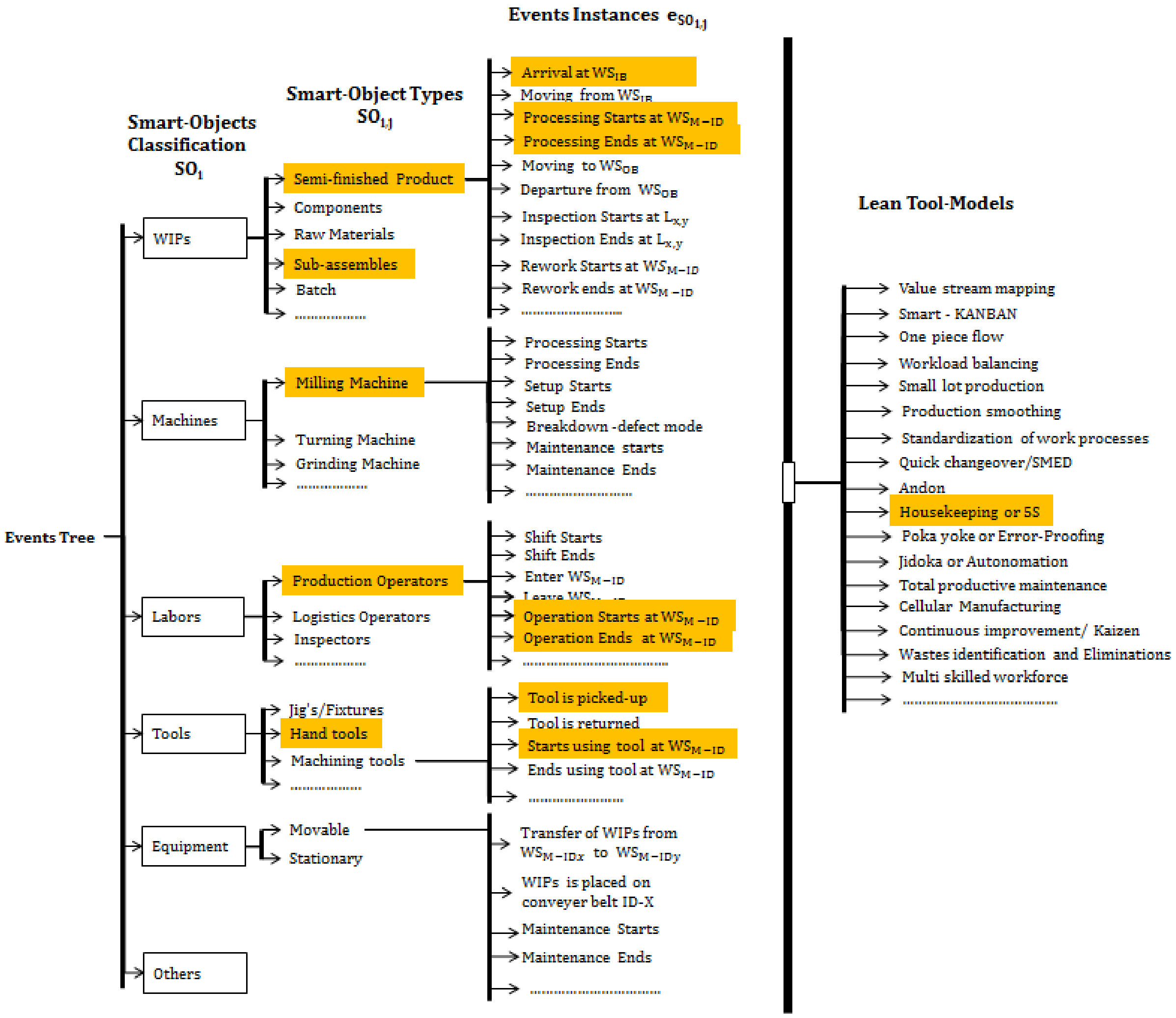


Figure 3.8. The Tree of Event Instances of the Smart-Objects.

3.6.2.1.4. VSM Data

This part of the RIE contains pre-defined graphical symbols, similar to those in the traditional VSM. Each symbol represents a specific product-state. These VSM symbols will be automatically imported, according to the current product-state along the value stream on the PSF, from the registry to provide the possibility to graph the AVSMs of the tracked WIPs and visualize it on the user interface (e.g. workers, supervisor). The relevant actual production 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 PSF.

3.6.2.1.5. Lean Tool Commands

As mentioned, the supervisors and workers are enabled to see all production-related information in details and accordingly make quick reactions or decisions; therefore the registry of the RIE contains predefined lean-based production commands or lean tools commands which can be used on the “re-(action) part” of RT-LCR body. Therefore, if the “conditions part” of the triggered RT-LCT is met, the commands in the “re-(action) part” will be automatically generated without human-intervention, such as changes in work-instructions, notification or warnings, etc., general examples of work-instructions include: WIP-withdrawal, dispatch, start processing, start setup, inspect, package, rework, etc. The generated commands are visualized on the authorized worker’s DVSM-TUI in order to be executed in near time or immediately to enhance lean practices during daily production runs and avoid waste.

3.6.2.1.6. Rules-Functions

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

3.6.2.2. Real-time Rule Expression Builder [RT-REB]

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

i. Building the appropriate RT-LCRs for each module in LPTE,
ii. Building the event processing rules for EEE to process the RFID-captured primitive events, such as events filtration rules to clear redundant events and save them in the temporarily database,
iii. Building rules to aggregate primitive events into complex events to detect specific production conditions (i.e. complex events) and save them in DVSM-DB for further uses,
iv. Building rules for the AVSM-Engine to translate the actual production-related data into VSM-format, and
v. Building rules for the VVSM-Engine to translate the standard lean-based production data into event context.

Our focus in this thesis is limited to describing the RT-LCRs that can be used in LPTE for real-time monitoring and controlling of LPTs during the daily production run.

RT-LCR's can use the "rule-based system" concepts to perform real-time analysis; accordingly, the body of the RT-LCRs encompasses two main parts, including:

i. Conditions part: the "conditions part" is represented through events aggregation, which represents a certain production situation; it contains specific event-data, constraints, attributes, and parameters. During the production run; the RT-LCR checks the validity of these conditions by invoking the subscribed events data (i.e. aggregated events) from the DVSM-DB and AVSM.

ii. Re-(action) part: if the conditions part with the defined constraints is met, then the "re-(action) part" of the RT-LCR will be triggered to generate the predefined re-(actions) to be executed by the right labor at the right time. The re-(action) part defines how the system must react when the predefined events occur and cause a specific status or condition during the production run. See figure 3.9. However, a complex RT-LCR could have different and more complex format.

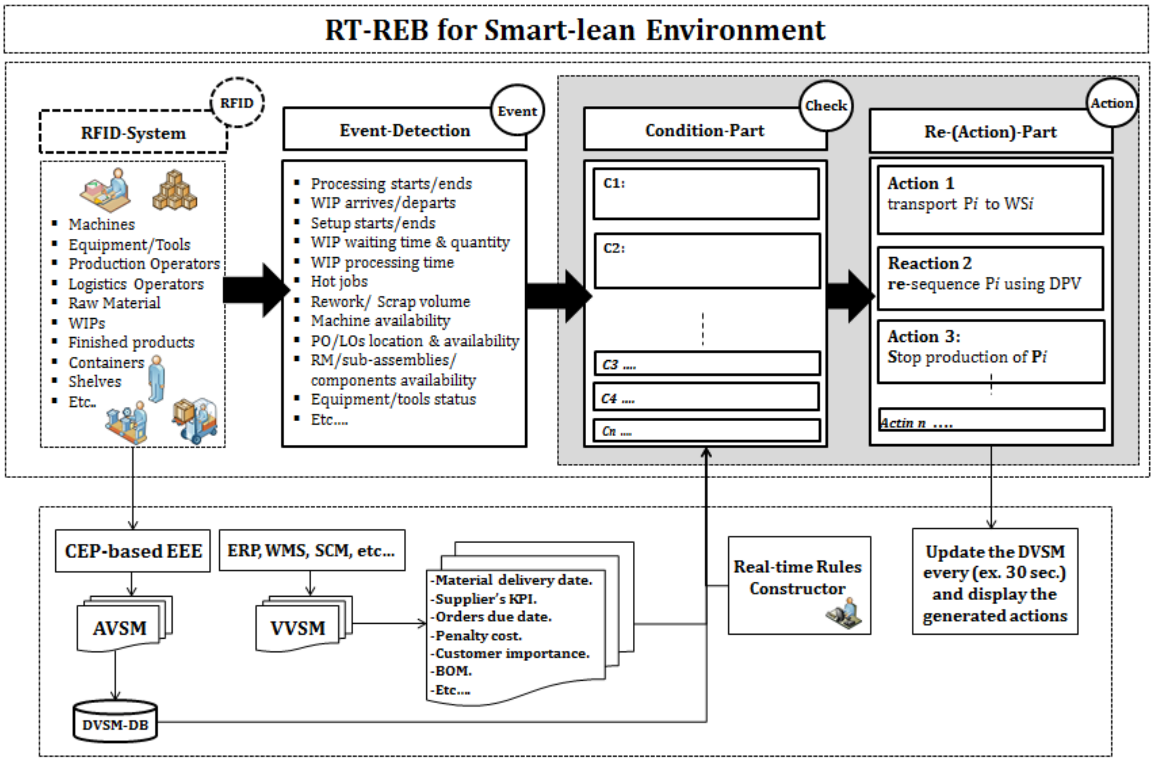


Figure 3.9. RT-REB for a Smart-lean Environment.

The RT-LCRs are classified according to their default functions into two types, including:

i. Local RT-LCRs which are directed to control a specific lean tool at a certain location on the PSF (e.g. 5S-rules at WS_i, Poka yoke-rules at WS_i), and

ii. Global RT-LCRs which are directed to control the interaction between different smart-objects at the overall PSF level to support a specific lean tool (e.g. line balancing and flow control along the value stream, re-scheduling the load-leveling box according to the current PSF situation). See figure 3.10.

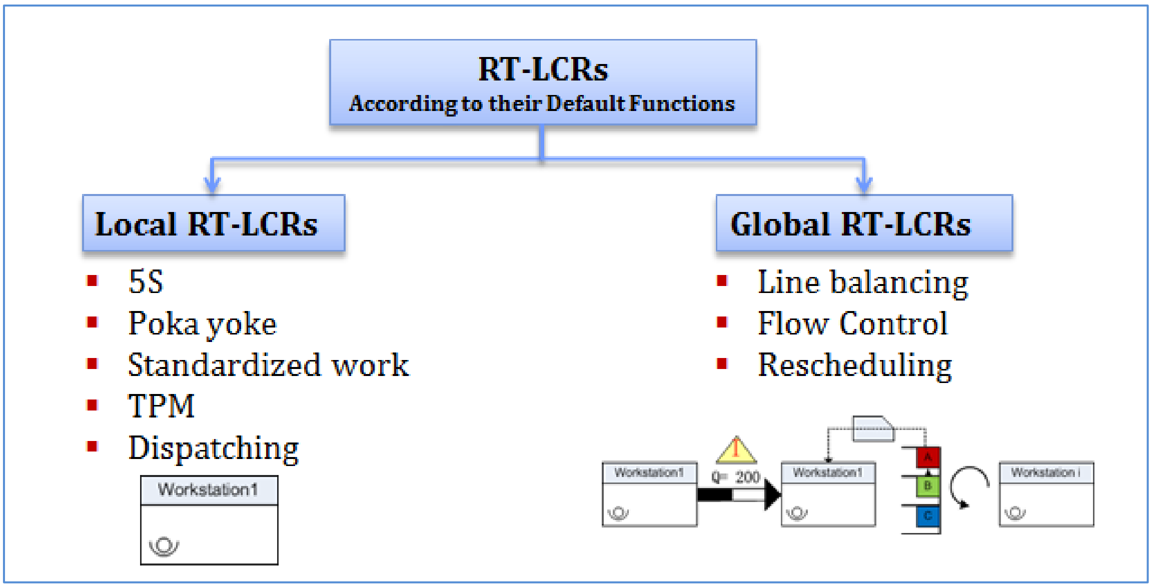


Figure 3.10. Types of RT-LCRs According their Default Functions.

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

i. Operational RT-LCRs: generate re-(actions) that are executed on the PSF, see the detailed discussion below,

ii. Analytical RT-LCRs: generate re-(actions) to execute an on-line analysis, the results of this re-(actions) can be used by other RT-LCRs or saved for further analysis, such as “update the average” of machining time based on the processing start/end-instances to monitor the Manufacturing Lead Time (MLT), “estimate and update the remaining life” of cutting tools or spare parts after each use to prevent tool shortages or breakdown , “incur cost” for cost tracking purposes, in other words they are abstract RT-LCRs, and

iii. Hybrid RT-LCRs: used for operational and analytical re-(actions), for example if the result of the analytical RT-LCR re-(action) requires a rapid a physical re-(action) on the ground, the associated operational RT-LCR will be triggered to generate the urgent re-(actions). Therefore, each RT-LCR should have a unique ID to be activated through other rules, see figure3.11.

The generated re-(actions) of the operational RT-LCRs can be classified into three types:

i. Machine-related reactions: smart and automatic re-(actions) without human intervention, such as “stop machine” if the Takt-time exceeds threshold, or manipulate certain manufacturing parameters such as “increase the temperature to -X- value” as in VVSM of P_i, if “arrival-event” of P_i at machine is detected in AVSM of P_i ,

ii. Human-related reactions: re-(actions) that only require human execution, such as lean tool commands which are visualized on the TUI, and

iii. Hybrid-related reactions: re-(actions) that need human approval using TUI in order to be executed by machines or workers, see figure 3.11.

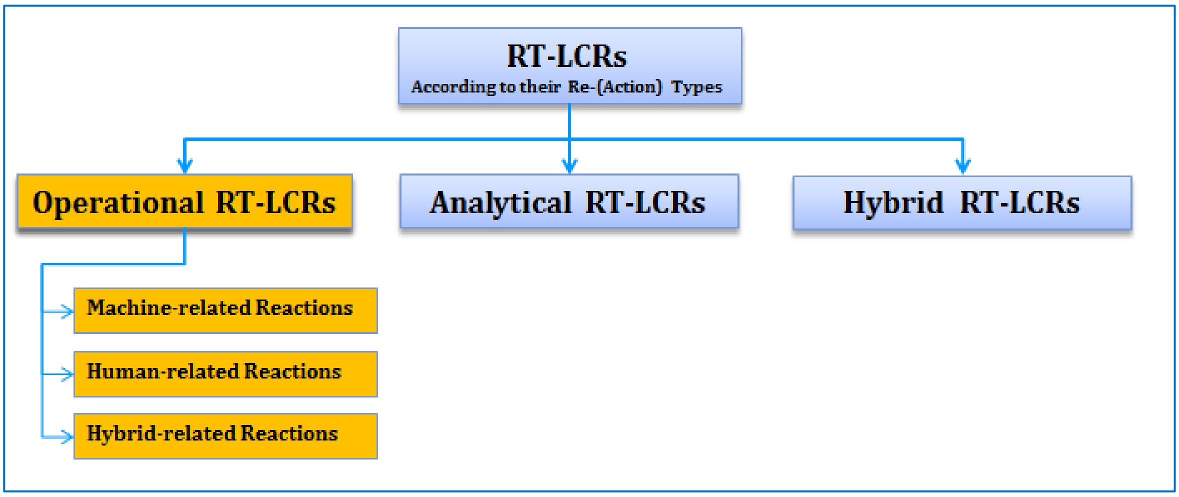


Figure 3.11. Types of RT-LCRs According their Generated Re-(action).

Therefore, these re-(actions) are operational reactions and are executed either by workers or machines at the PSF to keep lean initiatives alive and avoid wastes, unwanted incidents, and disturbances. In this regard, all re-(actions) commands should be predefined and saved in the registry of RIE. As a result, RT-LCRs aim to build a relation between RFID-captured events to identify a specific production situation and generate a re-(actions) with certain commands for labors or machines.

The RT-REB is one of the best DVSM’s features, which distinguish it from other lean-IT systems; it is expected to provide many advantages toward smart lean environments, including:

i. Enable a smart real-time re-(actions) mechanism without the needs for supervisors or human intervention,

ii. The DVSM modules can rapidly adapt with the critical situations and incidents during the execution of the manufacturing process, leading to the limitation of wastes,

iii. Lean initiatives are kept alive and valid in short periods of time (i.e. daily production runs) and in longer periods of time to prevent “lean death” due to the short-life cycle of products and the rapid changes in market behavior, as well as the high customization level in production systems,

iv. The real-time monitoring and controlling of LPTs become more flexible and adaptable in a dynamic manufacturing environment, and

v. RT-LCRs contribute to the self-learning process of some resources like machines and equipment, in order to avoid wastes in advance. The Real-time Knowledge Management (RT-KM) can be improved and enhanced, with regards to the extraction of production-related data from the DVSM-DB, in order to find new improvement opportunities (kaizen events).

3.6.3. Actual Value Stream Mapping Engine-[AVSM]

In the AVSM-Engine, the actual flow of each product along the value stream with all associated production data will be tracked and visualized in VSM-format, so it represents the current situation on the PSF, as seen in figure 3.12. The real-time tracking of flow in the AVSM-Engine is executed as follows:

i. Lean specialists express the AVSM-flow tracking rules through the RT-REB. The following algorithm describes a simple tracking RT-LCR. As seen, the AVSM- flow tracking rules subscribe all flow-related event instances (i.e. primitive events) and the associated production-related data to extract them in real-time.

```
RT-LCR_i = AVSM-Path
IF VVSM$_{P_i}$ released
    THEN
            FOR $\forall P_j \in VVSM - P_i$
               TRACK: $P_{i_j}\,[L_{iID}(T)]$
                     RECORD in Series $< P_{i_j}, L_{iID}, T_i >$
ENDIF
    FOR each $< \mathrm{P}_{i_j}, L_{iID}, T_i >, \in AVSM_{i_j}$
            RECORD $\left[d_{AVSM_{i_j}} =< P_{ID}; M_{ID}; O_{ID}; E_{ID}; Mat._{ID}; T_{ID}; \{Pa.1, Pa.2, Pa.3,\ \}\right]$
    ENDFOR

 END
```

ii. Once a subscribed event-instance is detected in the temporal database; it will be invoked through AVSM-rule for further flow analysis.

iii. The AVSM-rule defines the product-state (e.g. processing-state, transport-state, inspection-state, waiting-state, etc...) that the product passes through.

iv. After a product-state is defined (i.e. Name, timestamps, duration, location, etc.) in real-time; the AVSM-rule activates the action="import" to import the corresponding pre-defined VSM-graphical symbol and draw it in the user interface. This will define the current progress and actual route of single products in term of time and locations. The visualization will be done in coordination with the Real-time Visualization Engine (RT-VE).

v. The associated production-related events data can be synchronously with products flow-related events extracted and aggregated to be processed and visualized.

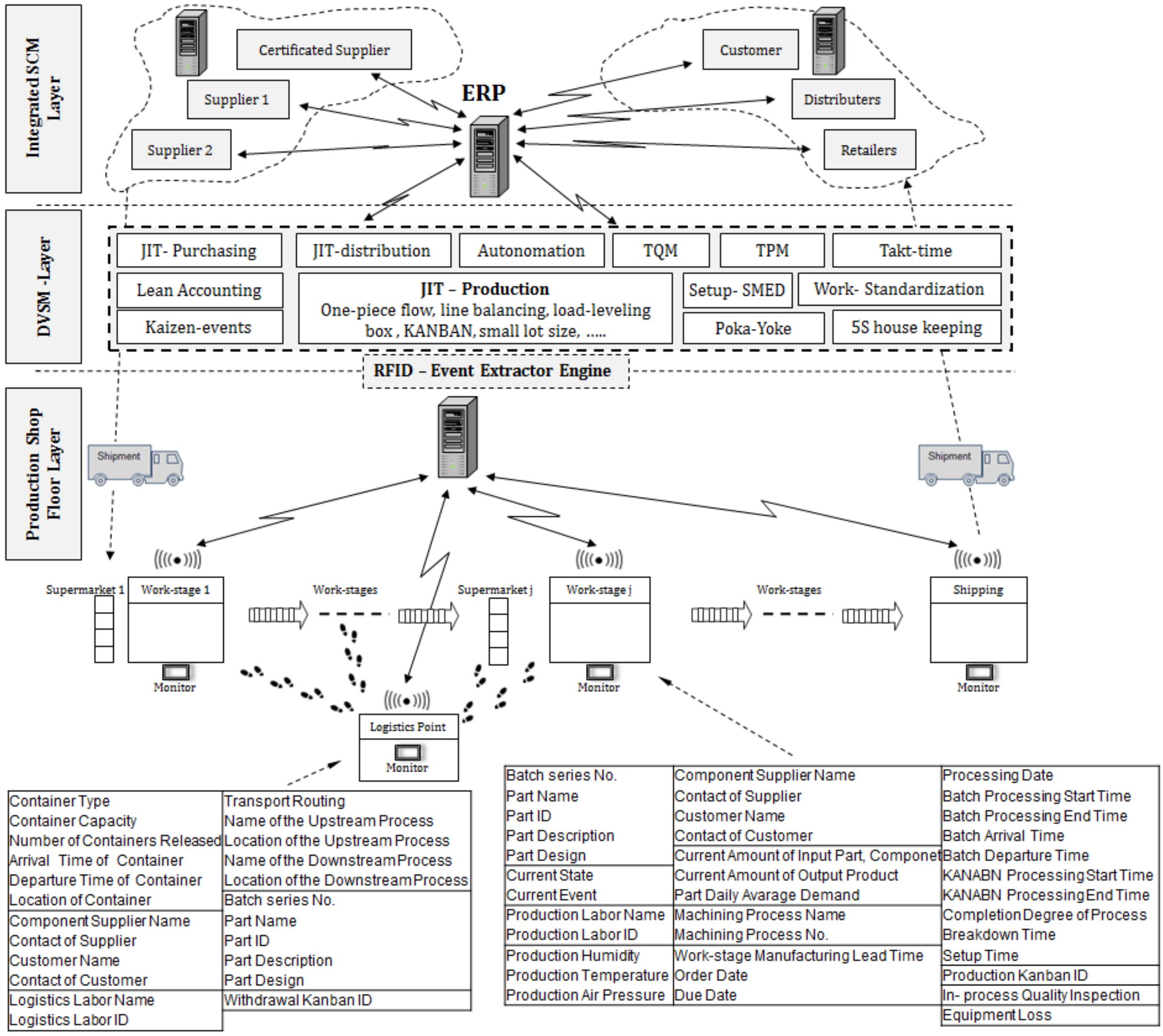
The AVSM-Engine can execute in parallel several real-time tracking processes to track all released product types on the PSF, therefore each product type has specific AVSM-rule to track its single items along the value stream (i.e. AVSM*ij* , where i = 1,2,3,..,n; i is the product type-index; n is maximum number of released product types on the PSF. j =1,2,3,……m, where j is the product-index; m is the maximum number of items from this type). For visualization issues, the AVSM is classified into two types:

i. Local-AVSM: visualizes the current item which is being processed by the labor at the local TUI, (i.e. Fine AVSM). Figure 3.12 depicts this type.
ii. Global-AVSM: visualizes the overall situation at the PSF (i.e. Rough AVSM), that contains all Local-AVSMs of the released product types with 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 production-related data will be constantly 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 lean-based control data should be considered in short and long-term lean practicing. For example the labors monitor the production progress through the local-AVSM with detailed information and current lean control data up-to second or minute depends on the production parameters, while the supervisor monitors the production progress through global-AVSM within time frame of hours (i.e. control charts, histogram, etc.) and the manager within time frame of days.

This engine synchronizes tracking of the physical flow of smart-products with capturing the associated data in real-time, which indicates that RFID significantly contributes to eliminate human intervention in data collection processes that eliminates the potential of errors and the wasted time in case of traditional data collection methods as well.

The AVSM supplies the manufacturer with the accurate picture of the resources along the value stream. This would help a company that has many scattered equipment and tools to track the status of resources and updates it over the time and checks their current availability, which enhances the real-time planning process and optimizes the interaction between the available resources to reach the optimum usage rate and eliminate the associated waste.



Container Type Container Capacity Number of Containers Released Arrival Time of Container Departure Time of Container Location of Container	Transport Routing Name of the Upstream Process Location of the Upstream Process Name of the Downstream Process Location of the Downstream Process
Component Supplier Name Contact of Supplier Customer Name Contact of Customer	Batch series No. Part Name Part ID Part Description Part Design
Logistics Labor Name Logistics Labor ID	Withdrawal Kanban ID

Batch series No. Part Name Part ID Part Description Part Design	Component Supplier Name Contact of Supplier Customer Name Contact of Customer	Processing Date Batch Processing Start Time Batch Processing End Time Batch Arrival Time Batch Departure Time KANABN Processing Start Time KANABN Processing End Time Completion Degree of Process Breakdown Time Setup Time
Current State Current Event	Current Amount of Input Part, Componet Current Amount of Output Product Part Daily Avarage Demand	Production Kanban ID
Production Labor Name Production Labor ID	Machining Process Name Machining Process No.	In- process Quality Inspection
Production Humidity Production Temperature Production Air Pressure	Work-stage Manufacturing Lead Time Order Date Due Date	Equipment Loss

Figure 3.12. AVSM with Flow and Production-related Data.

3.6.4. Virtual Value Stream Mapping Engine-[VVSM]

The VVSM represents the standard WIP flow along the value stream with all standard lean-based production data, i.e. the ideal or planned lean state. So it is considered as a standard lean technical information database of the currently products being manufactured, that involves all standard production data in term of flow.

Releasing the product to production operation starts by building the standard value stream mapping template for each new product to rapidly adapt with the production processes.

The standard flow and the associated lean-based production data are set during the pre-manufacturing phases such as product development, product design, process design, production planning, etc. This creates an integrated lean enterprise through integrating product and process planning, scheduling with execution, control, and decision making. Simulation software could be utilized for process design data especially analyzing the time span which is considered as the main basis for lean success.

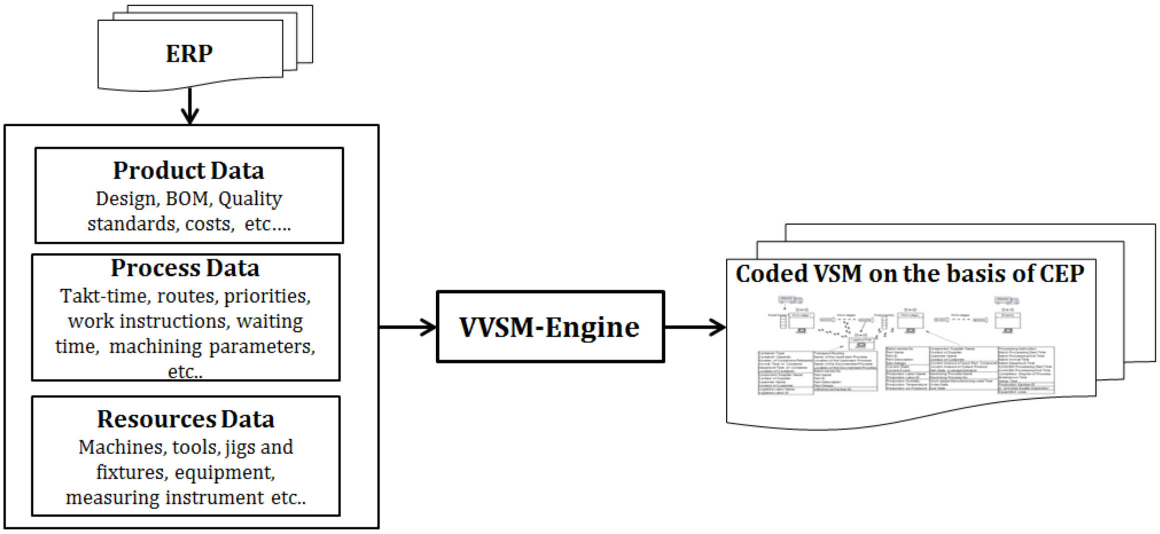


Figure 3.13. Integration of ERP with DVSM through the VVSM-Engine.

In this context, to bridge the gap between the standard lean state 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 VSM-format to automatically retrieve the lean standards in real-time if unexpected incidences occur and keep LPTs alive and effective (i.e. this done by different modules in LPTE). As seen in figure 3.13, the VVSM-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's event-data vector as described in RFID-operators section, the path's event-data vector will be saved in VVSM-registry with all production-related data.

The path's event-data vector accurately describes in details the standard value stream route with all product-states that the product must pass through in terms of time and location with the associated lean-based production data such as takt-time; kanban size, batch sizes, order size, sequence and priorities in load-leveling box; setup times and SMED procedure; product-states with standard time instances, duration, locations, required machines, tools, jigs and fixtures for each state location; quality standards; TPM data such as spare parts and tools life cycle time; standard data such as execution the manufacturing steps with the optimum sequence and required equipment, tools, skills level, and subassemblies at each step with durations; the standard machining 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 PSF and during manufacturing 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, and 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 VVSM-Engine and viewed as event-instances in relevant VVSMs, in order to make a quick real-time re-(action) to avoid wastes and NVA activities.

In an ideal situation, workers receive the standard work instructions from the 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 [HS08]. Therefore, to retrieve the lean standards and regulate all production activities to mitigate the impacts of variability; a real-time comparison between virtual world and physical world should be constantly executed.

This interaction can be done through LPTE modules between VVSM and AVSM as described in figure 3.14, where the differences between what is planned in VVSM and what is being produced in AVSM can be detected through different RT-LCRs in the LPTE and visualized on TUI through the RT-VE, for example wrong subassembly which has been mounted to product will be detected in poka-yoke module, tool is misplaced will be detected in 5S module, etc.

To detect the discrepancies through RT-LCRs; some events data and values from both VVSM and AVSM can be subscribed through "conditions part" of the RT-LCR. During the production, the subscribed events' values are constantly invoked, if there are any differences; a re-(actions) will be generated in accordance to "re-(action) part" of the RT-LCR. In this case, the actual lean-control data is visualized to be executed by labors.

Other examples, including (i) Flow tracking: the tracking process of the product-flow in LPTE can be done through comparison between the actual path event-data vector in AVSM and the ideal one in VVSM, if both are matched and no discrepancies are detected; then the product is allowed for further processing. Otherwise, a lean-control data signal as a re-(action) will be generated and sent to the LO to make a correction, (ii) Product-states duration: compares the duration of product-states in AVSM and VVSM, if discrepancies are detected; a quick reaction will be made such as slowdown or speedup. The results of both cases are saved in the DVSM-DB for further analysis and uses in ERP or LPTE.

3.6.5. Real-time Visualization Engine- [RT-VE]

This engine displays mainly the AVSM of each product at the local TUI of workers and supervisors. The RT-VE is equipped with rules to invoke and process the current production data from AVSM, to display them in VSM-format. For instance, the local-AVSM$_i$ of product "P$_i$" will be visualized on the TUI of PO$_i$ at WS$_i$, once an "arrival-event" of "Pi" at WS$_i$ is detected. Moreover, the RT-VE will invoke and display from VVSM the lean-based work instructions, sudden related changes by the employees in the higher enterprise level, and other important information needed for production to ensure that the PO$_i$ automatically acts according to lean concepts without being told. Finally, RT-VE displays the generated re-(action) towards the unplanned and unexpected production incidents and disturbances through LPTE. As result, RT-VE collects the actual production status from all production data sources (i.e. AVSM, VVSM, and LPTE) and visualizes it at local users' TUI. This is depicted in figure 3.14.

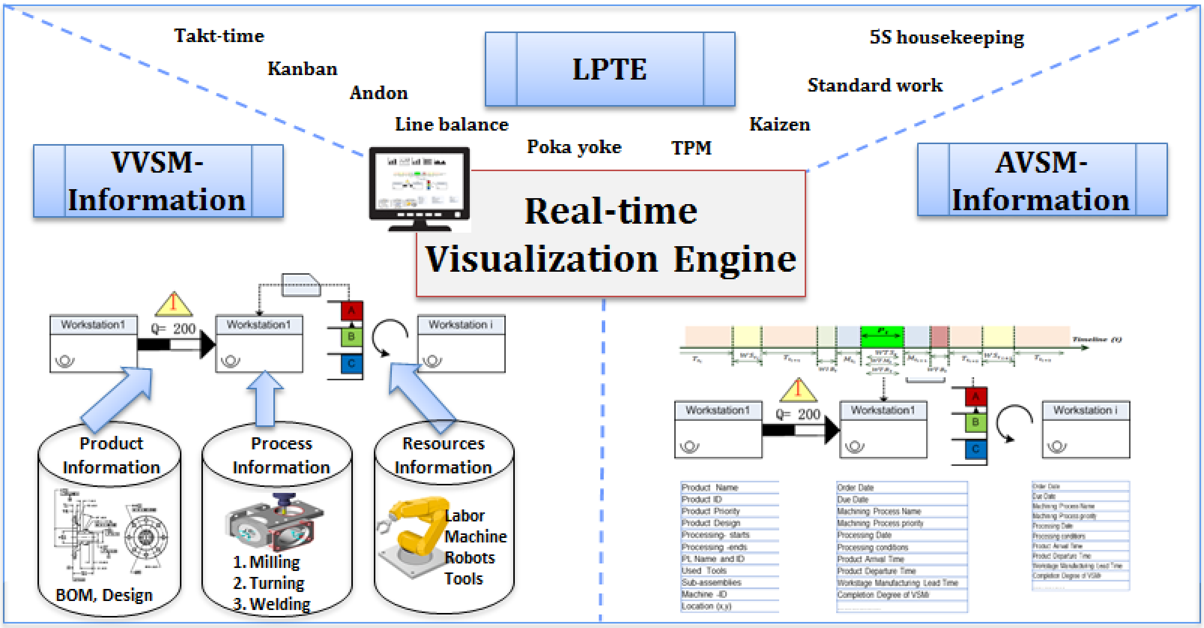


Figure 3.14. The Interaction between DVSM-Engines Through RT-VE.

3.7. Conclusion

This chapter presented the core of this thesis, where the integration of RFID system with lean concepts is proposed. The integration framework is based on real-time tracking of smart-objects by RFID in term of time and location with the associated event data and viewed on VSM-format. This framework is represented though developing a computerized real-time lean-oriented IT system, known as "Dynamic Value Stream

Mapping". DVSM is proposed to handle the enormous amount of triggered events on the manufacturing execution level as well as higher enterprise levels to enhance lean implementation in short and long-terms.

The DVSM is equipped with RT-RE that supply the real-time running DVSM-Engines e.g. AVSM, VVSM, LPTE with the needed rules based on CEP concepts. The LPTE is considered as the head of DVSM which involves several lean modules, each of which is specified to control a specific lean tool and it is equipped with the required real-time control rules called RT-LCRs. The RT-LCRs enable DVSM to smartly detect any production interruptions or incidents and accordingly trigger real-time re-(actions) to reduce the seven types of waste and achieve smart real-time lean environment.

With the implementation of this framework, the flexibility and adaptability of LPTs is expected to be increased and become versatile in facing the challenges of lean manufacturing and at the same time, maintaining the level of productivity and effectiveness of a production system, despite deviations and changes due to today's high dynamic and complex production systems. This framework could be further enhanced, through standardizing the CEP-rule semantics for constructing the RT-LCRs that can be easily translated into any programming language (code). A complex event compiler could be used to check the validity of a RT-LCRs code according to the information in the meta-data, as well as to conduct syntactical and lexical analysis and correction of the RT-LCRs expression.

CHAPTER 4
DVSM-enabled Real-time Time-Based Analysis

This chapter introduces a real-time time analysis framework to track the manufacturing lead time (MLT) of an individual product along the value stream in real-time, in order to identify its time-components, and accordingly measure the leanness of the production environment in terms of time. In this context, the wastes in a manufacturing environment are converted into time and hence, lead to longer MLT. Here, the traditional VSM lean tool is not able to understand the dynamic interactions, and thus, it is incapable of uncovering the potential wastes which are inherent within the processes or identify their root-causes. Therefore, this chapter also introduces a smart real-time waste analysis mechanism based on the time-segments of the MLT to pinpoint the most wasteful activities, and thus the most critical product-state that influences the duration of the MLT. This kind of mechanism is proposed to make the hidden root-causes of wastes immediately visible through real-time waste analysis, so that they can be avoided or treated directly.

4.1. Introduction

The leanness of manufacturing environments can be measured through a set of lean metrics, such as throughput rates, on-time deliveries, Manufacturing Lead Times (MLT), total costs , space utilization, travel distances, inventory levels, labor productivity, set-up times, etc. [CVS+11]. These measures can be mirrored in terms of time, since time is almost the main basis of these metrics. For instance, longer travel distances means consuming more time. Therefore, the time-based flow is considered as the most critical success factor of lean. However, using the conventional time-study approaches to evaluate the current performance, or whether the desired results have been achieved through lean improvements are prone to data errors, time-consuming, labor intensive and inaccurate snapshots of the current performance.

In this context, RFID is suggested to significantly improve the real-time performance measurement by means of providing a timely feedback about the current performance. However, utilizing the RFID captured data for time analysis and waste identification is still limited and scarcely reported [ZHD+12], since there are hardly any studies discussing how RFID captured data can be utilized to analyze the MLT and investigate the value stream process inefficiency in terms of time.

This chapter is concerned with studying the performance of lean environments using the product time-based flow (i.e. Manufacturing Lean Time (MLT)) along the value stream. Therefore, a new approach is developed to enhance the real-time analysis of WIP-flow time data in order to be used as the main basis to detect the incidents and unexpected events that lead to NVA-states, either for real-time use or searching for new improvement opportunities. This approach starts during designing the VVSM by breaking down the product's MLT into contiguous time segments called "product-state" or "time-component" which can be tracked and defined in real-time using RT-LCRs.

In this context, the consequences of incidents and interruptions are resulting in overproduction, excess inventory, rework or defects, excess transport, motion, and over-processing wastes, are converted into time and hence, lead to longer MLT. In this manner, to protect the lean system from an inevitable death due to continuous changes and prevent the dominance of waste root causes upon MLT on the ground; the incidents, unexpected, untimely, and unplanned event-instances must be made immediately visible and targeted to be avoided and eliminated. This section also introduces a time-based analysis approach called "Smart Real-Time Waste Analysis" (RT-SWA), which is inspired from the "cause and effect diagram", to smartly detect the wastes that cause the wasted time and investigate the root causes behind these wastes, in order to be eliminated. Therefore, the focus is to identify the critical product-states which consume more time and contribute in the deterioration of the overall performance in the lean environment.

4.2. DVSM-enabled Real-time Analysis of Manufacturing Lead Time

The Manufacturing Lead Time (MLT) analysis is recognized as an extremely important topic in the progress towards success in lean manufacturing. MLT is the total time from the time of release of a product/batch at the beginning of the value steam until the time the product/batch reaches the inventory point as finished goods. The MLT includes several time-components such as: processing time, queue time, setup time, run time, move time, inspection time, repair time, put away time, etc. Generally, it is the total time during which the product stays as a WIP at the PSF [HS08].

Through utilizing the powerful features of DVSM and the significant knowledge in the captured real-time data through RFID, this section introduces a framework for real-time analyzing and estimating of the MLT 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), a real-time waste analysis process will be conducted by DVSM_RT-SWA module to identify the type of wastes that lead to this deviation and investigate the root causes of each waste.

The root causes of the NVA activities are targeted to be eliminated through further lean improvements (i.e. kaizen events), in order to reduce the MLT. Further MLT reduction can be achieved through tightly synchronizing the interactions and timings of resources. In the next section, the time-components of the MLT will be discussed. Note that the product-state and time-component are used interchangeably and have the same meaning

4.2.1. Time-Components of MLT

Production value stream usually consists of a series of individual processing and assembly operations. Between these operations are material handling, storage, inspections, and other non-productive activities [Gro07]. The duration of these activities contribute to the total MLT.

In this regard, for precise and effective real-time analysis in order to identify and localize the criticalities and weaknesses along the value stream; the MLT will be decomposed into several time-components, where each activity type 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. machining or processing-state, transporting-state, waiting-state, inspection-state, etc.). In this case, each product-state can be tracked in real-time, so that the most critical states that consume more time, and cause disruptions, incidents and serious order delays are defined and targeted to be investigated and improved.

Figure 4.1 represents a general physical operations and WIP flow at a single workstation between two supermarkets at the PSF. The MLT in terms of flow is made up of several product-states. The total value stream MLT is the sum of all product-state durations along the value stream. According to the definition of cycle time by Hopp and Spearman 2008 [HS08], the product-states are defined in table 4.1.

In this diagram, the real-time tracking of the event-instances of each product-state is illustrated. Therefore, each product-state has start/end event-instances with respect to the production timeline. The difference between two successive event-instances is the duration of this state.

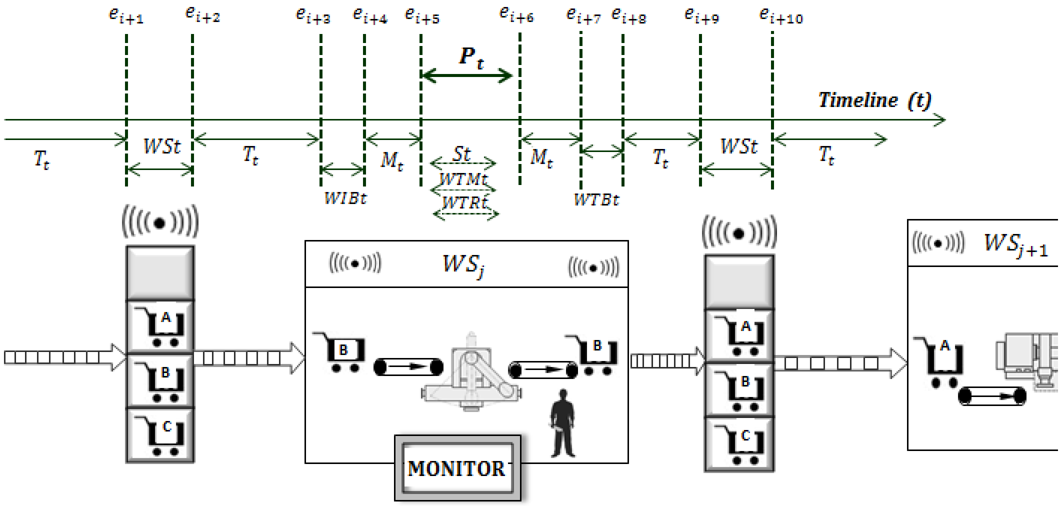


Figure 4.1. The Product-States at a Single Workstation.

Table 4.1. The Product-states of the MLT at a single workstation.

Product-state	State Description
P$_t$: Processing-state	The time in which product is actually being processed on the workstation.
T$_t$: Transporting-state	The time in which product is being transferred from upstream to downstream stations.
M$_t$: Moving -state	The time in which product is being moved to the next work-place or machine within a workstation.
WS$_t$: Waiting-in -Supermarket-state	The time in which product is waiting its turn to be transported at the next workstation for processing.
Q$_t$: Queuing-state	The time in which product is suspended between upstream and downstream workstations waiting to be processed or waiting for a resource, or waiting within a workstation to be moved.
WTS$_t$: Waiting-to-Setup–state	The time which the product spends waiting for the completion of the machine 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 station.
WTR$_t$: Waiting-to-Repair-state	The time which the product spends waiting for a machine which is being repaired.
WIB$_t$: Waiting-in-Batch-state	The time which the product spends in a batch at an input buffer waiting its turn on a machine within a workstation.
WTB$_t$: Waiting-to-Batch-state	The time which the product spends waiting to form a batch for either processing or moving.
WTM$_t$: Waiting-to-Match-state	The time which the products spend awaiting the arrival of their sub-assemblies to be matched with them.

Based on the manufacturing environment; other product-states can be defined such as Inspection-state, Rework-state, etc. Table 4.1 describes the MLT, with the assumption that the WIPs flow in batches. To represent the temporary storage of single WIPs in case of single product flow; instead of WIB$_t$ and WTB$_t$, the “Waiting-in-Input Buffer” (WIIB$_t$) and “Waiting-in-Output Buffer” (WIOB$_t$) respectively can be used. The queue-state Q$_t$ represents any waiting-states except the defined states in table 4.1. For example, a batch was completed 15 minutes ago and now is waiting to be transported by a forklift; the state here is considered to be Q$_t$. Another Q$_t$ state occurs, if a new batch of a certain product arrives at a workstation, where the workstation is still processing a previous batch, so the new batch must wait its turn, the state here is not WIB$_t$ but Qt. The same applies if the batch must wait for a machine that is being set-up or repaired; then it is WTS$_t$ or WTR$_t$ respectively. In an ideal lean scenario, as per standards established in VVSM, Qt is not defined; therefore it is 100% NVAT.

4.2.2. Estimating the Duration of MLT_ Product-States

The duration of each product-state along the value stream can be estimated in real-time and mapped in the AVSM based on the CEP method using RFID and Time-operators.

Figure 4.2 defines the method of real-time tracking and estimating the duration of each product-state. For instance, in order to track the MLT along a product value stream in real-time, there are ten event-instances (e_{i+x}) that are representing the product flow through the WS$_j$ and its Supermarket (SUP$_j$). The time interval between two homogenous and successive flow-events represents a specific product-state. For example, the timestamp of the event-instances ($(e'_{i+2}, e_{i+3}) \in E_{Tt\_i+1}$) represents the start/ end of the transporting-state (Tt$_{i+1}$) from SUP$_j$ to the WIB$_j$. The duration (D_{Ei}) of (Tt$_{i+1}$) can be estimated by tacking the absolute value of the subtracted timestamp (T_{ei}) of (e'_{i+2}) from (e_{i+3}), this can be represented as follows: $D_{Tt\_i+1} = |(T_{e'\_i+2}) - (T_{e\_i+3})|$.

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

- $D_{WS_{t_i}} = |T_{e'_{i+1}} - T_{e_{i+2}}|;\ e'_{i+1}, e_{i+2} \in E_{WS_{t_i}}$.
- $D_{WIB_t} = |T_{e'_{i+3}} - T_{e_{i+4}}|;\ e'_{i+3},\ e_{i+4} \in E_{WIB_t}$.
- $D_{M_{t_i}} = |T_{e'_{i+4}} - T_{e_{i+5}}|;\ e'_{i+4}, e_{i+5} \in E_{M_{t_i}}$.
- $D_{P_t} = |T_{e'_{i+5}} - T_{e_{i+6}}|;\ e'_{i+5}, e_{i+6} \in E_{P_t}$.
- The same mechanism can be used until $D_{WS_{t_{i+1}}}$.

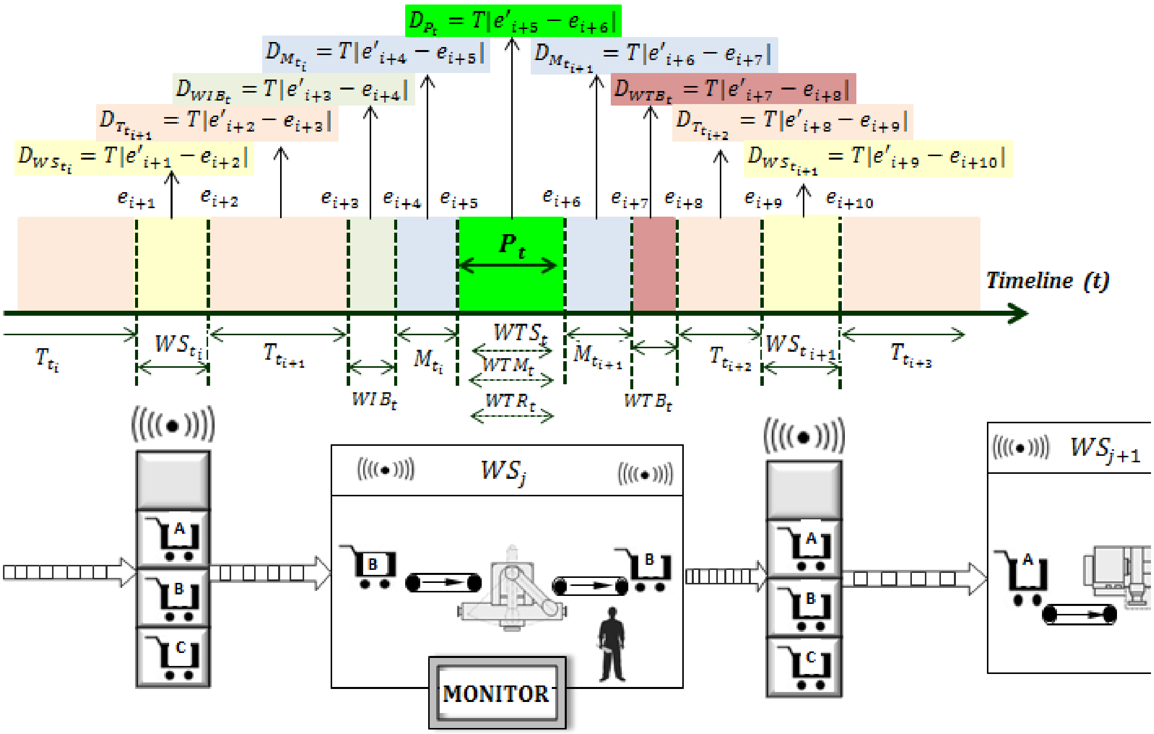


Figure 4.2. Estimating the MLT_ Product-States Using Event-Instances.

The total MLT at the WS$_j$ and SUP$_j$ *can* be estimated directly through the following expression:$MLT_{WS_j} = |T_{e'_{i+1}} - T_{e_{i+10}}|$; $e'_{i+1}, e_{i+10} \in E_{Flow\_WS_j}$. However, the real-time analysis of time-based activities becomes ineffective and inaccurate.

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 machining-state for an individual product becomes easy to be estimated, allowing for an estimation of the time deviation between VVSM and DVSM. Now, since the associated machining-state related data and key attributes are simultaneously recorded in the DVSM-DB, the potential factors or waste root causes that influence the amount of deviation can also be defined.

For example, the skill level of a new PO who is under probation could have been one of the factors that have caused a deviation in the machining time. In this regard, the skill level and gender of the PO-ID are defined in DVSM, and his learning curve will be updated from time to time depending on his performance reviews. Moreover, other influencing factors and waste root causes on MLT can be investigated such as using wrong tools or applying wrong process parameters on the machining-state, batching strategies, dispatching rules, product specification, etc.

The MLT at a signal workstation WS_j and SUP_j is estimated by the sum of the product-state durations together, as equation 4.1.:

$$MLT_{ws_j} = WS_{t_i} + T_{t_{i+1}} + WIB_t + M_{t_i} + P_t + M_{t_{i+1}} + WTB_t + T_{t_{i+2}} \qquad [4.1]$$

The WTS_t ,WTR_t,Q_t are considered when the product passes through them. Subsequently, the total *MLT* over the entire value stream of specific product is estimated through the summation of identical product-state, as equation below:

$$MLT_{AVSM_x} = \sum_{i=1}^{n} WIP\_state_i \times D_i \qquad [4.2]$$

Where: $AVSM_x$ is the product's actual value stream map, n is the number of states that the product passes through along its value stream, i=1,2,3 ……..n.

This can be explicitly expressed to show all types of product-states as follows:

$$MLT_{AVSM_x} = \sum_{i=1}^{n} Pt + \sum_{i=1}^{t} Tt + \sum_{i=1}^{m} Mt + \sum_{i=1}^{q} Qt + \sum_{i=1}^{k} WSt + \sum_{i=1}^{s} WTSt + \sum_{i=1}^{r} WTRt + \sum_{i=1}^{a} WIBt + \sum_{i=1}^{d} WTBt + \sum_{i=1}^{w} WTMt \qquad [4.3]$$

Where: n: number of processing-states, t: transporting-states, m: moving-states within WS_j, q: queuing-states, k: waiting in supermarket states, s: waiting_to_setup-states, r: waiting_to_repair-states, a and d: waiting_in/to_batch-states, and w: waiting_to_match-states. i = 0,1,2 ……. n,t,m,q,k,s,r,a,d,w.

4.2.3. Real-time Performance Analysis and Monitoring

Each product-state consists of value-added and non-value added time (VAT/NVAT). So if one of the product-states at a specific work-point frequently exceeds the VVSM designated time, then an investigation is to be conducted to determine the root cause of occurrences. To define the amount of waste in terms of time, a real-time waste analysis process is conducted. If the root causes are defined and lean improvements are applied, a time reduction due to the improvements should be achieved and displayed through the DVSM. The improvements must be embraced and maintained; otherwise the improvements would have been in vain.

Within the lean manufacturing context, comparing the undesirable or NVAT product-state duration into VAT product-state such as the processing-state will give one a shock [RS99]. Therefore, based on MLT, an in-depth analysis regarding lean tools efficiency can be automatically calculated as well as performing a statistical analysis. Through time quotients along the value stream, the ratio of VAT/NVAT product-state to total MLT can be estimated in real-time .This can be beneficial in the investigation of root causes that have been targeted for future improvements. According to equation 4.3, the following ratios can be estimated:

- ProcessingState Ratio $= \frac{\sum_{i=1}^{n} P_t}{MLT_{AVSM_x}}$
- TransportState Ratio $= \frac{\sum_{i=1}^{t} T_t}{MLT_{AVSM_x}}$
- MovingState Ratio $= \frac{\sum_{i=1}^{m} M_t}{MLT_{AVSM_x}}$
- WTS_tRatio $= \frac{\sum_{i=1}^{s} WST_t}{MLT_{AVSM_x}}$
- Q_tRatio $= \frac{\sum_{i=1}^{q} Q_t}{MLT_{AVSM_x}}$

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

During the production, a general overview about the real-time performance in terms of the MLT 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 lean operational purposes or be used as an analysis for other lean operational purposes (e.g. JIT-replenishment, smart real-time production control, real-time manufacturing cost tracking and analysis, etc.).

4.3. Smart Real-Time Waste Analysis [RT-SWA]

It is well-known that wastes along the value stream map cause a significant deviation between the actual MLT and the designated standard MLT. The time difference reflects the amount of discrepancies between the virtual and actual status in terms of activities.

To reduce time differences, the wasteful activities related to process-state segments must be made immediately visible through a real-time waste analysis, so that they can be avoided or treated directly. This section presents a tool called “Smart Real-time Wastes Analysis” (RT-SWA). This tool was inspired by the cause-and-effect diagram to effectively determine the criticalities and weaknesses in each product-state along the value stream in order to detect the impact of the seven main wastes on the amount of the NVAT. With RT-SWA, the root causes of each main waste can be defined in terms of time and location along the value stream. Thus, this tool serves as a real-time explorer in systems riddled with hidden root causes of wastes, to find inefficient processes and their locations along the value stream. In other words, during the production run, if the 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 production line 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.

The RT-SWA module is equipped with suitable RT-LCRs to constantly estimate the time deviation and investigate the potential causes. The algorithms presented later in this 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-SWA.

4.3.1. Characteristics of Waste

Before introducing the RT-SWA framework, the attributes of the wastes should be understood. Therefore, this section highlights the main characteristics of wastes, as follows [CCH13][BK11]:

- Waste takes many forms and can be found at any time and in any place along the value stream.
- Wastes consume resources but do not add any value to the product.
- Wastes differ by products, processes, facilities, etc.
- Wastes negatively impact productivity, flexibility, and profitability.
- Waste is not always visible. The hidden waste poses the real threat and should be identified and eliminated.
- Waste can be hidden within VA activities.
- Some wastes propagate causing additional wastes (e.g., overproduction could increase chances of defects, increase inventory, transportation, etc.).

4.3.2. The Working Mechanism of the RT-SWA

This section discusses how RT-SWA could be configured to help the manufactures to identify the potential waste which is inherent to the individual product-state along the value stream. This postulates that every waste root-cause is directly or indirectly related to time, which lengthens the actual MLT, such as, using the wrong tool may lead to lengthening the processing-state or quality problems that need rework, neglecting the standardized work instruction may lead to over processing and lengthening of the processing-state, etc.

As mentioned, the idea of the developed RT-SWA is inspired from the cause and effect diagram. In this regard, Figure 4.3 represents the working mechanism of the RT-SWA as a graphical real-time waste explorer which detects firstly the amount of deviation (i.e. NVAT ratio) in terms of time and location on the value stream timeline, this time will be listed on the empty square. With the help of digitalizing the concepts of 5Why’s, using causality analysis, event correlation and hierarchical relationships between event instances in the RT-SWA_RT-LCRs, the potential waste and their root-causes can be identified. The deviation reasoning process takes knowledge from the event-data set and deduces main root-causes.

The initiation of RT-SWA starts with constant estimation of the differences between standard and actual product-state values. Once a time deviation at any location is detected; the RT-SWA will trigger a root-cause analysis to uncover the wastes that lead to this deviation. Figure 4.3 below describes the working logic of the RT-SWA module to investigate and identify the root causes of time-based wastes.

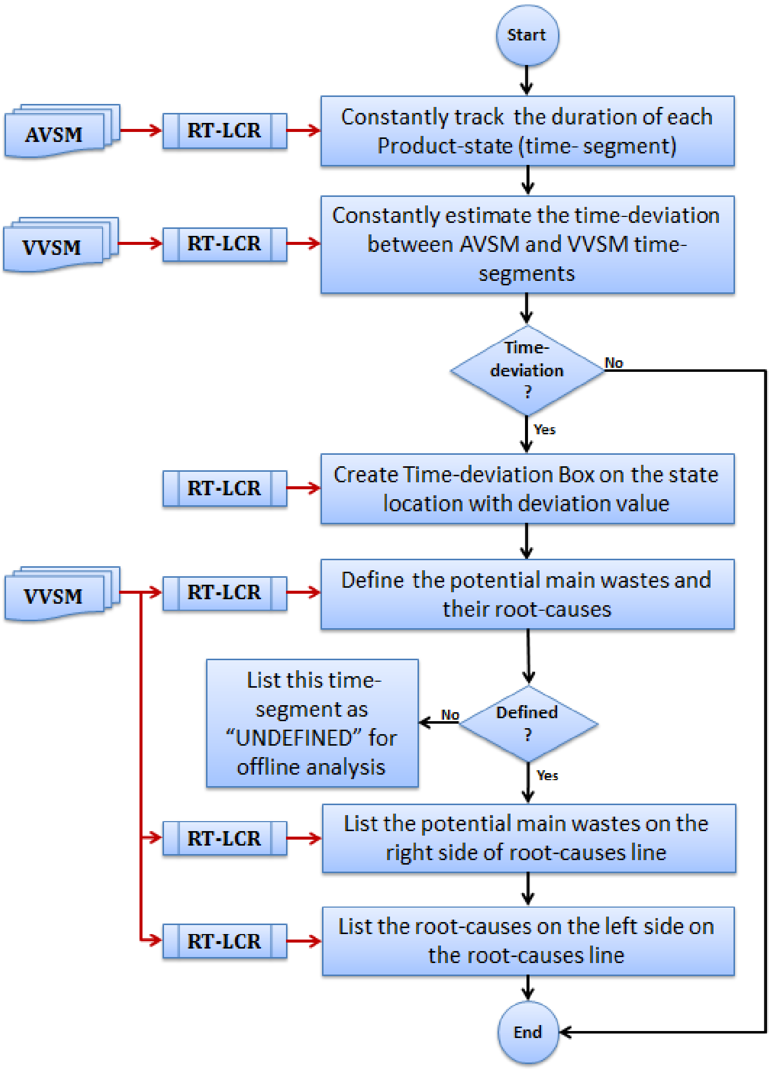


Figure 4.3. The Working Logic of the RT-SWA.

The following steps describe figure 4.3 in details, the detected root-cases and wastes can be graphically displayed as figure 4.4:

1. The standard product-states (duration, location) along the value stream time-line should be predefined in VVSM.
2. RT-LCRs will be expressed to keep track of the actual product-state and its duration along the value stream.

3. After each product-state, the time-deviation will be estimated and the value of the deviation will be entered in the “state-time deviation” box.
4. In the same fashion, if an undefined product-state has been detected, a new box will be created automatically and the value of the deviation will be entered.
5. Next, the potential main wastes which have caused the time-deviation or undefined product-state will be listed with the help of using the causality analysis and hierarchical relationships between event-instances in RT-SWA_RT-LCRs. The potential waste 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 main wastes as a root cause (i.e. overproduction causes inventory waste and thus more waiting time as a waste).
6. Then, the time impact-ratio of each waste on the MLT will be estimated. If the root causes are not time-based, their impacts will be translated into time.
7. The sum of the total time duration of all main wastes 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 MLT.
8. If a part of the time-deviation still has unknown causes, the RT-SWA will list it as undefined-time to re-investigate the product-state details and eventually assign the actual waste root cause to this time.
9. The amount of time-deviation reflects on the gap between the actual manufacturing environment and the perfect lean manufacturing environment.
10. The root-causes will be a guide to the lean practitioner, for him to decide on the lean tool which is most suitable to eliminate the waste.

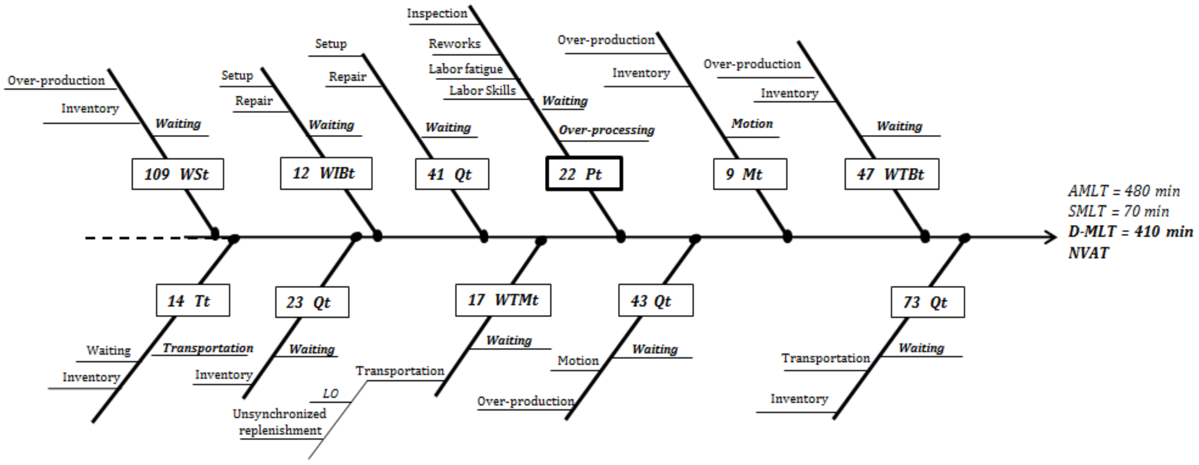


Figure 4.4. The Graphical Representation of the Detected Root-Causes.

4.3.3. The RT-SWA_RT-LCRs

As aforementioned, the RT-SWA module is equipped with suitable RT-LCRs. These smart real-time waste 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-LCRs should be able to extract the causal and hierarchical relationships between event-instances based on the event-data set (i.e. production related-data). Thus, facilitate the real-time analysis of interaction between smart-objects to identify the root-causes.

For effective RT-LCRs, 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 4.1.
2. Define the expected standard duration of each product-state.
3. Predefine the expected undesired conditions along the value streams on the PSF.
4. Investigate the potential causes for each condition and define them in the DVSM_RT-SWA module. For example, if the Waiting-in-Buffer time rapidly increases, the potential causes include:

➔ Machine is not available (Breakdown mode)

➔ Labor is not available (Log-off mode)

➔ Longer set-up-time (unsuitable SMED)

➔ Processing-state at downstream machine is increasing (Defects detected, looking for a tool)

➔ Upstream machine is producing too quickly (Over-production)

5. Define a real-time correction that needs to be triggered as a part of the real-time controlling mechanism.

For an effective functionality of RT-SWA, all potential root-causes according to the technical expertise and historical data should be pre-defined in the DVSM-RT-SWA in order to be automatically identified through RT-SWA_RT-LCRs diagnosing process. However, during production runs, some situations are unclear. Therefore, since the workers are provided with the user-friendly interface “TUI-DVSM”, the PO is enabled to select the actual root-cause from the listed root-causes if they are not automatically identified by RT-LCRs for any reason, or typing in the actual root cause if it is not originally pre-defined in the DVSM-RT-SWA.

For the real-time investigation process, the RT-LCRs 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 DVSM-DB. Therefore the real-time tracking of events data in AVSM and traceability of the recorded data in DVSM-DB significantly benefits the functionality of the RT-SWA.

In general, the IF-THEN heuristic rule serves as a 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, if the 'IF' part has been detected to be true [SZM06][GA00]. 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 initiation condition for further conditions checking actions in order to narrow down the possible root-causes, and then precisely pinpoint the right root-causes, this is described as follows:

RT-LCR$_i$ = AVSM-D$_{ProductState}$

```
01: ESTIMATE $P\_D_X\ (e^{i}{}_{ws_{t_i}};\ e^{i+1}{}_{ws_{t_i}}) \in E_{ws_{t_i}}$
02:     IF [$D_X\ (e^{i}{}_{ws_{t_i}};\ e^{i+1}{}_{ws_{t_i}})$] > [VVSM-$D_X$] THEN DO 03, ELSE, GO TO STEP 09
03:             CHECK {RT-LCR$_{condition}$.....}
04:     IF [RT-LCR$_{i\_condition}$] is matched
05:             THEN
06:             CHECK {$^{i}E_{defined}$ – event-instances.....}
07:     IF [$^{i}E_x$] is detected
08:             RETUN [$^{i}E_x$] as "root-cause"
09: END
```

Line 01 checks if a product exceeds the waiting-time threshold in SUP$_j$. In **line 02** if the time is exceeded, **line03** will check the conditions (i.e. event-instances) of each waste type through a predefined RT-LCR$_{i\_condition}$. **Line04&05** will initiate RT-LCR$_{i\text{-}condition}$ 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. **END.**

This above RT-LCR illustrates a simple expression to define the potential root-cause if a time deviation is detected. The next section addresses two real-time waste analysis scenarios.

4.4. Real-time Waste Analysis Scenarios

The RT-SWA_RT-LCR will run through the possible scenarios that are listed in the form of algorithms, to determine the root cause of consuming extra time during individual product-states. To demonstrate how the RT-SWA is working in reality, basic examples of these algorithms regarding the common waste scenarios along with the possible scenarios that cause these wastes will be discussed in this section.

To identify the wastes and their impacts-ratio on the MLT; the wastes should be measured in time units. On the ground, the quantity-based wastes which include overproduction, defects/rework, and excess inventory are converted into "time-based wastes". For instance, the overproduction causes more inventories which may contain high ratio of defective parts, to handle this situation the time-based wastes are created through unnecessary transport, waiting, motion time and extra processing time for the reworkable defective parts. Empirically, the majority of WIP time is spent waiting such as WS_t, Q_t, WTS_t, WTR_t, WIB_t, WTM_t, WTB_t, while less than 10 % is actually processing or moving [HS08] Therefore, most of inefficiencies, incidents, and failures are translated into waiting-state. So the main focus should be on investigating the waiting time-states to uncover the hidden wastes and identify their root-causes.

➔ Supermarket Waiting Scenario [WS_t]

Suppose two workstations WS_1 and WS_2, and SUP_2 between them, transportation equipment with LO is used to transport the semi-finished WIP from WS_1 to SUP_2.

The proposed initiation condition of this scenario is: If the pattern of the waiting-state of consecutive products is ascending (plot the time-deviations in WS_t-state of successive products).

To identify the potential root-causes, further sub-conditions should be checked, such as : check the Takt-time, inventory level in SUP_2, and the sent Transportation Commands (TC) to LO between WS_1 and SUP_2.

- *Control at workstation (Takt-time)*

If the occurrence of the "process finish" events at WS_1 start to increase more than the designated Takt-time as defined in the VVSM (e.g. with rate 15 min while the designated rate according to Takt-time is 25 min), then the RT-LCR identifies that WS_1 is in "overproduction-state" as potential main causes.

- *Control the transporter*

If the TCs are increasing more than the designated rate; then the RT-LCR identify that WS_1 is in an "overproduction-state".

- *Control of inventory*

If the inventory level at SUP_2 is increasing, the RT-LCR identify that the upstream WS_1 is in "overproduction-state", or the downstream WS_2 is blocked (e.g. waiting for labor, waiting for subassembly, breakdown, etc.).

The potential root-cause may refer to the following: due to the available capacity of the machine the PO continues producing without any consideration to the task-to-time list resulting overproduction, and hence lengthen WS_t, this refers to the capacity planning problems. If the takt-time rate is not exceeded then there is an unbalanced line problem. Parallel to that, reactions should be generated as such: alerts will be sent to both the supervisor and the PO to slow down the machine throughput rate for example. Also, this time implies there is wasted capacity that should be taken into consideration for future effective production planning.

A basic algorithm to be used in the detection of events that cause longer waiting time shall be presented as follows:

Definitions:

D_{WSt} =	Duration of waiting state at SUP_2
UCL_{VVSM} =	Upper control limit
LCL_{VVSM} =	Lower control limit
$\longrightarrow \notin$ =	Goes to be not an element of {x:y}
$R_{i\{WS1:SUP2\}}$ =	Route {from:to}
$Q_{WIP}\_SUP_2$ =	Inventory level at SUP_2
$\uparrow/\downarrow$ =	Values in Increasing /Decreasing
T_{VVSM} =	Time in VVSM
T_{AVSM} =	Time in AVSM
D_{WS1_Ps} =	Duration of processing-state at WS_1
TASK $(e_s^i;e_e^{i+1})$ =	Task start/end events

RT-LCR$_1$=SUP- WS$_t$

```
01:   IF Plot [$D_{WSt}$] at $SUP_2 \uparrow$ AND $\longrightarrow \notin P\{UCL_{VVSM} : LCL_{VVSM}\}$, THEN
02:          CHECK [RT-LCR = Takt-time_$WS_1$];
03:          CHECK [RT-LCR= TC, $R_{i\{WS1:SUP2\}}$];
04:          CHECK [RT-LCR= $Q_{WIP}$, $SUP_2$];
05:   IF ([$e^i{}_{P_{WS1}}; e^{i+1}{}_{P_{WS1}}; e^{i+2}{}_{P_{WS1}}; \ldots . e^{i+x}{}_{P_{WS1}}, T_{AVSM}], e^i{}_{P_{WS1}} \in E_P), T_{AVSM}\downarrow < T_{VVSM} = 25$
06:          AND IF $D_{Pt\_WS1} \downarrow < LCL_{VVSM}$      -- check for improvement opportunity --
07:          ELSE, DO STEP 26
08:                THEN $WS_1$ is in {Over-production}
09:          CHECK [$TASK_{AVSM}$ ($e_S^i;e_E^{i+1}$)]$\ncong$ [$TASK_{VVSM}$ ($e_S^i;e_E^{i+1}$)],
10:                RETURN {PO disregards standardized work} = root-cause1
11:                SEND To PO {slow down throughput-rate}
12:                REPORT {free capacity at $WS_1$}
13:
14:   IF [$TC_{i\_AVSM}$; $T_{AVSM}$] to $LO_i$ = [$P_{ix}$, $WS_1$:$SUP2_j$, $Ri_{\{WS1:SUP2\}}$] , $T\downarrow < T_{VVSM}$
15:          AND IF [$e_{TCi\_AVSM} > e_{TCi\_VVSM}$], $e_{TCi} \in E_{TCi}$
16:                THEN $WS_1$ is in {Over-production}
17:                RETURN {PO disregards standardized work} = root-cause1
18:
19:   IF [$Q_{WIP}\_SUP_2$]$_{AVSM} \uparrow >$ [$Q_{WIP}\_SUP_2$]$_{VVSM}$
20:          CHECK [RT-LCR = Takt-time_$WS_1$];
```

```
21:         CHECK [RT-LCR= TC, $R_{i\{WS1 : SUP2\}}$];
22:         CHECK [STATUS_$WS_2$] = {e.g. waiting for subassembly}
23:               THEN potential causes = {overproduction at $WS_1$; $WS_2$ blocked}
24:         RETURN {PO disregards standardized work, waiting for subassembly}
25:
26:    IF $AVSM\_D_{Pt\_WS1} \in |UCL_{VVSM}, LCL_{VVSM}|$
27:    THEN {¬over-production}
28: END
```

Line01 checks if the time-deviation is in increasing mode which goes out of control. **Lines02-04** check the initiation condition of three rules. **Lines 05,06** check the Takt-time and duration of processing-state, **Line 09** checks a potential root-cause = PO does not follow the standardized task, and return it as root-cause and then sends an alarm and a report as **lines 10,11,12. Lines 14-17** check TC and compares it with VVSM to return again the waste "overproduction" and its root-cause to "PO disregards standardized work". **Lines 19-24** check the quantity of inventory level at SUP_2 and check if the problems from the upstream or downstream WS1/WS2, then return the potential root-causes. **Line 26, 27** check if the production-state ranges between the control limits without ascending behavior, then there is no "overproduction". **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 elimination of variability causes.

The same fashion can be followed to identify the root-causes of time deviations; the following scenario has been narratively discussed, as follows:

➔ Processing-state Scenario [P_t]

If the processing-state, Pt_{AVSM} at WS_1 is exceeding the standard processing time, Pt_{VVSM}, then the "initiation condition" is matched, that indicates potential incidents have occurred (e.g. over-processing, searching for lost tools, quality and rework problems, etc.). To identify the exact root-causes, the $RT\text{-}LCR_{pt}$ should go through the predefined root-causes and check which root-causes related event-instances have been observed during $((e_{pt}^{s};e_{pt}^{e}) \in E_{pt})$ period, or which factors may influence the length of P_t during $((e_{pt}^{s};e_{pt}^{e}) \in E_{pt})$ period. Therefore, the following conditions are proposed to be tracked

- During E_{pt} , the product is "waiting for subassemblies", THEN check [the potential root-causes = wrong replenished material, delay in material replenishment, inefficient transportation activities, etc.]
- During E_{pt}, "quality problems occur", THEN check [the potential root-causes = set wrong production parameters, using wrong tool, wrong subassembly, PO discarding the tasks sequences]

- During E_{pt}, “searching for a tool”, THEN check [the potential root-causes = tool is misplaced, tool is lost, tool is reported as broken]
- During E_{pt}, “human nature”, THEN check [the potential root-causes = unskilled PO, PO fatigue and concentration goes down over working hours or after lunch break or due to late shifts, PO accident, new product, etc.]
- During E_{pt}, “changing in machine-state” THEN check [the potential root-causes = short breakdown events, reset the machine, etc.)

The working starts with checking the conditions: “waiting for subassemblies”, “wrong replenished material”, “quality problems occur”, “searching for a tool”, “human nature” and “changing in machine-state”. If one of these conditions is matched, then the RT-LCR_{pt} should investigate which root-causes event-instances have been detected in AVSM.

The discussed two scenarios show how RFID captured real-time data can be analyzed by RT-SWA to detect the suspicious behavior of some PSF objects (e.g. machine, product, labor, etc.) and notify the operators to fix the problems in advance during the production run.

4.5. Conclusion

In this chapter, a method for MLT estimation per product through utilizing the RFID captured event-instances is developed. Here, the real-time tracking and analysis of the product-state or time-components of the MLT was presented to investigate the root causes behind the time deviation through developing a smart real-time waste analysis and detection tool called RT-SWA. The objectives of this real-time analysis on the MLT are to provide up-to-the-minute reports of the actual manufacturing operations performance, including: identify where the value is being added in terms of times, identify the deviations in terms of time with the standard allowable values, the amount of wastes in terms of time can be quantified, the influences of the NVA activities that are applied during the MLT can be identified and prevented through future improvement efforts and also improve the process understanding.

As a result of the analysis of the MLT of individual products through the DVSM with the help of the RT-SWA, the estimation and design of the MLT of processes will become more accurate, especially for the new customized products on the market in recent times, as well as, more accurate production plans (e.g. accurate delivery date for customers, accurate resource planning, etc.) will be made available. Besides that, the usage of the RT-SWA will allow companies to identify the causes of waste in their production lines effectively and improve their manufacturing performances leading to lower production costs as well as help the quality management to write the 8D-reports which are requested by the customers more accurately and quickly. 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 production lead-time and enhance the productivity and efficiency.

CHAPTER 5
DVSM-enabled Smart Real-Time Lean Manufacturing Environment

This chapter addresses the significant role of RFID in smart lean manufacturing environments or lean-based digital factories. This chapter systematically discusses the utilization of RFID systems beyond tracking purposes to include intelligent real-time monitoring and controlling of production operations concerning lean targets. Therefore, in this chapter the best practice of RFID technology to smartly support LPTs during daily production runs to keep lean system alive and effective is introduced.

Introduction

This chapter includes three parts; the first part introduces a real-time dynamic re-prioritizing generator module that runs on DVSM-LPTE and contains different material flow control rules (i.e. RT-LCRs) to re-prioritize the product in an unpredictable dynamic production environment to enhance real-time dynamic dispatching activities. The second part introduces another smart lean-based mechanism, called “Real-time Smart Production Control” (RT-SPC), to smartly control the material flow between workstations and tightly synchronize the activities to meet the scheduled production and avoid NVA time. Moreover, to further enhance the effectiveness of the RT-SPC module, this part also addresses supplementary RT-SPC_RT-LCRs to support the ability for quick response to mitigate the adverse impacts of the sudden disruptions and incidents in order to obviate the propagation of their consequences and keep the system controllable.

The third part introduces a framework that describes how the lean method tools 5S, standardized work, and poka-yoke, can be smartly monitored and controlled through DVSM. A framework of the three tools has been discussed and put in practice in the switchgear manufacturing company.

PART 1
DVSM-enabled Real-Time Dispatching Priority Generator

During production operations, the major time of WIP is wasted through waiting for processing. A part of this problem refers to the way of prioritizing products and dispatching synchronization problems, thus the total MLT is significantly increased and thereby production cost is increased. Therefore, we have to emphasize that production scheduling and dispatching activities are one of the main pillars of an effective production control system [NV03].

Typically, the scheduling level in lean manufacturing uses the heijunka-board (i.e. load-leveling box). Here the first release of job orders to the PSF operations starts at the pacemaker process through the load-leveling box based on actual customer demand and demand forecasts to support dispatching tasks using kanban control and to enhance "one piece flow" and meeting "Takt time". However, in today's highly dynamic and customized manufacturing environment with unpredictable material flow, diverse jobs that move through different sequences of workstations, different due dates, priorities, routings, process times, resource and material requirements, no kanban system can provide the predictability of workflow, WIP-inventory, lead times, resource utilization patterns and job completion times, etc. Such predictability is also essential for capacity planning and effective production control in production systems with a heterogeneous environment. Also, with kanban systems, it is not easy to determine the right time for dispatching and loading a job into the machines based production constraints like due date, quantity and routing of the job, the resource availability and current workload on the PSF [Vel12].

The Dispatching Rules (DRs) play an important role on the scheduling level, thereby impacting the production controlling level. DRs are used to prioritize the WIPs that are waiting in the workstation's queue or supermarket for processing at the next work-stage [BDG82]. The importance of dispatching priorities lies in decreasing line variability, reducing job waiting times before workstations, increasing utilization of resources, and improving the production smoothness [BBD13]. But in reality, due to high variability causes throughout the production runs such as machine breakdown or material shortage, no specific DR works well all the time [HS08].

Therefore, wide variations exist and frequently cause serious discrepancies in executing plans and schedules. This means, an effective re-sequencing or reprioritizing of kanban commands at local workstations can greatly improve the overall production performance.

Literately, many dispatching priority or sequencing rules have been proposed and investigated [BDG82][Pin08][HR11]. The most popular DRs are summarized as follows: First-In-First-Out (FIFO), Shortest Processing Time (SPT), Earliest Due Date (EDD), Longest Processing Time (LPT), Smallest Number of Remaining Operations (SNRO), Largest Number of Remaining Operations (LNRO), Job of Identical Setup (JIS), and Critical Ratio Scheduling (CR).

Several research papers have contributed towards improving scheduling and dispatching levels. However, most of the developed scheduling models and algorithms are largely inappropriate to the actual scheduling problems of the PSF. This is mostly because they are buried in mathematical treatments with unrealistic assumptions [Vel12].

Typically, the production schedule is generated for a specific period (e.g. per week), while unpredictable events either internal or external, such as manufacturing operations related problems like machine failures, misplaced items and tools, material shortages, production line congestions, changes in product design or order due date by the customer occur in real-time. This may cause the production schedule to become infeasible and outdated [HS08]. Moreover, the supervisors may not be able to address the current problems at the right time which leads to serious consequences and thus deteriorating the overall performance.

Therefore, without up-to-date information, it is impossible to make accurate shop-floor decisions. The serious gap between reality on the PSF and the offline scheduling algorithms or mathematical models should be solved through developing a real-time dynamic re-prioritizing system to generate the optimal product sequence at local workstations based on the current status, and after a certain time revise the overall schedule in the load-leveling box. In this context, RFID provides the manufacturers with deterministic values of the smart-objects throughout the production process, which can be used for re-prioritizing the products at supermarkets and queues. After RFID deployment, a few studies [ZHD+11][ZHD+12][CS13] have investigated the utility of RFID to improve production scheduling and dispatching levels. However, none of these studies tackle the scheduling problems from lean perspectives in a dynamic manufacturing environment.

In context of RFID utilization, the manual editing of the schedule based on RFID captured data done by supervisors through drag-and-drop may turn out to be infeasible, since the real-time decisions need real-time and historical data. In addition to that, they are unable to monitor all real-time production-related data in detail and make quick decisions accordingly.

The objective of this section is to introduce a conceptual framework for a real-time dynamic reprioritizing and dispatching system, which runs online through DVSM-LPTE to deal with the dynamic nature of production systems to achieve lean objectives; this can be accomplished by generating the optimal sequence of products that are waiting their turn to be processed at the next workstation/machine throughout the production operations.

To deal with the dynamic nature of job shops, we proposed two DVSM-LPTE Modules; the first is Real-time Dynamic Scheduling Generator (RT-DSG) module that generates the initial schedule at the global-VVSM level. The second, which is our concern, is called the Real-time Dispatching Priority Generator (RT-DPG) module and it re-prioritizes the products that are waiting in supermarkets or queues. A case study has been modeled using simulation software ProModel to demonstrate that RT-DPG significantly reduces the MLT of the individual products.

5.1.1. Real-time Dynamic Scheduling Generator (RT-DSG) Module

To start production, this module runs on DVSM-LPTE to generate the initial schedule of the production orders. The release of a production order is represented through releasing its VVSM, since each product is represented through a VVSM. The production-related information of the released VVSMs and the available information from the enterprise level as well as the DVSM-DB (e.g. available capacity, material, operators, customer demands and takt-times, etc.) will be used by RT-DSG to generate the optimal schedule, thereby giving the supervisors thorough production details about what should be produced, how much quantity is needed and in which sequence the production should be carried out. The initial schedule will be uploaded to the global-VVSM to be visualized and executed by operators. If significant changes have been occurred on the PSF; the RT-DSG will revise (re-schedule) the initial sequence and update it according to the current status.

To achieve lean purposes, the RT-DSG is equipped with a Real-Time Scheduling Model (RT-SM), the objective functions and constraints of the constructed RT-SM that run online in RT-DSG should minimize the MLT and inventory level along the value stream, while maximizing the utilization of the available resources. Normally, the RT-SM is mathematically constructed; therefore it should be translated to RT-LCR format by RT-RE and uploaded to LPTE. Building a RT-SM is beyond the scope of this study, but a viable option for future works. During production runs, the running RT-LCR will invoke the variable values of constraints from VVSMs, AVSMs, DVSM-DB, ERP, etc.

5.1.2. Real-time Dispatching Priority Generator (RT-DPG) Module

The horizon of the scheduler is measured in days or weeks depending on nondeterministic factors, while the dispatching horizon is measured in minutes or hours depending on the deterministic real-time data. Therefore, in an attempt to follow and meet what is already planned and scheduled in the RT-DSG module in real-time and mitigate the consequences of the unplanned or unpredictable events (e.g. machine breakdowns, material shortage, defective problems, disparity in operator performance, Hot-Jobs, etc.), a smart real-time lean-based production control module called RT-DPG is presented in this section. RT-DPG utilizes RFID event-instances in AVSM and VVSM to smartly generate in real-time the optimal sequence of products that are waiting at the local workstations' supermarkets or queues, which can't be addressed through RT-DSG.

RT-DPG is equipped with different RT-LCRs to directly re-prioritize the material flow in unpredictable dynamic production environments to reduce the total waiting time along the value stream and maximize the utilization of all resources, thereby reduce the overall manufacturing lead time, avoid discrepancies in executing the planned schedules, and meet customer demands.

As aforementioned, in reality no specific traditional DR works well all the time [HS08].Therefore, a dynamic priority method is proposed to re-prioritize the products in real-time, it is called the Dispatching Priority Value (DPV) method, which starts at integer "1" as the highest DPV and extends according to the number of product types that are waiting, (i.e. the lower the DPV value, the higher the priority). According to the RT-DPG, the product with the highest DPV will be displayed on the LO's PDAs to be dispatched.

5.1.3. Constructing the RT-LCRs of the RT-DPG

The RT-DPG module runs locally at each workstation/machine to re-prioritize the products according to the latest conditions. It is equipped with the appropriate RT-LCRs concerning re-prioritizing or re-sequencing the products throughout the production process. The RT-LCRs must deal with very detailed real-time data, including all information that can affect the choice of the optimal sequence. Therefore, the required information to make real-time re-prioritizing through the RT-LCRs should be defined in order to invoke their event-instances. Two types of information should be defined. Firstly, the information from the enterprise level which is translated into event-context in VVSM, and secondly, the production-related information from AVSM; examples of these events are seen in table 5.1.

Table 5.1. The Required VVSM and AVSM Data for Real-time Reprioritization.

VVSM information	AVSM information
Due date of each VVSM products/penalty costs/customer importance/BOM and the point of use/ the required machines/the skill level of operators/tools/equipment/ standard VVSM route and alternative routes/total number of items or batches per VVSM/ product-states/standard time of each state/ setup time-events/maintenance -events/ maximum capacity of resources e.g. capacity of each containers, supermarkets, shelves, and in/out-put buffers, etc. /required replenishment time of the subassemblies, components and materials from storage place to point of use. Other …….	actual product-state e.g. actual processing time/machine-breakdown events/ operators' absenteeism event, current state of the tooling/ actual availability, capacities and utilization of resources/ current availability of material/ waiting time at each workstation's input & output buffer/ actual remaining number of operations for each VVSM items/ actual quantity of WIPs at each intermediate storage point / actual quantities of sub-assemblies and components at line side-inventories/ number of late jobs/ volume of defective and reworked products so far. Other ….

Since customers always change their minds about their orders such as changing the due date or asking for changes in the product design, these changes in the enterprise level can be viewed directly in the VVSM information to be considered in the real-time re-prioritizing process, like changing the product status to be a Hot-Job (HJ).

The real-time generation of the optimal sequence in RT-DPG depends mainly on the constructed RT-LCRs; the RT-LCR is proposed to contain several Sub-Rules (SR_i) that are running within RT-LCR frame, each SR_i has a "Key-Condition" (KC) to be activated. As presented in figure 5.1, the RT-LCRs in RT-DPG are proposed to work as follows:

- The overall PSF's conditions will be checked based on AVSM, DVSM-DB data; this is done periodically according to the time frame of the production based on the processing time, (i.e. if the processing time is on the order of an hour, a check every 10 minutes can be done).
- The results of the latest overall check will be initially checked through the KCs of SR_i. A certain SR_i is activated; if its KC is detected. For instance, if we have a SR_i with KC = [Machine-breakdown], and if a "machine-breakdown" event is detected in the latest

overall check, then the SR_i = "machine-breakdown" is satisfied. Accordingly, the RT-DPG module will determine how the products' sequence should be changed.

- The SR_i with detected KC will be activated, where further sub-conditions will be checked from VVSM, AVSM, and DVSM-DB to generate a new sequence of the waiting products using the DPV method.
- The new sequence will be translated to lean commands (e.g. withdrawal P_i at time T and location $L_{xi,yi}$ to location $L_{xi+1,yi+2}$) and displayed at the authorized operators' monitors (i.e. LO's PDAs) through the RT-VE to be executed.

In this regard, the more the tracked smart-objects, the more precise the decisions to be taken will be. The most important aim of this module is to:

- Locally re-prioritize the products at each workstation's supermarket and machine's queue.
- Determine which WIP should be processed, when and where.
- Real-time coordination of logistics and production tasks.
- Real-time assigning and reassigning of manufacturing resources such as machines, labors, equipment, raw materials, supermarkets, tooling, etc.
- Notify the PO and LO immediately about unplanned events occurring during production which might disrupt the production schedule.

This smart mechanism can improve the flow of operation, and of course the production smoothness, flexibility and quick-response ability of the manufacturing system, and thereby the higher customer service level, being one of the lean targets, will be enhanced.

The construction of re-sequencing RT-LCRs starts with (i) defining the conditions that initially should be checked, as stated in table 1, (ii) defining the KC of the SR_i, and (iii) defining the sub-conditions of each SR_i. The KCs represent several specific cases at specific times and locations. Deciding the KCs depends on several normal and abnormal production factors, constrains and parameters, and internal policies, such as:

- Hot-Jobs (HJs): waiting at preceding supermarket or queue.
- Machine-breakdown (MB): disturb the production schedule.
- Identical sub-assemblies (ISA): products with similar sub-assemblies.
- Identical machine-setup (IMS): products with the same machine setup.
- Exceeding-waiting time (EWT): waiting product exceeds the permitted waiting time.
- Material-shortage (MS): raw material, sub-assemblies, components shortage.
- Operator- skill level (OSl): special-product needs specific skill-level to be executed.

- Labor- temporal absence (LTA): the worker is temporally not in his location.
- Free-capacity (FC): if specific resources become in “idleness-state”.
- Others.

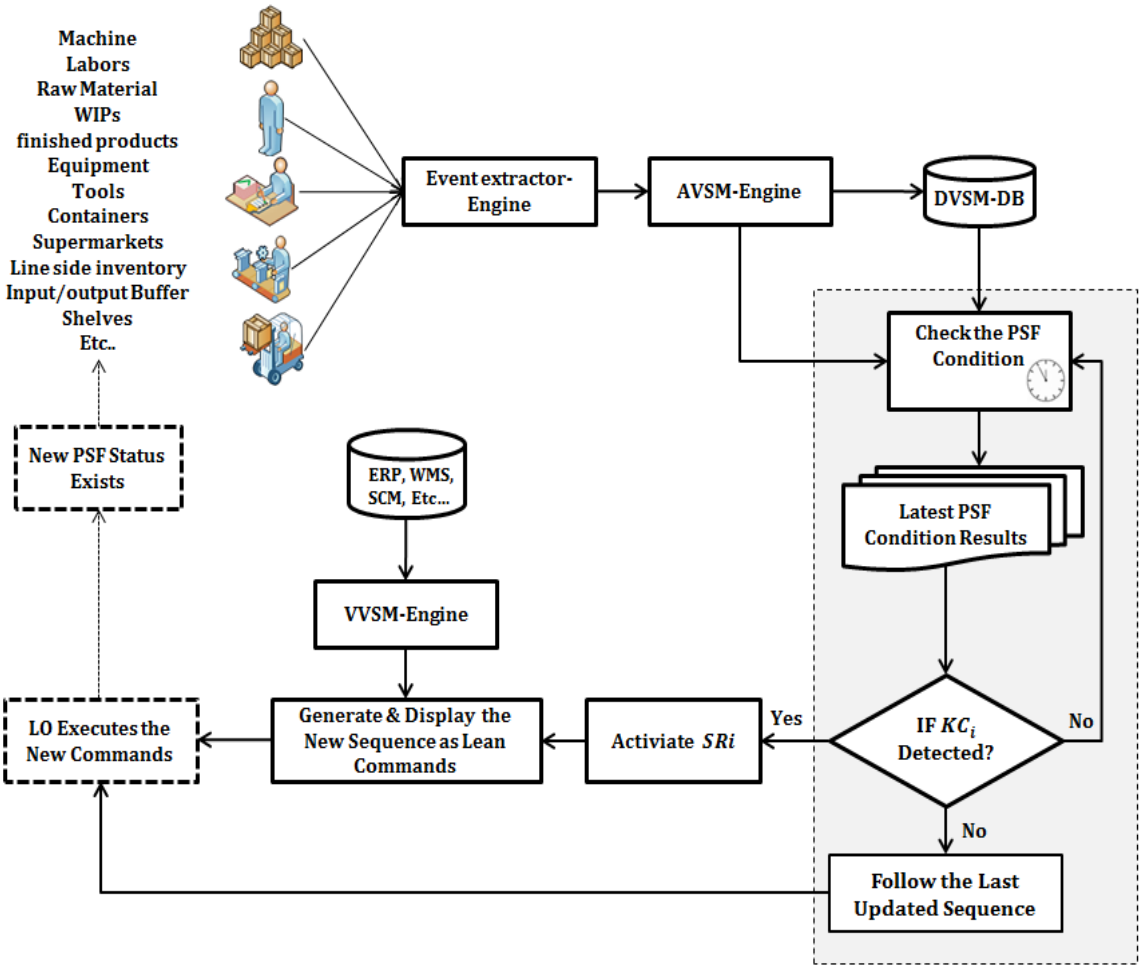


Figure 5.1. The Working Logic of Generating a Real-Time Dispatching Priority.

As mentioned, a SR_i will be activated if its KC is detected. However, in reality several SR_i-KCs could be detected at the same time and location, this doesn’t mean that all SR_i will be activated. To avoid the conflict between some rules and decide which SR_i is dominant (e.g. P_{ij} is assigned as a HJ while P_{i+1j} exceeds the waiting-time threshold are waiting at the same storage location), each KC is pre-assigned with an importance-factor “i”, i= 1, 2, 3....n, where “1” is the highest important KC, and “n” is the number of KCs, which decides in which sequence the rules KCs must be checked. The shadowed part in Figure 5.1 shows heuristic steps to decide in which sequence the SR_i should be checked. Other methods could be used to avoid the conflict between SR_i .

The CEP-semantic of the RT-LCR for checking the SR_i sequence at specific workstations is described as follows:

Definitions:

E_{HJ_i} = Arrival of hot-job to the supermarket (SUP_i)
SUP_i = Supermarket
AVSM-D_{WIB_i} = The actual duration of the WIB_i
VVSM-D_{WIB_i} = The virtual duration of the WIB_i
EWT = Exceeding the waiting time

RT-LCR = KC*i*

```
01: CHECK the Overall-Status in [AVSM; DVSM-DB]
02:     IF [$E_{HJ\_i}$] detected at $SUP_i$
03:             THEN "Activate" $SR_1$ = [$HJ\_i$], AND Go to Step 10
04:     IF [¬ $E_{HJ\_i}$ ]; CHECK KC =[AVSM- $D_{WIB\_i}$ > VVSM-$D_{WIB\_i}$]
05:     IF [AVSM- $D_{WIB\_i}$ > VVSM-$D_{WIB\_i}$] detected
06:             THEN "Activate" $SR_2$ = [EWT], AND Go to step 10
07:     IF [¬ AVSM- $D_{WIB\_i}$ > VVSM-$D_{WIB\_i}$]; CHECK KC = [$KC_{i+2}$]
08:
09:     IF [¬$KC_{i+1}$]; THEN "Follow the Last Updated Sequence"
10: END
```

Line01 checks the overall PSF status, in **line02** the KC_i=[E_{HJ_i}] at SUP_i will be checked. If KC_i in **line02** is satisfied; then in **line03** the SR_1 = [HJ_i] will be activated, and further checks will be stopped. Likewise, in **line04,** if "E_{HJ_i}" "arrival-event" is not observed; the next SR_2 with KC_{i+1} =[E_{EWT}] at SUP_i or queue will be checked. In **line05** if [AVSM-D_{WIB_i} > VVSM-D_{WIB_i}] is right, then in **line6** SR_2 = [EWT] will be activated, and further checks will be stopped. In **Line07,** If "E_{EWT}" is not detected; then check the next SR_3 with KC = [KC_{i+2}] and so on. In **line09**, if there are no changes in the last updated status (i.e. no KC is detected); then the workers should follow the last updated sequence, END.

After the activation of SR_1 = [HJ_i], further sub-conditions will be checked to find the optimum decision to reduce the waiting time and accordingly reprioritize the waiting products. If several HJs are detected; then a number of comparison criteria and parameters belonging to HJs will be checked, such as their earliest due date (EDD), Penalty Cost (PC), and Customer Importance Factor (CIF). Further cases can be checked, such as the possibility to bypass the current machine to the next available machines and then return back later.

Definitions:

Q_HJ_{ij} = The quantity of waiting hot-jobs
EDD_{ij},PC_{ij},CI_{ij} = The earliest due date, Penalty Cost, and Customer Importance Factor of each hot-job type
M_i = The machine where the products should be processed
LO_i = Logistics operator
PO_i = Production operator
RM_i = Sub-assembly of each hot-job

SR_1= [HJ] at SUP*i*

```
01:     IF $e_{arrival}$[AVSM- $HJ_{ij}$] at $SUP_i$ detected , AND Q_$HJ_{ij}$ = 1;
```

```
02:          SET $HJ_{ij}$ with "DPV=1", AND Go to Step 8, else
03:     IF $e_{arrival}$[AVSM- $HJ_{ij}$] at $SUP_i$ detected , AND $Q\_HJ_{ij} > 1$;
04:               CHECK [$EDD_{ij}$,$PC_{ij}$,$CI_{ij}$] from global-VVSM, AND
05:               CHECK A-[$M_i$ , LO,PO, RM of $HJ_{ij}$ ] from global-AVSM
06:     IF A-[$M_i$, LO, PO, $RM\_{HJij}$ ] detected, THEN "Set" DPV=1 for $HJ_{ij}$ with best [$EDD_{ij}$,
        $PC_{ij}$ & $CII_{ij}$] values;
07:     For (lower [EDDij, $PC_{ij}$ & $CII_{ij}$] values; set $HJi_{-1,j}$ with DPV=1+i ),
08:     END
```

Line01 check the HJ in the SUP_i, if just one HJ is observed (i.e. $Q\_HJ_{ij} = 1$), in **line02** set HJ_{ij} with the highest priority. **Line03**, if the observed quantity (Q_HJ_{ij}) is more than one (i.e. $Q\_HJ_{ij} > 1$), then in **line04** the SR_1 *will check the* [EDD_{ij},PC_{ij},CI_{ij}] values from VVSM, and in **line05** the actual status will be checked such as the availability "**A**" of the required machine for each product and the LO and PO who serve it, moreover the required material "RM" like the sub-assemblies, if the subassemblies are not available; then the associated product will be excluded from reprioritization, since it is not logic to set it with the highest priority. For more complexity, if the replenishment time of this subassemblies is less than the time that the machine become available, then the product will be considered in the reprioritization. In **line06** the product which met the conditions in **line05** and has the highest values in **line04**, then it will be set with the highest priority value "DPV=1". In **line07** The remaining HJ_{i+1j+1} will be further prioritized, where the better the [EDDij,PCij,CIij] values has, the better the priority value DPV will take. The non HJs waiting products will be prioritized according to other RS_{i+1} which give less priority, END.

In case of backlog orders, the real-time cost-analysis results from the RT-MCT module might be used to determine the highest priority products.

The next proposed RS_2 checks the KC_{i+1} = [E_{EWT}], in this case the highest priority value is assigned to those products with the longest waiting time on the buffers (e.g. WIB, WTB, WTM, WIIB, and WIOB) or SUP_i. The SR_2 = [EWT] is expressed as follows:

Definitions:

P_{ij} = All types of products arrives the SUP_i
$Te_{arrival}$-[Pj_i] = The timestamp of the "arrival-event" of each product P_{ij}
VVSM-P_{ij} = The maximum allowable waiting time as VVSM of the P_{ij}
Q-[EWT-P_{ij}] = The quantity of the waiting products
EDD_{ij},PC_{ij},CI_{ij} = The earliest due date, Penalty Cost, and Customer Importance Factor of each hot-job type
M_i = The machine where the products should be processed
LO_i = Logistics operator
PO_i = Production operator
RM_i = Sub-assembly of each hot-job

SR_2 = [EWT] at SUP_i

```
01:   CHECK   $e_{arrival}$-[$P_{ij}$] at $SUP_{i,}$,
02:   CHECK   [$Te_{arrival}$-[$P_{ji}$] – CurrentTime];
03:           IF [$Te_{arrival}$-[$P_{ij}$] – CurrentTime] > [VVSM-$P_{ij}$],
04:           THEN "Set" [EWT-$P_{ij}$] with DPV=1, AND Go to Step 10, else
05:           IF Q-[EWT-$P_{ij}$]> 1;
```

```
06:             CHECK [$EDD_{ij}$,$PC_{ij}$,$CI_{ij}$] from global-VVSM, AND
07:             CHECK A-[$M_i$, $LO$,$PO$, RM _EWT-$P_{ij}$] from global-AVSM
08:     IF A-[$M_i$, $LO$, $PO$, RM_EWT-$P_{ij}$] are detected, THEN "Set" DPV=1 for EWT-$P_{ij}$
        with best [$EDD_{ij}$, $PC_{ij}$ & $CII_{ij}$] values;
09:     For (lower [$EDD_{ij}$, $PC_{ij}$ & $CII_{ij}$] values; set EWT-$P_{i+1j+1}$ with $DPV=1+i$ ),
10:     END
```

Line01 checks the arrival events of products.**Line02** checks their waiting-time so far. **Line03**, if the actual waiting-time is more than the standard waiting-time in VVSM of this product, then in **line04**, this product will be prioritized with DPV=1. Now, **line05** check if several products exceeded their standard waiting time, then similarly as SR_1, **line06&07** use comparing criteria to prioritize them accordingly.**Line08&09** prioritize the products according to these criteria. **END**.

In this regard, other factors, that play an important role in preventing longer/exceeding waiting-times such as IMS, ISA, or Longest Processing-State Duration (LD_{PS}), could be considered. The SR'_2 = [EWT] with an IMS factor to reduce the changeover time could be expressed as follows:

SR'_2= [EWT] at SUP_i

```
11:   CHECK $e_{\text{arrival}}$-[$P_{ij}$] at $SUP_{i,}$,
12:           IF VVSM-[$Setup_{ID}$-$P_{ij}$] == AVSM-[$Setup_{ID}$]
13:           THEN "Set" DPV=1 for [$P_{ij}$] AND [¬EWT-$P_{i-1j-1}$]
14: END
```

In **line11** P_{ij} will be prioritized with highest DPV; if P_{ij} "arrival-event" at SUP_i is detected, in **line12** if the currently setup of running machine AVSM-[$Setup_{ID}$] is similar to the required setup by VVSM-[$Setup_{ID}$-P_{ij}], **Line13** prioritizes P_{ij} with DPV=1, unless the currently waiting products will not exceed their waiting-time threshold. **END**.

Similarly in the case of LD_{PS}, the products with long "processing-state" durations (D_{PS}) significantly increase the waiting-time of other waiting products, and thus lead to higher WIP levels as well. So if P_{ij} has LD_{PS} compared to other waiting products, then it could be a marginally delayed to prevent the delay of other products, unless its waiting-time threshold is not exceeded. As a result, through several combinations between different factors and constraints, the RT-LCRs can prevent the exceeding waiting-time threshold and keep the WIP level below the standard value as in VVSM.

The above constructed RT-LCRs are representing general scenarios based on a production environment of a job-shop manufacturing environment of a switchgear manufacturer in Germany. But for more specified production conditions and criteria; more specific RT-LCRs could be constructed to manage scheduling and dispatching activities to minimize the total MLT.

5.1.4. Case Study with a Simulation Model

To demonstrate the feasibility of the proposed module, this section investigates how the RT-DPG module impacts the MLT using the simulation software ProModel.

The modeled production system data is based on [GLB+13]. The abstracted production system is a job shop production environment consisting of five machines and seven product types, as shown in table 5.2.

Table 5.2. Process Data for Model Configuration.

Products	Release date	Due Date	Machine/Processing times
A	0	39	1/7 - 2/6 - 3/8 - 4/9 - 5/4
B	0	42	2/3 - 1/8 - 5/3 - 3/8 - 4/9
C	0	41	3/3 - 2/7 - 1/7 - 5/9 - 4/7
D	0	41	2/3 - 1/4 - 3/9 - 4/3 - 5/3
E	0	36	2/5 - 3/4 - 5/4 - 4/2 - 1/7
F	0	40	2/9 - 1/2 - 3/8 - 4/9 - 5/6
G	0	38	5/8 - 2/9 - 4/6 - 3/2 - 1/3

We used these data to estimate the process start/end times at each machine under three scenarios. The first two scenarios are representing the traditional DRs, namely EDD and FIFO, whereas the third scenario represents real-time dynamic priority rules (i.e. RT-LCRs or SRi), that RT-DPG module is equipped with. The proposed SR_i are described as follows:

1. Upon Customer request, product "A" is converted to be a HJ after 30 minutes of the production run. Product D is assigned in VVSM as HJ before order release.
2. Reallocation of the free capacities to the machine with waiting queues more than two products.
3. Due to the high load on machine 2, product A as a HJ can bypass it to the next machine.
4. It is supposed that the RM of B and E will not be available in the first 5 minutes, and then prioritize the products with the available materials.
5. On machine 2, the products with the highest waiting time have the highest priority.
6. We supposed that the sequence of manufacturing process is flexible; therefore it is supposed that the products can start processing from the idle machines.

For the SR_1= HJ, it was assumed to have the highest important key condition KC=1, except at machine 2, where SR_2 = [Exceeding Waiting-Time] is the dominant.

➔ Simulation Results

To demonstrate the preference of RT-DPG module with its real-time dynamic priority rules over the traditional DRs; the times results of FIFO and EDD are compared with the results of the third scenario, as follows:

The completion time of "A and D" is seen in tables 5.3a & b and figure 5.2, product A is finished after 28 minutes and D after 31 minutes, the order makespan is 61 minutes which is less than the completion time in case of EDD (A=57, D= 66 and makespan=78 minutes) and FIFO (A=48, D=57 and makespan=76 minutes). The total number of products waiting in queues is reduced from 12 to 10 products, and the processing starting times become earlier for each product.

Because the waiting time threshold becomes limited on machine 2, the products with the highest waiting time have the highest priority, the total waiting time of products becomes as follows: SR_i is 131 minutes, while in the cases of EDD is 169 minutes and FIFO is 193 minutes. The reduction in MLT will be mirrored on more reduction in the total cost of the product and the investment cost as well as seen in chapter 6.

Table 5.3a. Summary of the Simulation Results.

Material Flow Rules	Makespan	Max. Tardiness	Total Tardiness	Total Waiting time
EDD	78	36	110	193
FIFO	76	38	131	169
RT-DPG	61	19	51	131

Table 5.3b. Times Results of the Three Scenarios.

Products	FIFO		EDD		RT-LCRs	
	Start	End	Start	End	Start	End
A	0	48	0	57	0	28,0
B	0	35	39	78	6	61,5
C	0	51	0	60	0	50,5
D	3	57	36	66	0	31,0
E	19	63	0	23	7,5	59,5
F	24	71	5	44	1,5	50,0
G	0	76	0	46	0	41,0

However, the simulation model is just an abstraction of the reality and cannot fully represent the complexity of the dynamic PSF, since many production aspects, which contribute in further reduction in MLT, cannot be represented in this simulation, these parameters can be captured through RFID and utilized in RT-DPG to reduce MLT.

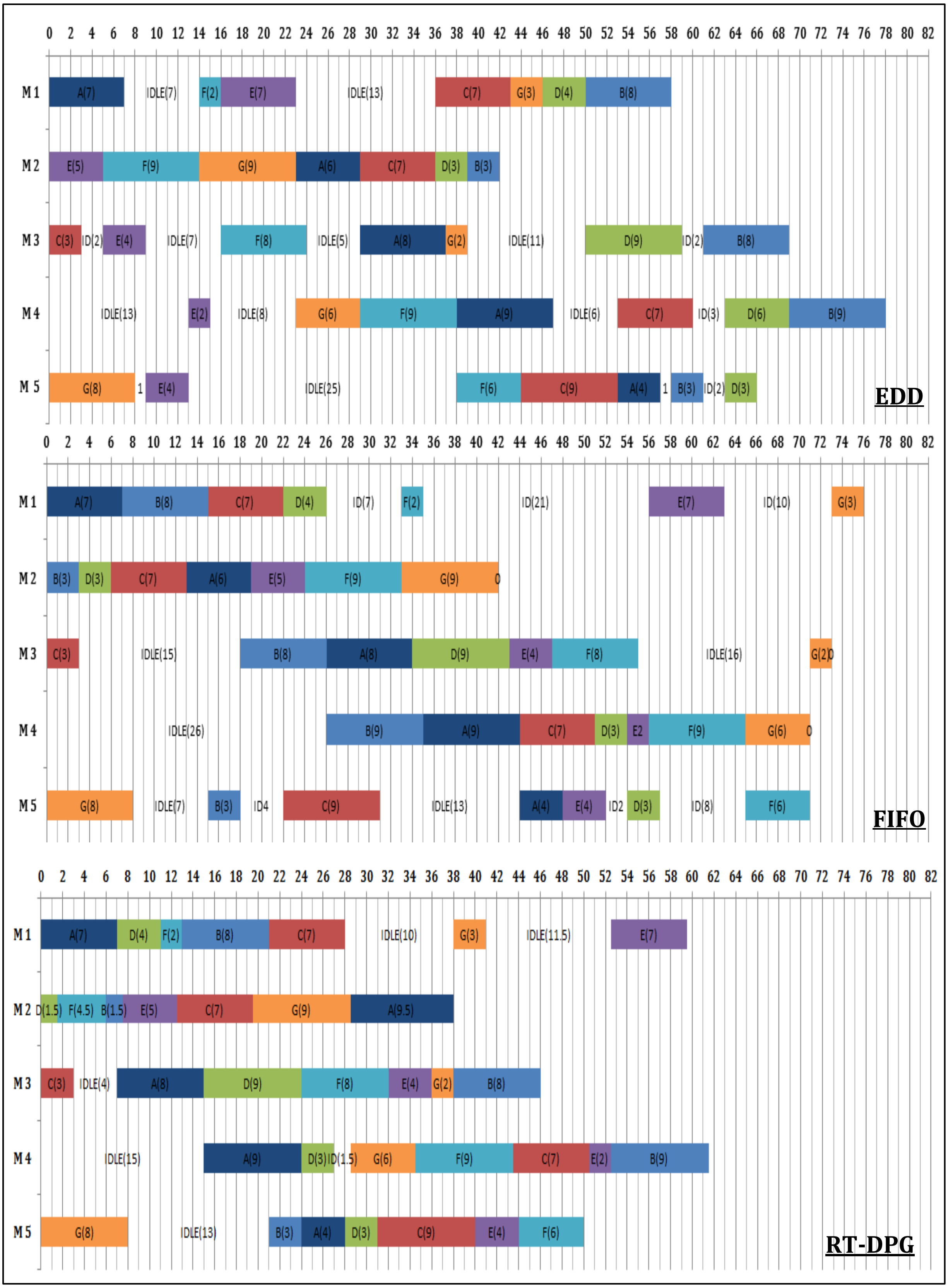


Figure 5.2. Simulation Results in Gantt Chart for the Applied Rules.

PART 2
DVSM- enabled Smart Real-Time Production Control

The previous part introduced a smart real-time reprioritizing mechanism of the waiting products; this mechanism plays a significant role in mitigating the influence of the dynamic behavior of the production environment on the overall performance. In this context, in order to guarantee an effective and smooth material flow across the value stream to meet the reprioritized products generated by RT-DPG, this part introduces in the first place another smart real-time lean-based mechanism called "Real-time Smart Production Control" (RT-SPC). RT-SPC is proposed to smartly control the material flow between workstations and tightly synchronize the activities to avoid NVA time. However, in practice and due to the sudden or unplanned disruptions, the actual situation on the PSF never follows the generated sequenced by RT-DPG, regardless of how accurate and sophisticated the RT-LCRs are [HS08]. In this regard, to further mitigate the impacts and consequences of the random disruptions and unexpected events of incidents on the overall PSF performance; it is not enough to determine how the product sequence should be changed and control the flow accordingly, but more importantly, that the ability to quickly react against these incidents or unexpected events should be enhanced. Therefore, this part addresses the construction of further RT-LCRs to mitigate the adverse impacts of the sudden disruptions and incidents, also obviate the propagation of their consequences to keep the system controllable.

5.2.1. Smart Real-Time Production Control System [RT-SPC]

The RT-SPC is considered as a central nervous system for the material flow system in a smart lean environment by directing materials JIT to workstations as well as coordinating the interaction between smart-objects on the PSF.

Moreover, this mechanism not only focuses on the inventory level between the workstations, as is the case with traditional kanban, but on other factors such as the capacity constraints of the workstations, the replenishment times of sub-assemblies, the transport times between workstations, the random incident events, etc.

Smart real-time material flow control plays an important role in achieving a tight synchronization between activities on the PSF in order to achieve the optimal order schedule and product sequence, which is generated through the RT-DPG module. This section explains the working mechanism of RT-SPC that aims to smartly coordinate the interaction between the smart-objects in order to generate optimal decentralized decisions in real-time.

Figure 5.3 illustrates the working mechanism of the RT-SPC module, where a part from a value stream with WSj and its input and output buffer (IBj) and (OBj) are shown. WSj is the customer for Supermarket (SUPj) and supplier for SUPj+1. The machines, IBs, OBs and SUPs have inflow and outflow RFID-readers to track the real-time events of WIPs flow and workers which are updated in the AVSM and DVSM-DB.

As shown, the steps 1, 6, 12a, 11a, 17 are representing the material flow from upstream to downstream points, where the rest are representing the tracking process of material flow steps. The smart real-time control mechanism is described in the following RT-LCR using CEP-semantic:

Definitions:

P_{ix} = Product "i" in Quantity *x*
R_i = Route
WS_j = Workstation j
M_i = Machine
IB_j = Input buffer at workstation j
OB_j = Output buffer at workstation j
SUP_j = Supermarket j
Q_{Pi}= Quantity of Product *i*
":" = Separator between start location and end location [from:to]
"{:}" = Transport Route
LO = Logistic Operator
PO_i = Production Operator
TC_i = Transport Command
PC_i= Production Command
E_{TC} = Transport Command Event
E_{PC} = Production Command Event
e_{TS} ,e_{TE} = Transport start/end events
e_{PS} ,e_{PE} = Production start/end events
DPV_i: Dynamic Priority Value

RT-LCR$_1$ = Smart Real-Time Material Flow Control

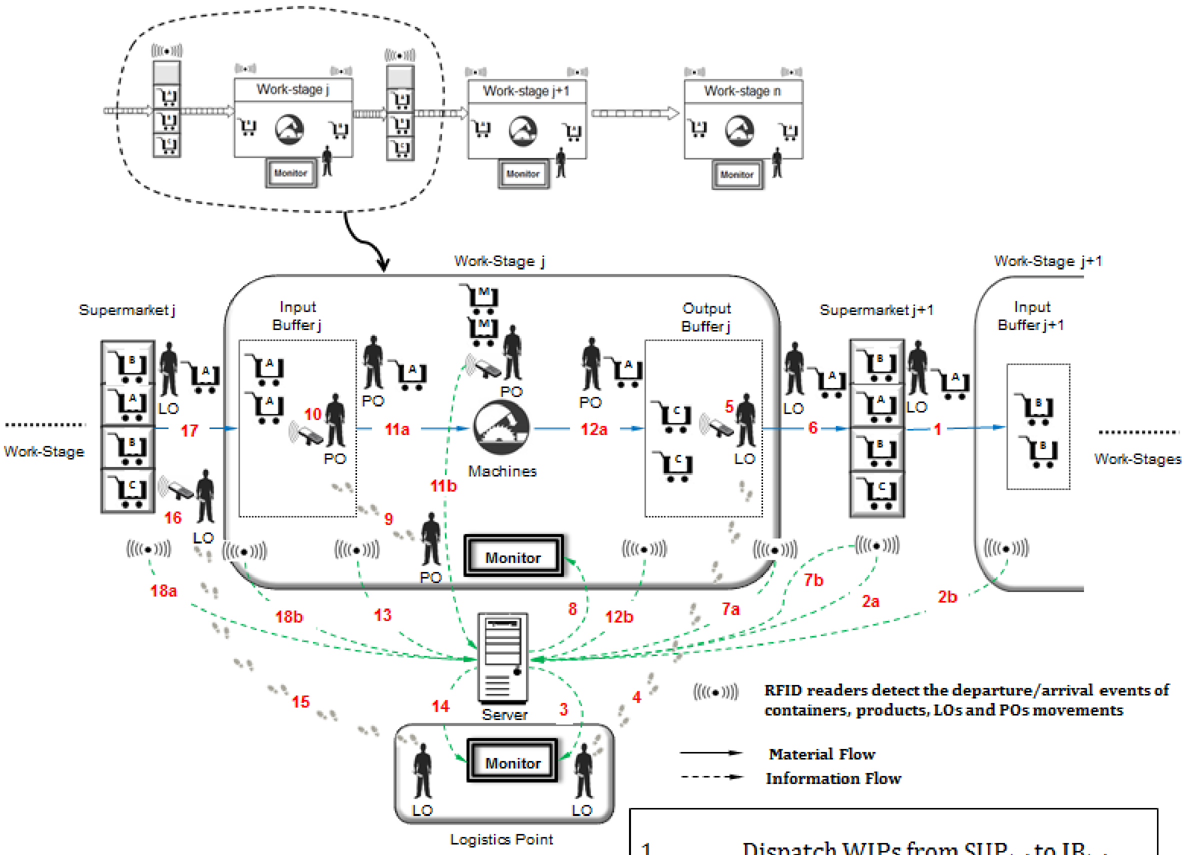
```
01:  IF [$e_{TS}$- $P_{ix,}$: $SUP_{j+1}$:$IB_{j+1}$] detected, THEN
02:      UPDATE AVSM-[$Q_{Pi}$-$SUP_{j+1}$]
03:  IF [AVSM-$Q_{Pi}$-$SUP_{j+1}$ < VVSM$Q_{Pi}$-$SUP_{j+1}$], THEN
04:      SEND [TC] to $LO_i$ = [$P_{ix}$, $OB_j$: $SUP_{j+1}$, $R_{i\{OBj : SUPj+1\}}$, T, $DPV_i$]
05:      TRACK $LO_i$ [$e_{TS,OBj:SUPj+1}$];[$e_{TE,OBj:SUPj+1}$]
06:  IF [$e_{TS\ Pix,\ OBj:\ SUPj+1}$] $\in E_{TC}$ detected, THEN
07:      UPDATE AVSM-[$P_{ix}$ depart $OB_j$] & [$Q_{Pi}$-$OB_j$]
08:  IF [$e_{TE\ Pix,\ OBj:SUPj+1}$]$\in E_{TC}$ detected, THEN
09:      UPDATE AVSM-[$P_{ix}$ arrive $SUP_{j+1}$] & [$Q_{Pi}$-$SUP_{j+1}$]
10:  IF [AVSM-$Q_{Pi}$- $OB_j$ < VVSM$Q_{Pi}$- $OB_j$] THEN
11:      SEND [PC] to $PO_i$ = [$P_{ix}$, $DPV_i$, $M_i$]
```

```
12:         TRACK $PO_i$ [$e_{TS}$, $R_{i\{IBj : Mi\}}$];[$e_{TE}$, $R_{i\{IBj : Mi\}}$]$\in E_{TC}$, [$e_{PS}$, $e_{PE} \in E_{PC}$]
13:         UPDATE AVSM-[$Q_{Pi}$-$IB_j$]&[$e_{PS}$, $e_{PE} \in E_{TC}$ ]
14:     IF [AVSM-$Q_{Pi}$-$IB_j$ < VVSM$Q_{Pi}$-$IB_j$], THEN
15:         SEND [TC] to $LO_i$ = [$P_{ix}$, $SUP_j$:$IB_j$, $R_{i\{SUPj:IBj\}}$, T, $DPV_i$]
16:         TRACK $LO_i$ [$e_{TS, SUPj:IB}$];[$e_{TE, SUPj:IB}$]
17:     IF [$e_{TS\ Pix, SUPj:\ IBj}$] $\in E_{TC}$ detected, THEN
18:         UPDATE AVSM-[$P_{ix}$ depart $SUP_j$] & [$Q_{Pi}$-$SUP_j$]
19:     IF [$e_{TE\ Pix, SUPj:\ IBj}$] $\in E_{TC}$ detected, THEN
20:         UPDATE AVSM-[$P_{ix}$ arrive $IB_j$ ] & [$Q_{Pi}$-$IB_j$]
21:     End
```

Line01-02 check If WIP transport event from SUP_{j+1} to IB_{j+1} is detected; then the RT-SPC updates the remaining quantity at Q_{Pi}-SUP_{j+1}. **Lines03-04** check If the Q_{Pi}-SUP_{j+1} is below the threshold value in the VVSM, then the RT-SPC sends a transport command to LO_i to replenish the deficit Q_{Pi} at SUP_{j+1}, the product with the highest DPV will be dispatched. **Lines 05-09** are representing the tracking of the transport command execution from OB_j to the SUP_{j+1} and update the transported quantity at each location. In **line 10-11** a production command will be generated and sent to PO to replenish the deficit Q_{Pi} at OB_j , the results of this command will be updated in AVSM. The same logic will be followed in the RT-SPC during the production run to coordinate the flow of materials from upstream to downstream workstations, END.

To enhance the functionality of the real-time material flow control RT-LCR, other RT-LCRs can be expressed to react upon the latest status, such as new WIP level at storage points, the status of the PO and LO, location of materials, the transport time, distance and routes, processing starts/ends, etc.

For effective sub-assemblies replenishment, RT-SPC is supplied with RT-LCR to automatically determine the remaining sub-assemblies parts (i.e. WTM) and based on the current average processing time and the usage-rate of the WTM items, or if the remaining WTM items become under the predefined level; RT-SPC generates a new replenishment command within an exact time-interval of the specific amount of sub-assemblies for LO_i. Thus, enhancing a smart JIT-replenishment mechanism with new levels of efficiency and responsiveness.



2a&b.	track the events of 1.
7a&b.	track the events of 6.
12b.	tracks the events of 12a.
11b.	LO uses the PDAs to pick the right sub-assemblies
13.	tracks the events of 11a.
18a&b.	track the events of 17.
3/8/14.	monitor the real-time decisions on the DVSM-user interfaces

1.	Dispatch WIPs from SUP_{j+1} to IB_{j+1}
6.	Replenish SUP_{j+1} with WIPs from OB_j
12a.	Move WIPs from M_i to OB_j
11a.	Move WIPs from IB_j to M_i
17.	Dispatch WIPs from SUP_j to IB_j
5/10/16.	LO or PO uses PDAs to pick the right WIP
4./9./15.	track the LO &PO locations

Figure 5.3. The Working Mechanism of the RT-SPC.

Other smart aspects can be added to RT-SPC_RT-LCRs, for example the RT-LCR estimate the time to complete a certain batch, If the remaining time approaches completion; a setup command (SC) according to the type of waiting product with “DPV_i=1” will be generated and displayed to the authorized worker with the required instructions.

In similar fashion, if the setup event ($e_{ST} \in E_{SC}$) is detected, the $e_{SE} \in E_{SC}$ will automatically be estimated and uploaded to the production time line, then a withdrawal command according to the waiting product with “DPV_i=1” from IB_j to M_i will be generated to be executed shortly before $e_{SE} \in E_{SC}$. Such mechanism can significantly contribute in achieving a tightened synchronization between events, as well as the last minute decision-making process benefits from the latest updated status like reallocated resources, machine availability and setup, changed priorities, moved materials, free capacities, etc., to generate the optimal decisions.

In context of transportation activities, shortly before sending TC to any LO$_i$, a RT-LCR can be expressed to search for the nearest LO$_i$ to location (L$_i$) with ongoing tasks and has free capacity for the transported quantity (P_{ix}) that pass through the route $R_{i\{L_i:L_{i+1}\}}$, if no LO is available then the nearest LO$_i$ to location (L$_i$) with the earliest end time; then the TC will be assigned to him. This will significantly optimize the time required for the tasks to be done and contribute to avoid unnecessary transport activities. This can be expressed as the following CEP-semantic:

Definitions:

P_{ix} = Product "i" in Quantity x
R_i = Route
":" = Separator between start location and end location [from:to]
"{:}" = Transport Route
L_i = Location with x,y-coordinate
D_i = Distance
C_{free} = Free Capacity
LO = Logistic Operator
TC = Transport Command
C_{TE} = End time of the ongoing commands

RT-LCR$_2$ = TC assignment

```
CHECK $D_i$ [L-LO$_i$: L$_i$] & [$C_{free} \geq P_{ix}$]& [$R_{i\{L_i:L_{i+1}\}}$], THEN
        ASSIGN $TC_i$ to LO$_i$-[min $D_i$], ELSE
CHECK $D_i$ [L-LO$_i$: L$_i$]& [$C_{TE} \rightarrow 0$], THEN
        ASSIGN $TC_i$ to LO$_i$-[min $D_i$][min $C_{TE}$]
END
```

Another example regarding task allocation, if no machine is currently available; then check the nearest time-based available machine with the most suitable setting (e.g. tools, equipment, skills level, setup, sub-assemblies availability) and assign the PC to it. In this case the PCs are triggered according to the available capacity in the downstream, and thus no TC will be triggered unless an available capacity is found to process the products.

As a result, this mechanism with supportive RT-LCRs guarantees a balanced production line and smoothed flow using kanban and one piece flow lean concepts, which helps in avoiding machine starvation and line congestion and keeping the inventory level as per the standards established in VVSM. It also increases the utilization of resources and the flexibility of production systems.

5.2.2. RT-SPC in Production Disturbances and Incidents

In section 5.2; The RT-SPC_RT-LCRs are expressed in accordance with normal production situations to achieve a perfect and smooth material flow across the value stream to meet the production plan and schedule and avoid any deviations. However, a production environment is fraught with numerous types of random incidents and uncertainties, including variations in processing time or material arrivals, planned interruptions such as setup or preventive maintenance and unplanned interruptions such as reworks or machine breakdowns [HS08]. To further enhance the effectiveness of the RT-SPC module, supplementary RT-LCRs can be expressed to support the quick response ability in order to deal with sudden disruptions, incidents and unexpected internal or external disturbances and mitigate their impact on the overall performance.

Initially, to deal with such uncertainties in real-time, the RT-SPC should decide if the sudden interruptions will significantly affect the production plan or not. Therefore, according to technical experience and classification of pre-defined incidents in VVSM; the RT-SPC checks the expected duration of incident, (the PO or supervisors are requested to enter the expected required time to fix the problem through TUI-DVSM). If it can be fixed in a short-term, then the ongoing state-event “E” should be stopped. “Short-term” means the production plan will not be delayed. But, if the incident fix time is long and leads to production delay, then the suitable RT-LCR will be automatically triggered to check for alternative activities such as alternative routes, free capacities, reallocate resources, etc. This can be depicted in figure 5.4. The CEP-semantic can be expressed as follows:

Definitions:

IN_i = The incident type_ All possible incidents should be pre-defined in VVSM
$IN_i\_DU_{EX}$ = The expected duration of the detected incident
$IN_i\_DU_{VVSM}$ = The acceptable duration without consequences
$E_{current}$ = The current executed event
$F_{E(e_{SE};e_{EE})}$ = Fix start/end event
IN_i_RT-LCR = The corresponding rule of incident IN_i

RT-LCR$_3$: Incident Detection

```
IF [$IN_i$] detected, THEN
        Request [$IN_i\_DU_{EX}$] to $PO_i$
IF [$IN_i\_DU_{EX} \leq INi\_DU_{VVSM}$], THEN
        STOP [$E_{current}$] & WAIT $e_{EE} \in F_E$
ELSE
        TRIGGER [$IN_i$_RT-LCR]
END
```

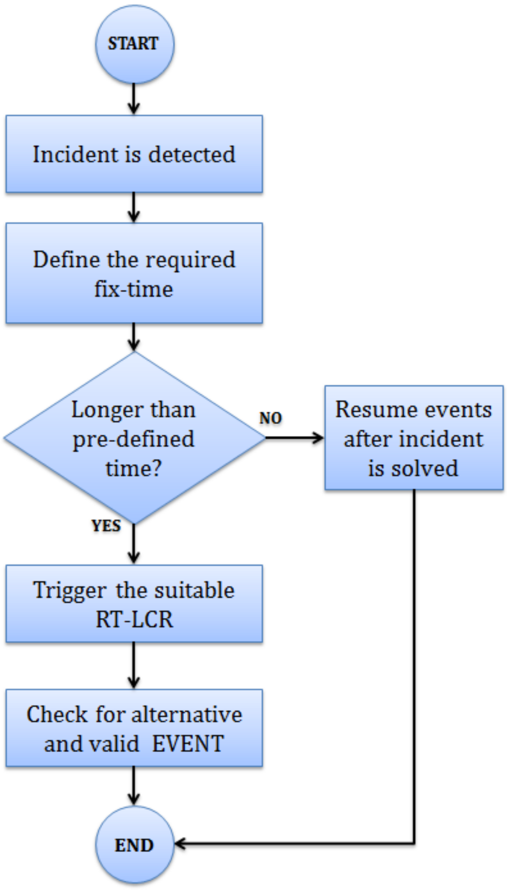


Figure 5.4. A Real-time Evaluation of Sudden Interruptions' Impacts.

Several urgent commands can be defined to be used in such problems, like a produce more-command, stop production-command, preventive maintenance-command (if the machine in the near time not used), change lot-size (i.e. lot sizes are changeable from time to time and could contain different product types with the same machine setup and tools). The above mechanism can be used to deal with different types of incidents, such as: labor absence, labor accident, machine breakdown, misplaced material, lost tool and the volume of the reworked products. For example, the machine breakdown can be expressed as follows:

Definitions:
M_iBD = Machine breakdown
$M_iF_{(e_{ES};\, e_{EE})}$ = Breakdown start/end event
M_i = Machine
$M_{i}\_L_i$ = Location the machine with failure
P_{ix} = Product "i" in Quantity x
R_i = Route
":" = Separator between start location and end location [from:to]
"{:}" = Transport Route
LO_i = Logistic Operator
PO_i = Production Operator

TC_i = Transport Command
PC_i= Production Command
MC_i = Maintenance command to the Maintenance Operator (MO)
E_{MCi} = Maintenance Command Event
e_{MS}, e_{ME} = Maintenance start/end events

RT-LCR$_4$: Machine Breakdown

```
01: IF [$M_iFe_{ES}$] detected, THEN
02:         UPDATE $M_i$ < UNAVAILABLE>
03:         ASSIGN $M_i\_PO_i$ <FREE CAPACITY>
04:         SEND [TC] to $LO_i = [P_{ix}, M_i\_L_i: L_{i+1}, R_{i\{M_i\_L_i: L_{i+1}\}}]$
05:         SEDN [$MC_i$ ] to $MO_i$
06: IF [$e_{MS} \in E_{MCi}$] detected, THEN
07:                 Estimate [$e_{ME} \in E_{MCi}$]
08: IF [$e_{ME} \in E_{MCi}$] detected, THEN
09:         UPDATE $M_i$ <AVAILABLE>
10: END
```

Line01 detects the machine breakdown event or machine stop. **line02** updates the machine status in DVSM-DB as "unavailable". **Line03** shows that PO as free capacity which may be used by workplaces that requested extra capacity. **Line04** sends a TC in order to assign the Machine products to other machine. **Line05** sends maintenance command to MO; the maintenance commands could be prioritized through other RT-LCR and check if they started or not and check the maintenance progress to assign new tasks to it, a little bit before the expected end time of "E_{MCi}", this is described in **line06-08**. **Line09** updates the machine status as "available", END.

According to the status-events timestamps; the processing-status, setup-status, maintenance-status, breakdown-status of machines and equipment can be tracked and analysed to determine the percentage of utilization, availability and unavailability.

Another intelligent aspect to enhance smoothed material flow is the detection of machine starvation (MStr.) in advance. The symptoms of starvation can be diagnosed and detected in advance. The CEP-semantic of the MStr._RT-LCR is expressed as follows:

Definitions:
PCL_{Mi} = The production commands list at machine M_i
PC_i= Production Command
E_{PC} = Production Command Event
e_{PS}, e_{PE} = Production start/end events.
$P_i\_SFP_x$= Semi-finished product of product "*i*", x is quantity
$P_i\_Sub\text{-}A_x$ = Subassemblies parts of product "*i*", x is quantity
E_{TC} = Transport Command Event
e_{TS}, e_{TE} = Transport start/end events
M_i = Machine
IB_j = Input buffer of M_i
L_i = Location of material
R_i = Route

“:” = Separator between start location and end location [from:to]
“{:}” = Transport Route
LO$_i$ = Logistic Operator
PO$_i$ = Production Operator
TC$_i$ = Transport Command
H_TC$_i$ = Hot Transport Command

RT-LCR$_5$: Machine Starvation

```
01: IF [ ($e_{PE} \in E_{PC}$) ≤ 10 Min], Then
02:     DETERMINE [PCL$_{Mi}$+1], THEN
03:     CHECK [P$_i$_SFP, P$_i$_Sub]$_{VVSM}$
04: IF [P$_i$_SFP, P$_i$_Sub]= “AVAILABLE”, THEN
05:     CHECK [L$_i$ _[P$_i$_SFP, P$_i$_Sub]]
06: IF [L$_i$ _[P$_i$_SFP, P$_i$_Sub]] = “IB$_j$”, THEN
07:     GO TO STEP “11”, ELSE
08: IF [TC$_i$ = P$_i$_SFP$_x$, P$_i$_Sub $_x$, L$_i$: M$_i$, R$_{i\{L_i : M_i\}}$]& [($e_{TE} \in E_{TCi}$) ≤ ($e_{PE} \in E_{PC}$)], THEN
09:     GO TO STEP “11”, ELSE
10:         GENERATE [H_TC$_i$ ] to LO$_i$
11: END
```

Line01-02 “10” minutes before the end of the current processing-status; the MStr._RT-LCR checks the listed PCs in the AVSM. For the next determined PC$_i$ **line03** checks the required material either semi-finished products or subassemblies based on VVSM, **line04** checks if they are available, **line05** checks their location (upstream buffers or side-line inventory points, warehouse, etc.), **line06-07** check if material is available in the IB$_j$ of the M*i*, then ends the checking steps, else in **line08-09** check if there is any TC is listed to LO to transport the required material in the near time before machine become free, if yes, then ends the checking, else **line10** generates a hot-TC” to be executed immediately.

In some cases, the semi-finished products are still being processed at an upstream machine, in this case, MStr._RT-LCR generates TC for LO to transport the partially filled container in the OBj to avoid the starvation of downstream workstations; the rest of the quantity will be transported when they are finished. An excess transportation occurs, but a production interruption has been avoided which may cost more than excess transportation. This mechanism helps to avoid any delays in assembly lines and the long idle times of the available resources.

As a result, the RT-SPC introduces a new level of production monitoring and controlling efficiency and responsiveness, where the manufacturers become capable of “looking ahead” which aids in real-time decision-making processes. In this context, several uncertainties and interruptions can be solved in real-time and their impact can be reduced, this is summarized as follows:

- The impact of machine and equipment breakdown and maintenance activities on the current schedule can be mitigated through alternative activities.
- Machine Setups (e.g. unnecessary setups) can be avoided.
- Inventory level can be maintained within the standard levels as planned in VVSM.
- The impacts of the material shortage (e.g. delays in supplied material or defect/non-conforming supplied material) can be avoided or mitigated.
- The impact of temporal labor absence and accidents can be mitigated.
- Move WIP at the wrong place and wrong time can be avoided in real-time.
- Unexpected rework/defect volume stopped before become uncontrollable.
- Breaking the propagation of variability from the upstream to downstream and avoiding its consequences such as more WIP, excess waiting time and congestion.

Production systems vary in their complexity level. Generally, the greater the complexity in a manufacturing system the greater the efforts needed to control it and the more complex and elaborated the RT-LCRs needed to be. Thus, avoiding any serious production disruptions and its consequences, and effectively coordinating and synchronizing the interaction between the executed activities.

PART 3
DVSM- enabled Smart Real-Time Lean Method Tools

In traditional lean environments, the lean-based established instructions are not always followed by the workers due to the lacking of real-time sustaining mechanisms that enhance the practicing of lean instructions. In this part, three frameworks have been discussed to converted the three lean method tools 5S, standardized work and poka-yoke to become smart, in order to prompt the workers to follow lean standards during daily production runs to support the effectiveness of the overall lean system, especially there are some LPTs may not work effectively without reinforcement from other LPTs, since LPTs are mutually supportive. A framework of smart 5S, standardized work, and poka-yoke has been proposed to be implemented in the switchgear manufacturing company. The smart lean method tools is expected to significantly reduce the MLT through reducing the duration of the individual MLT-time components such as reducing the setup-state, processing-state, transport-state, maintenance-state, etc., through eliminating the time wasted searching for the required tools and equipment for each state, or waiting to solve interruptions.

5.3.1. Smart 5S

Backsliding to the old way of working and indiscipline contributes to increasing the size of challenges facing lean environments. 5S is significantly affected due to these problems, and this refers to the absence of a real-time sustaining mechanism that make 5S instructions constantly followed by the workers and kept alive during the production run.

In this section, a framework for smart-5S mechanism has been developed. The prerequisites to develop a smart-5S mechanism; the random location of equipment, tools, fixers, movable material handling and other resources should be constantly monitored during the production run. This mechanism keeps the PSF thoroughly organized, and thus enhances the lean environment through preventing frequent production interruptions that are caused by missing tools or equipment and eliminates the time wasted when searching for the lost tools in the manufacturing facility. The following steps describe how the traditional 5S can be converted into smart-5S:

- First Step “Sort”

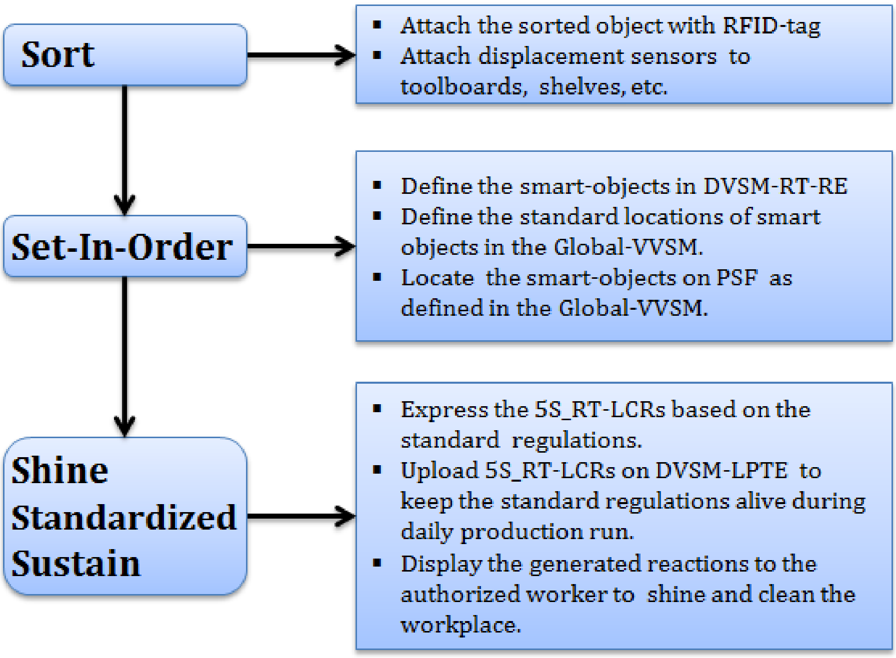
During the deployment of an RFID system on the PSF and before converting the manufacturing assets into smart objects; all unnecessary objects (machines, equipment, containers, shelves, tools, such as jigs and fixtures; cutting tools, spare parts, etc…) which are not relevant to production should be eliminated. Then, the remaining objects will be attached with RFID-tags and become smart-objects and thus identifiable in real-time. Tracking the tools enables the DVSM to track the exact usage time start/end, location of each tool, the sequence of using the tools in processing-states, etc.

- Second Step "Set-In-Order"

After the sorted objects become smart, these smart-tools will be defined in the DVSM-RT-RE as described in chapter 3, with their event-instances and data. According to the nature of tasks at each location, the location of each smart-object will be defined and saved in the global-VVSM. In this way each smart-object becomes virtually assigned to specific locations or routes. Physically, manufacturers should organize and locate the tools as defined in the global-VVSM. On the PSF, the tool boards and shelves can be equipped with sensors to detect the tools' pick-up and return events. For a safe working environment, the tools' work instructions and the ergonomic guidelines can be uploaded to the DVSM to instruct PO about the safest ways of using the tools.

- Third Step "Shine, Standardize and Sustain"

These three steps are combined in one step "3S", because they are related to the detailed physical activities on the PSF. For instance, shine is related to periodic and systematic cleaning and ensuring that every smart-object is located in the right place after each use during the daily production run. Standardize aims to formulate the best work details and the best practices in the workplace into standard regulations to be maintained every minute throughout production run. Sustain aims to keep these regulations alive and effective for the long-term and prevents the workers to fall back into the old way of working. To achieve smart-5S, RT-LCRs to enhance 5S should be expressed based on technical experiences and in accordance with the lean tool "standardized work". The real-time running of the 5S_RT-LCRs on DVSM-LPTE represents the S5 = "sustain". Warning signals for workers about any misplaced or missed tools in order to be returned to the right place represent the S3 ="shine". The logic, on which the 5S_RT-LCRs expression is based, represents the S4 ="standardized-regulations". These steps are depicted in figure 5.5.



- Attach the sorted object with RFID-tag
- Attach displacement sensors to toolboards, shelves, etc.

- Define the smart-objects in DVSM-RT-RE
- Define the standard locations of smart objects in the Global-VVSM.
- Locate the smart-objects on PSF as defined in the Global-VVSM.

- Express the 5S_RT-LCRs based on the standard regulations.
- Upload 5S_RT-LCRs on DVSM-LPTE to keep the standard regulations alive during daily production run.
- Display the generated reactions to the authorized worker to shine and clean the workplace.

Figure 5.5. Development of a Smart-5S Mechanism in DVSM.

➔ The Working Logic of Smart-5S are described as follows:

During the production run, the 5S_RT-LCR constantly checks if any picked tool is misplaced or left for a specific time out of its standard location as defined in the VVSM or equipment is detected out of its designated location at a specific time; RT-LCR will generate a suitable command or re/action for the PO to prompt him to follow the 5S instructions or return back the tools to their right location. The displacement sensors help to detect the picking up and return events of tools. Another RT-LCR can constantly monitor and check if the routes are free from hindrances, like the existence of a smart-object on a certain route (e.g. container, box, etc.) that interrupts the transport-state of the material. In this case, a hot-TC will be generated to the nearest LO to remove that object before the transported material arrives to that point. Now, if the LO reports through his PDA that the object can't be removed for any reason, then the DVSM_RT-LCR$_{Ri}$ should find an alternative route for the current transported material and update the status of this route as "unavailable".

Therefore, 5S_RT-LCRs can be expressed based on the potential problems on the PSF, such as: when the sequence of processing tasks is interrupted, when the tool is not returned to its toolboard after the usage, when the tool has been misplaced inside or outside the workplace, when the time for returning the tool to the toolboard exceeds the standard time in VVSM, when a wrong tool is picked up for a specific task, when a tool is damaged, then it should be reported and canceled from DVSM-DB.

In this regard, as discussed in chapter3, the 5S_RT-LCRs are divided into two types, local-RT-LCRs that are concerned with monitoring and controlling the practicing of 5S at the local workplaces' level, and the global-RT-LCRs that are concerned monitoring and controlling the practicing of 5S at PSF level.

For more effective smart-5S, additional activities and time analysis can be done. For instance, a tool picks up-event from toolboard by worker, moving to machine, processing starts/ends-events, and tool return-event to the same shelf which is attached by displacement sensors can be detected and saved in DVSM-DB. This information can be used to estimate the access time to the tool through estimating the elapsed time between picking the tool from the shelf and placing it back in the event's timestamps, subtracting from them the processing duration (start/end). According to this accurate time analysis, the exact utilization of the tool and frequency of use can be determined and used for further analysis, such as the duplication of expensive tools which could be reduced based on the frequency of using the expensive tools, the life cycle of tools can be updated and accordingly new purchasing orders could be generated to avoid tool shortage.

An effective smart-5S should work in combination with standardized work. Smart standardized work tool is addressed in the next section.

5.3.2. Smart Standardized Work –[SSW]

The best practice of production process can be computerized, in order to be smartly monitored and controlled using the DVSM-LPTE. In this section, a framework for Smart Standardized Work (SSW) is developed. Initially, the WIP flow and times, technical experience, and the latest changes on the used technologies should be considered by lean specialists in pre-manufacturing product and process design stages.In this context the following steps should be followed:

1. Define the product-states and durations along the value stream.
2. For each product-state, define the required resources such as machines, equipment, tools workers, etc.
3. Define the location/destination of each product-state.
4. According to the best practice, split the duration of each product-state into tasks context.
5. Define the optimal sequence of the tasks and the duration of each task.
6. For each task, define the required tool, machine, equipment, components, subassemblies, skill level, etc.

7. Save these production-related data on the product-VVSM in event context.

The instructions of the standardized work can be visualized using the standardized work chart. The steps from 1-7 are summarized in figure 5.6.

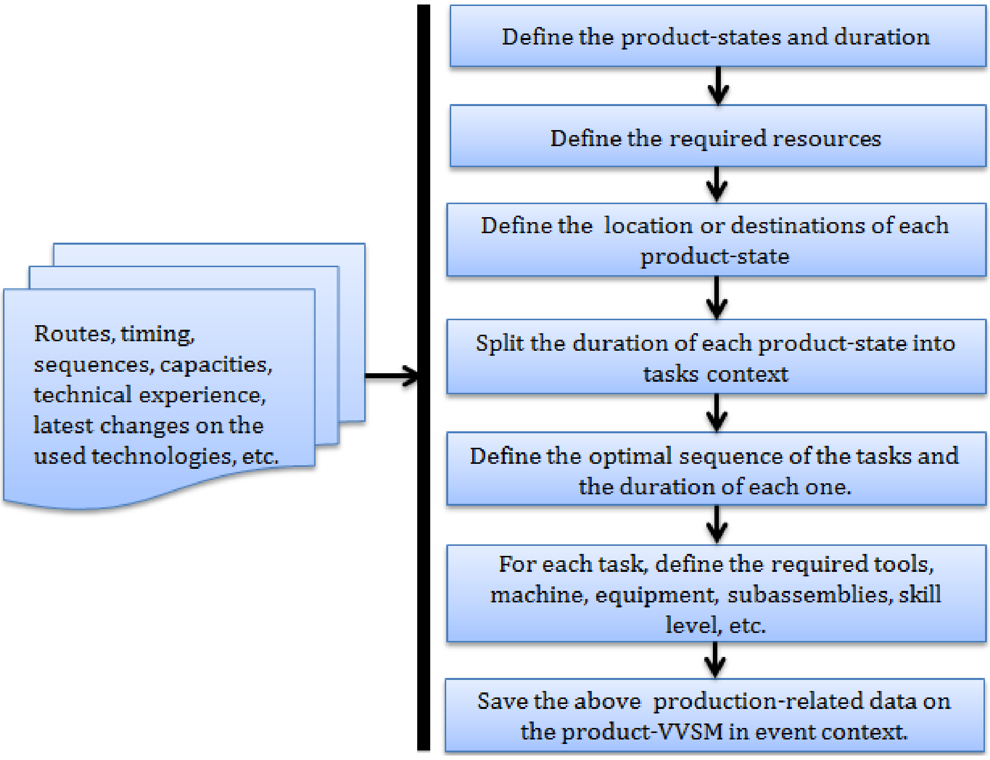


Figure 5.6. Development of a Smart Standardized Work in DVSM.

➔ The Working Logic of SSW are described as follows:

1- During the production run, the product-related standardized work instructions (P_i) will be displayed on the TUI-DVSM at the moment that the product arrival-event at machine (M_i) is detected.

2- According to the current production timeline, the start/end time of this product-state and its tasks will be automatically estimated and uploaded on the local-AVSM of this machine.

3- The PO must execute the tasks according to the defined sequence in the standardized work-chart. For real-time self-learning of PO, videos or audio instructions can be integrated with standardized work-chart and displayed on TUI-DVSM.

4- To ensure that the PO follows the optimal tasks sequence, he is requested to press before and after each task “task-start” and “task-finish” button through using TUI-DVAM.

The start/end timestamps of tasks ensure that the PO follows the standardized work step by step. The timing information can be used to check the PO's progress and performance curve, analyse the root causes of failure like using wrong tool, (i.e. if a tool picking-event is detected during a task-time which is not required for it), find improvement opportunities, etc. The functionality of SSW can be used to enhance a smart poka-yoke mechanism, for example SSW information is used to ensure that all processing-tasks have been completed before transferring a part to the next process.

5.3.3. Smart Poka-Yoke

The design of different mechanical mechanisms is one of poka-yoke's methods to achieve-zero defects and avoid failures. However, mechanical solutions are not always possible. Therefore, using real-time information would be an alternative and an effective way to avoid failures. In this section, a smart poka-yoke methodology is introduced based on the RFID captured data. The introduced smart poka-yoke is a real-time validation mechanism that uses the current production information in AVSM and the standard VVSM data to smartly notify the POs immediately or in advance about any quality problems and failure potentials. As a result, smart poka-yoke prevents the propagation of quality problems and forwarding them to downstream workstations which results in extra waste in time and processing; for either reworked products, or those that need to be scrapped immediately. The digitalization of poka-yoke to become a smart lean tool is descried as figure 5.7.

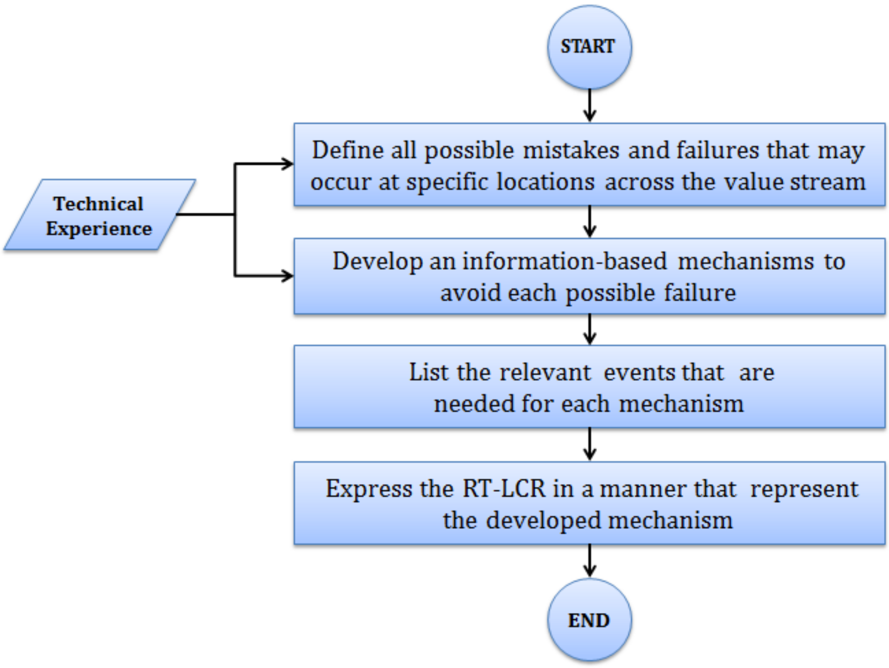


Figure 5.7. Development of a Smart Poka-Yoke in DVSM.

For instance, to deploy smart poka-yoke mechanisms in assembly production lines; the BOM of the specific product (P_i) is already uploaded to the product's VVSM, each subassembly is defined at which location it will be assembled with P_i, ,during assembly operations and after each "Assembly Finish-event" is detected, the RT-LCR should compare between the actually assembled items in AVSM and the standard items in VVSM, if they are identical, then the product will be forwarded to the next station, otherwise a notification will be sent to the PO to replace it with the right item. After the last assembly workstation, another smart poka-yoke aspect is deployed to ensure that all components have been installed. Further smart poka-yoke RT-LCRs can be expressed to ensure that the right tools and equipment are used to perform certain production tasks, since using the wrong tools may lead to failures or quality problems, such as wrong usage of the thread cutting taps or dies that have the same diameter but different pitches.

Before wrong subassemblies enter the side line inventory points of the assembly points, additional smart poka-yoke RT-LCRs can be expressed to detect the arrival of subassemblies and check if the correct subassemblies have arrived. These RT-LCRs eliminate in advance the creation of errors, and prevent the wrong assembly from its origin. Other smart poka-yoke RT-LCRs concerning production parameters (e.g. depth of cut, temperature, speed, vibration, etc.) can also be used to reduce the potential of further quality failures.

5.3.4. Case Study for the Smart 5S, SSW and Poka-Yoke

The concepts of frameworks introduced in part three of this chapter have been put into practice in switchgear assembly line with the aim to enhance smart-5S, smart standardized work and smart poka-yoke principles. The switchgear assembly line is characterized by a high-mix low-volume production environment. There are 40,000 different components and subassemblies used in the assembly stations, 30,000 of them are frequently used in daily production runs in the main switchgear assembly stations. The layout of this facility and the process flow is shown in figure 5.8. At this facility there are several workstations, including: (i) welding station that contains a laser machine, welding robots, edging machine, crane, and different type of tools in toolboards, (ii) SG0 assembly station, (iii) SG0.7 assembly station, (iv) SG1.7/ SG2.5 assembly station, (v) the disconnector-operating system and auxiliary switch assembly station, (vi) GAS filling station, (vii) wiring station, (viii) testing chamber, and (ix) high-voltage testing station. Each assembly station is equipped with steel-compartment fixing and rotating machine, toolboard with different type of tools, subassemblies trolley and monitor to see the work instructions. The number of workers inside the assembly station is five assembly operators (AO).The moving of steel-compartments inside the assembly station is done using an electrified-monorail system. Transporting of steel- compartments and finished-switchgears between stations is done using a manual pallet jack. The subassemblies are transported using shelf trolley to JIT replenishes the subassemblies trolley.

After releasing the orders to PSF, the manufacturing operations start with fabricating different types of steel-compartments (i.e. SG0, SG0.7, SG1.7, and SG2.5) in welding station. After that, they are stored at the end of the station waiting their turns to be transported and sent to the related assembly station. Each switchgear unit consists at least of one steel-compartment where all the auxiliary instruments and components in various sizes are assembled and highly customized on an order-to-order basis. In an assembly station, according to work instructions; the AO starts to assemble the subassemblies inside the steel-compartment and then the steel-compartment will be totally closed by “pressure relief disk”, after that the main three-position disconnector will be assembled onto steel-compartment. The finished steel-compartment will be transported to be filled with isolation-gas, and then mechanically tested in the testing station. Finally the finished assembled switchgear will be transported using a manual pallet jack to the high-voltage testing station.

During daily work hours there are different interruptions and incident aspects caused by human. Some of these interruptions aspects are listed below:

- The high potential, that a tool is forgotten inside the steel-compartment after closing the “pressure relief disk” of the steel-compartment. This can lead to hazardous situations.
- Another complexity aspect arises due to the high similarities between the subassemblies that lead to frequent wrong assembly problems, since it is hard to distinguish the subassemblies from each other visually.
- Routes are frequently blocked with a container or products stored out of their designated location and interrupt the transport-states.
- Subassemblies are replenished to the wrong assembly station by LO.
- Steel-compartments arrive very often to the wrong assembly station.
- Tools and equipment are frequently misplaced or lost.
- The papers in paper-based material transportation are frequently lost.
- The sequence of the standardized work tasks is not always followed by AOs, etc.

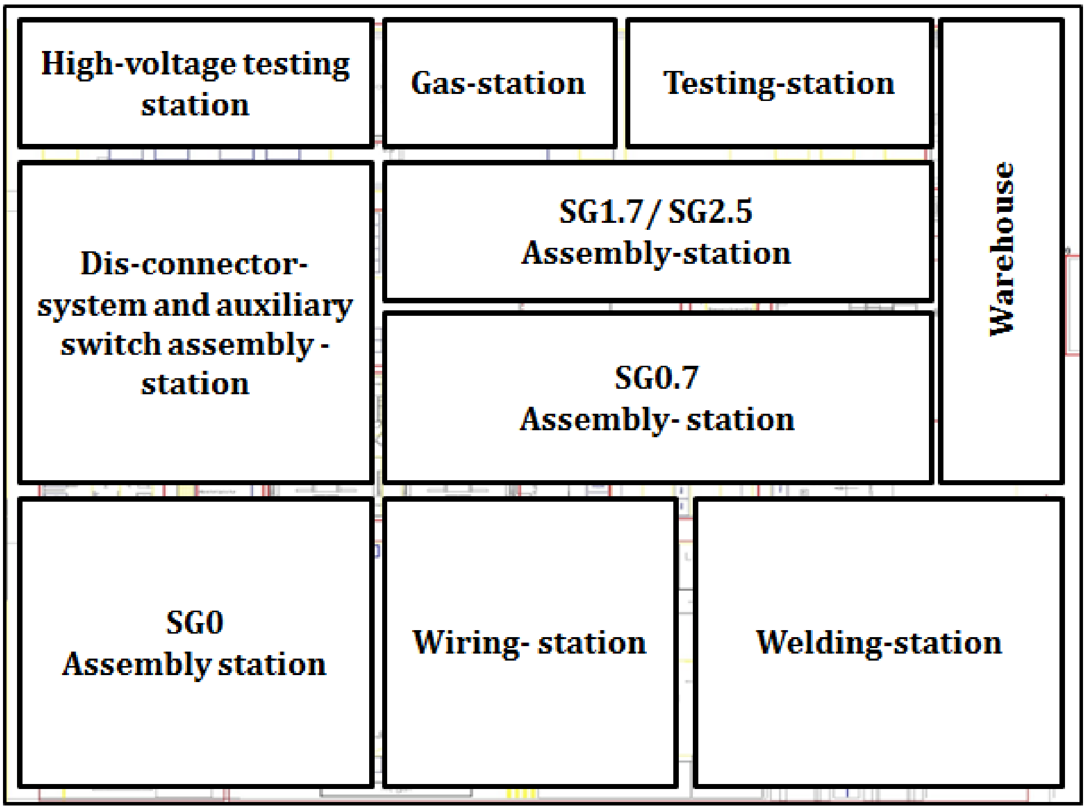


Figure 5.8. The Facility Layout of the Assembly Line.

In addition to that, the duration of each assembly task is not standardized; this causes a high variability in assembly-state duration that ranges between 90-160 minutes, referring to the high-customized orders.

To avoid or rectify these interruptions and failures in real-time, a smart real-time mechanism based on the three smart lean tools has been proposed. For instance, for quality-related problems; smart poka-yoke mechanism can be developed, and it will be supported from smart-5S and SSW. The smart 5S mechanism can be developed to constantly keep the PSF organized in order to reduce the possibility of interruptions. The SSW mechanism can be implemented to guarantee that the best work practice is always followed by the AOs, and any deviation will be directly reported to the supervisor as well as the impact of this deviation will be analysed in terms of assembly time and quality aspects to find any improvement opportunities.

In this context, RFID deployment steps should be implemented. Initially, RFID-tags are proposed to be attached to each steel-compartment, sub-assembly, component, hand tool, container, equipment, AOs, LOs, etc. Then it is proposed to install RFID-readers at each station. The toolboards should be equipped with a displacement sensor system to detect the presence of the tools and pick up/return events. The steel-component is considered as the main part of the switchgear. Therefore, the RFID-tags attached to the steel-components are considered as the reference of the final assembled switchgear.

After all PSF objects become smart, the event-instance of each smart-object is defined, and then the tree of event- instances of the smart-objects is built, parts of the generated events tree is shown in figure 5.9.

The product-driven events along the value stream of each switchgear type should be defined, especially the assembly-state. The assembly-state has been split into event-instances (i.e. compartment arrival/ departure event, sub-assembly arrival event at side line inventory point, tool removal/return event from/to toolboard, etc.). The BOM and the point of use as well as the production-related data of each switchgear order should be predefined and uploaded to its VVSM to be translated in event-context.

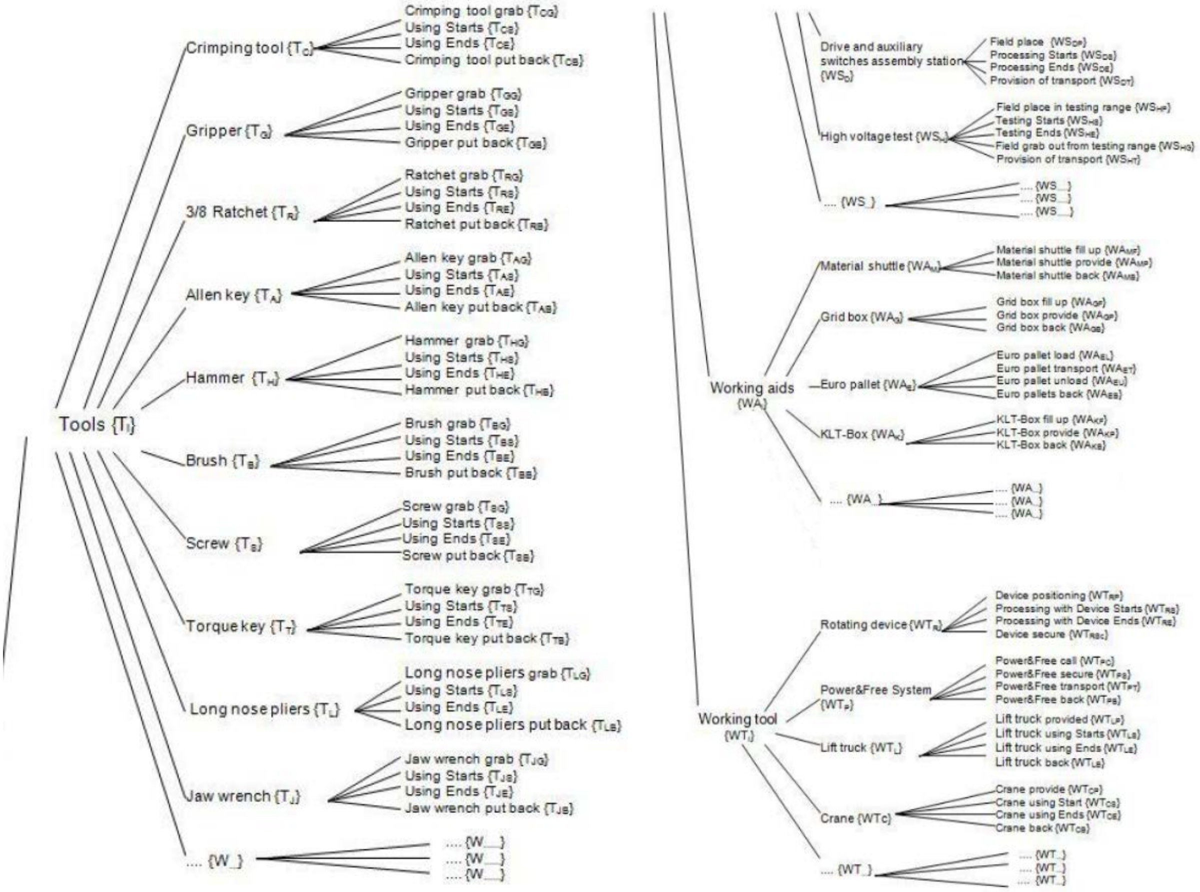


Figure 5.9. The Tree of Event Instances of the Smart-Objects.

Finally, concerning the above three tools, the associated RT-LCRs should be expressed to achieve their targets in reducing the interruptions, reducing assembly-state duration, avoid quality problems. The RT-LCRs that utilize the real-time production-related data are narratively presented as follows:

- ➔ The first RT-LCR takes poka-yoke into consideration to detect the wrong sub-assemblies. Once the "arrival-event" of switchgear "SG_i" at assembly-station is detected, the DVSM will display the required sub-assemblies at this station with the standardized tasks sequence. After assembly-state ends (i.e. though pressing "task-finish" button using TUI-DVAM) and before a "departure-event" is detected; the RT-$LCR_{poka\text{-}yoke}$ will be triggered to check if the right items have been assembled.
- ➔ Since hand tools are not related to the BOM of switchgear; the same fashion is followed to express the second RT-$LCR_{poka\text{-}yoke}$ to detect if one of the used tools has been left inside the steel-compartment once the "departure-event" is detected.

If either one of the above two cases or both occur, the worker will be notified before forwarding the compartment to the next process.

To support the first rule, a supportive RT-LCR is proposed to prevent the replenishment of wrong sub-assemblies to the side line inventory point and guarantee JIT-replenishment. The proposed RT-LCR will check the next planned switchgear at the assembly station. Then based on BOM of this switchgear, a TC will be generated and sent to the related LO to be executed before the "arrival-event" is detected. Once the shelf trolley arrives, the RT-LCR will check again if they are the right items.

- ➔ The third RT-LCR monitors if the AO follows the standardized work sequence. Once the "arrival-event" of a steel-compartment is detected, the related VVSM-standardized work sequence will be displayed to AO-TUI. Through using TUI-DVAM, the AO is enabled to press before and after each task "task-start" and "task-finish" button to interact with the DVSM, so the RT-LCR checks if he follows the right sequence or not.
- ➔ The fourth RT-LCR will enhance the practice of the 5S lean tool; this rule will prompt the worker to return the tools to the toolboard after each use. The prerequisite of RT-LCR to works well is to equipping the toolboard with a displacement-sensor system. Therefore, the "removal-event" of a specific tool will be detected once the AO pick it up. Now, if the tool is not needed for the next task, then it should be returned after the "task-finish" is detected. Therefore, if this tool has not been returned to the toolboard before "$tasks\text{-}start_{i+1}$" is detected; then the AO will be notified to return it directly. After finishing all tasks and before detecting the "departure-event" of the switchgear, all tools should be returned; otherwise, the RT-LCR will send reaction to the electrified-monorail system to stop forwarding the steel-compartment to the next station. This rule spontaneously supports the second RT-LCR.

- The fifth RT-LCR is concerned with the use of the right tools for the right compartment and during the right task. As aforementioned, the required tools for each task should be predefined during the defining of the tasks in the standardized work stage. Once the “arrival-event” is detected, and the first “task-start” event is detected; the RT-LCR will display which tools are required to be picked up. If the AO picks the wrong tool up, the RT-LCR will generate a notification signal for the AO. For further analysis this event will be saved in DVSM-DB, for example it is used for smart real-time waste analysis.

These RT-LCRs should be translated into CEP-sematic. These RT-LCRs are expected to significantly reduce the MLT of switchgear through reducing the time wasted searching for the required tools and equipment for each state, or waiting to solve interruptions.

CHAPTER 6
DVSM-enabled Real-time Manufacturing Cost Tracking System

In this chapter, an innovative real-time costing framework incorporating lean manufacturing and RFID is developed for bridging the gap between lean operational aspects and financial costs together in real-time. The developed framework is called Real-time Manufacturing Cost Tracking System (RT-MCT) module, which is executed in real-time by DVSM-LPTE. The need for such a costing method is vital in identifying the root causes of redundant costs and pinpointing the most costly root causes and their locations, so they are targeted with the highest priority to be eliminated. Furthermore, this costing method mirrors the monetary impacts of implementing lean improvements at various value stream stages in today's mass-customization production environments. The system presented is validated through ProModel simulation software along with extensive calculations, moreover, a demo software using java has been developed.

6.1. Introduction

While manufacturing companies are striving to be lean, they need to have a real-time assessment tool that aims to measure the monetary impacts of implementing lean improvements in order to bridge the gap between the operational and financial views in one pool, thereby, demonstrating and approving these improvements with higher degrees of confidence [WA10].

In this manner, many companies failed to see the monetary impacts of lean manufacturing improvements in their production facility. This is because the traditional costing systems are not based on lean principles and are not concerned with the monetary aspects of lean manufacturing. Moreover, they consider the accumulation of costs regardless of their timing [SK08].

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 manufacturing systems [Kap83]. Using the traditional costing systems in a lean environment, the costs of labor, material, and overhead cannot be precisely incurred into the custom products; as a result, the actual manufacturing costs are not reflected [SZ13].

Furthermore, the traditional costing systems do not concern themselves much with eliminating waste [Sti09].Therefore, Using average costing techniques to calculate the individual product cost in today's mass-customization production 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 [Bag03].Moreover, some products consume more time and thus more cost than others in the value stream so it is important to define the parameters that cause extra costs.

In addition, traditional accounting systems which are based on the monthly accounting period in a real-time lean enterprise 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 [SZ13].

In order to avoid potential conflicts with the lean implementation; companies are beginning to implement other accounting systems such as activity-based costing (ABC) or lean accounting, which are oriented to solving the problem of overhead allocation [GLB+13]. 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 [Vel10]. Due to limitations and problems of traditional costing systems and ABC from the lean point of view, other alternatives have been developed.

In this context, lean accounting was developed based on VSM, where all cost allocations become direct along the value stream [MBG11]. Moreover, few academic literatures have discussed the integration methodology of costing systems with lean manufacturing [RFC13]. This integration starts with the lean tool VSM which lacks any economic measures for "value" like profit, throughput, operating costs, and inventory expenses [KI01]. For instance, [RFC13] assess the applicability of one of the lean accounting techniques called "value stream costing"(VSC) which was initially developed by [MB04]. As a result, [RFC13] found out, that the proposed lean costing techniques developed based on VSM principles are still not mature enough to be brought into reality [RFC13]. In this regard, [Sti09] also added, that because the major portion of product -flow in lean manufacturing is not trackable, their cost will be not traceable, and thus uncontrollable.

Recently and after RFID insertion in industry [ZJH+12] alluded to the possibility of using RFID in a real-time manufacturing cost tracking technique. It is clear that almost no study tries to tie the product cost accumulation along the value stream and the timing together in real-time to mirror the impact of lean improvements at each value stream stage. This part of research, presents a real-time manufacturing cost tracking tool, which is able to track the development or accumulation of actual product costs during the flow of product along a value stream. This tool can further analyze the incurred costs with respect to the utilized resources and consumed material in order to recognize the most critical and costly work-stages. In other words, tracking and viewing the details of activity costs including all resources consumed in each and every moment, in each and every step.

In this context, it is important for lean measurements to identify the costs of wastes and delays as well as reflect the impact of implemented improvements on cost reduction. All in all, this part of the research aims to develop a real-time lean accounting system.

6.2. Conceptual Framework of RT-MCT in DVSM

This part of the research outlines a new pragmatic product manufacturing costing approach called "Real-time manufacturing costs tracking module" (RT-MCT) which is considered as a new generation in costing techniques. RT-MCT module is proposed to run through DVSM in order to enable the manufacturers to monitor the real-time gradual development of the products' associated manufacturing costs during flow along their value stream as well as monitoring the operations' performance in terms of cost. The target of RT-MCT is to only track the manufacturing costs which belong to manufacturing operations, while the non-manufacturing expenses are estimated separately as shown in figure 6.1.

RT-MCT enables the companies to see how the corresponding lean improvements impact their financial performance and monitor the saved costs due to lean improvements which are not seen in traditional costing systems. The RT-MCT module is designed to estimate the actual manufacturing costs synchronously while the operations are being executed.

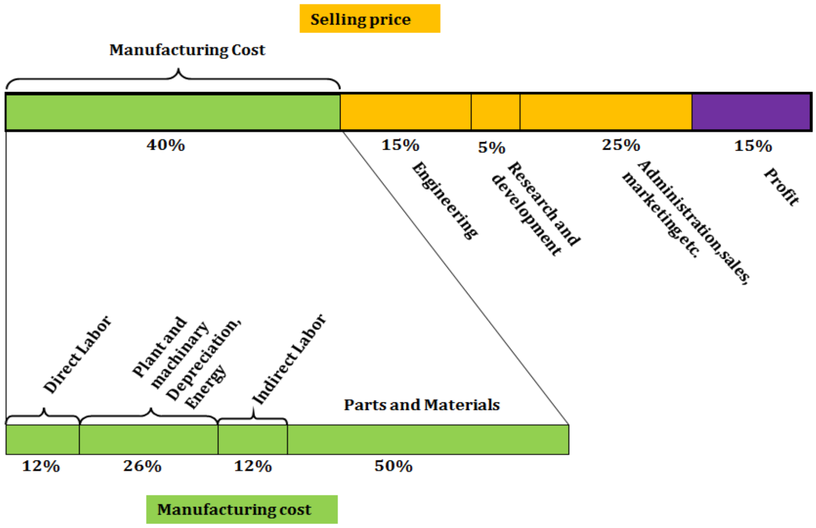


Figure 6.1. Breakdown of Costs for a Manufactured Product [Gro07].

The idea behind 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 final prices of the products. RT-MCT module can be defined as a real-time manufacturing cost tracking method that estimates the manufacturing cost of the production activities being executed and the material being consumed simultaneously with the flow of the corresponding object. After that, the RT-MCT reports the cost information with deep cost details to the relevant users on real-time production under regular production 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 lean improvements on the total product manufacturing cost, as well as define the impact of each waste type on the final product cost and to support better decision-making processes.

6.3. Real-time Cost-time Profile (RT-CTP)

Traditional VSM maps the manufacturing processes along with their corresponding resource usage with respect to time and locations, without any concern to costs or monetary aspects. In response to this deficiency and to translate the timing in VSM into cost, we propose to integrate cost-time profile (CTP) tool in RT-MCT module to display costs accumulation with respect to time simultaneously.

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.

Figure 6.2 gives a simple illustration of a CTP. The diagonal lines represent the costs of activities. The gradient of each line depends on the activity's 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 [Gal92][Foo93].

As seen in figure 6.2, the waiting time has no impact on the total cost. This assumption does not agree with lean philosophy which considers waiting time a cost-driver contributing in the total cost. 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.

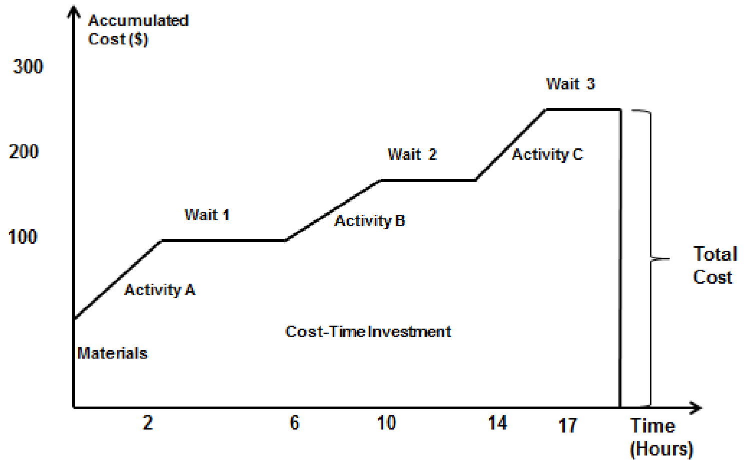


Figure 6.2. Cost-Time Profile Components [RF07].

However, in real-time manufacturing, the construction of CTP during a production run needs a clear methodology which is not discussed in the recent literatures (especially 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), but in reality the products' waiting times incur additional costs 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.

For real-time manufacturing 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 operational aspects. Secondly, VSM focuses on the operational aspects of the manufacturing operation with respect to time but it does not track the accumulation of product costs during the product flow from upstream to downstream workstations. Thirdly, RFID, a powerful auto-ID technology, 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 triple integration of three tools is represented through RT-MCT module in DVSM as figure 6.3.

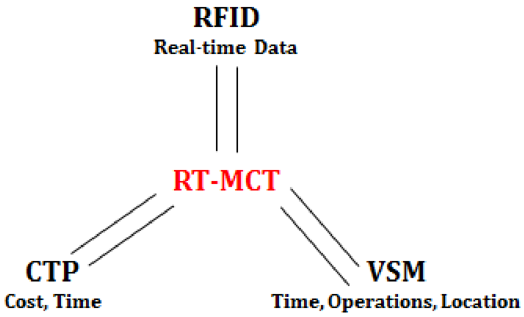


Figure 6.3. Triple Integration of VSM, RFID, and CTP in RT-MCT.

6.4. Real-time Manufacturing Costing Method

Designing a costing system must take into consideration the nature of production environments. In this matter, the increasing product customization in global markets is forcing the companies to adopt mass customization production environments. This means, that each customized product with special requirements and specifications required by customers has a different value stream with different resource requirements, material types, components or sub-assemblies, work-instructions, etc. This implies that, the cost of an individual product and the associated services will vary according to the product's custom requirements. Because of this situation, it is necessary to estimate the cost of each product separately and find out the impact of operational performance on its manufacturing cost.

The total costs of an actualized VVSM_i include all events costs (e.g. material consumption events, machining events, labor events, inspection events, etc.) which are classified according to their characteristics into: time-driven manufacturing costs and material-usage driven costs as shown in equation 1. 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's WIPs until the product is totally finished:

$$C_{AVSM_i} = \underbrace{\left[\sum_{i=1}^{n} Product_{StateDuration_i} * TCostRate_i\right]}_{T_{tc}} + \underbrace{\left[\sum_{j=1}^{m} M_{L_j} * C_{BOM\,j}\right]}_{T_{mc}} \qquad [1]$$

Where:

- C_{AVSM_x} : Manufacturing cost of $AVSM_x$ products
- T_{tc}: Time-driven manufacturing costs based on product-states' duration.
- $Product_{StateDuration_i}$: The duration of production-state along the value stream.
- *TCostRate:* the total cost-rate for$Product_{StateDuration_i}$.
- T_{mc}: Material usage-driven manufacturing costs.
- M_{L_j}: The consumed material which is mounted directly with the main product at specific location along the value stream.
- C_{BOM}: The cost of the material/components as defined in the Bill of Material (BOM) in VVSM.

The cost-segments extend from *i=1, 2, 3…….n*, and material consumption points are *j=1, 2, 3……m.*

The Total cost-rate of each product-state is composed of several cost-drivers where each cost-driver has its unique predefined cost-rate. This is summarized in the following formula:

$$TCostRate_{\,u} = \left[\sum_{i=1}^{q} (CostDriver * ICostRate)_i\right] \qquad [2]$$

Where:

- *TCostRate* $_u$: the unique cost-rate of a specific product-state.
- *CostDriver*: the consumed resources during a product-state.
- ICostRate: the individual cost-rate of each cost-driver.

The cost-drivers exist in each product-state extending from *i=1, 2, 3…….q.*

In order 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 RFID real-time remote location constructors, which is defined in chapter 3.

The next sections present the product-states along the 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.

6.4.1. Time-driven Manufacturing Costs

The manufacturing cost of any product is primarily dependent upon how quickly it flows through the value stream [SZ13].This means; the products that require more time to be manufactured consume more cost.

During the production progress, the WIPs pass through different work-stages where different WIP-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 chapter 4, the duration of each product-state is based on the captured events' timestamps through the event-data vector of AVSM as shown in figure 6.4.

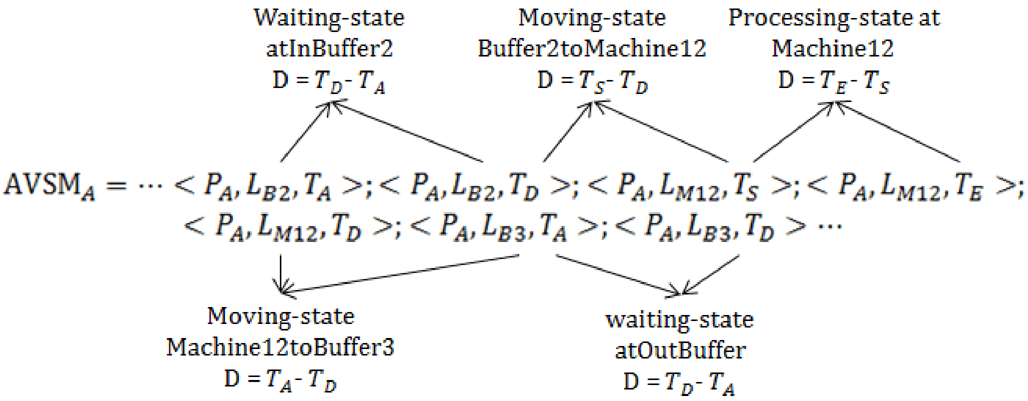


Figure 6.4. Product-state Durations Based on Event-data Vector Paths.

The cost of each product-state depends on the duration and the cost-drivers being consumed. In figure 6.4 the duration can be estimated, as well as the being consumed cost-drivers can be detected in real-time using the RT-CEP method.

The product-states represent the time-components of the MLT; therefore the cost at one workstation is the sum of the costs of product-stats at this workstation as shown in equation 3:

$$WS_c = P_c + M_c + St_c + WIB_c + WTB_c + WTM_c + Q_c + etc \ldots \qquad [3]$$

Where: WS_c :cost at one workstation, P_c : Processing cost, M_c : Moving cost , St_c: Setup cost, WIB_c : waiting in batch cost, WTB_c : waiting to batch cost, WTM_c: waiting to match cost, Q_c: Queuing time cost, other state-costs are possible.

Similarly, the time-based total manufacturing cost (T_{tc}) of the entire AVSM is the summation of product-states' cost (i.e. cost of MLT components) along the value stream which include workstations and the states between them, such as the waiting-state cost (Sp_c) in supermarket and the transport cost (Tr_c) using movable or stationary equipment, inspection cost, etc. This is illustrated in equation 4:

$$T_{tc} = \sum_{i=1}^{w} (P_c + M_c + St_c + WIB_c + WTB_c + WTM_c + Q_c + etc)_i + \sum_{i=1}^{t} Tr_c + \sum_{i=1}^{s} Sp_c \quad [4]$$

Where: *i=1, 2, 3……. w/t/s, "w"* is the number of workstations, *"t"* is the number of transport-states, and *"s"* is the number of supermarkets along the product value stream. 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 manufacturing system. This is discussed in the next section.

6.4.2. Estimating the Cost-rate of Product-states

Using the traditional costing techniques to allocate the manufacturing costs to products on the basis of volume-related drivers distorts the products' manufacturing cost [RFC13].

In the DVSM, the real-time tracking of the individual products' flow during the production run enable the manufacturers to determine the exact information needed for the RT-MCT module like labor, machines, tools, equipment, space, etc… being used by each AVSM. In other words, any used resources in any product-state can be detected from RFID 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 value stream costs.

The first step towards real-time manufacturing 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 cost of wastes which are mainly hidden within overhead and indirect costs, they are converted and incurred as direct costs, therefore there is no distinction between direct and indirect costs, all costs that contribute to manufacturing operations are considered and incurred as direct costs in terms of (€/time-unit). For example, convert the machine depreciation 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. They are generally explained because a detailed description goes beyond the scope of this study.

- 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 (Dl_c) cost-rate 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.

- Tooling cost-rate (TE_c): The cost of using equipment or tools for production activities per time-unit. This cost depends upon the relation between the life cycle of the used tool and its purchased price. For example, if the cost of a cutting tool used in a lath machine is 150$ and the expected average life cycle time is 120 working hours under regular production conditions, ignoring machining parameters like depth of cut, feed rate and velocity, then the cost-rate is equal to 2.1 ct/minutes. In this regard, an exact estimation of the tooling cost during the product machining-state is determined. In this regard, [CP07 used a sensor RFID-based maintenance system for cutting tools and spare parts of CNC machines to estimate the exact usage time per product and update the remaining life.
- Machine cost-rate: This cost-rate includes all machine-related costs like depreciation-cost, maintenance-cost which include spare parts and repair costs, energy consumption cost, and others. For example, the depreciation cost De_c depends on the consumption ratio of a machine and its initial purchased price as well as the salvage value. The calculation of the depreciation cost-rate is presented in equation 5:

$$De_c = \frac{Price\ of\ eqiupmet - salvage\ value}{Life\ span\ in\ TimeUnit\ (e.g. minute)} \qquad [5]$$

  For instance, if the cost of a milling machine is 10000 $ and its average life span 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 0.708 ct/minute. To accurately estimate the product-state duration of the machine, it is proposed to use the machine’s real-time data beside RFID-event data. In order to estimate the machine cost-rate, it is important to use some machine related data such as: initial price, expected life span in minutes, energy 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 value stream based on the space used by it with respect to time. To do that, [Bag03] divided all facility costs by the total square footage of the PSF 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. This will motivate the value stream members to reduce the amount of space used by the value stream which contributes to reducing waiting time and thus the inventory level.

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 processing-state at a workstation ($\mathrm{P_{c-ws_i}}$) equals to 3.8 $/minute. This cost is composed from several cost-drivers' cost-rate such as direct and indirect labor cost ($\mathrm{Dl_c + IDl_c}$), energy cost ($\mathrm{E_c}$), tooling and equipment cost ($\mathrm{TE_c}$), depreciation cost ($\mathrm{De_c}$), maintenance and spare parts cost, etc. The processing-state cost-rate is presented in equation 6:

$$\mathrm{P_{c-ws_i} = Dl_c + IDl_c + E_c + TE_c + De_c + Main_c + etc.} \qquad [6]$$

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 production run, the RT-MCT displays on the RT-CTP how much money product "X" costs so far.

In order to estimate just the cost of VA product-states; the expected VA product-states must be defined firstly. Equation 7 considers the processing-state the only state that has VA on the final product. Therefore, the overall processing costs ($\mathrm{P_c}$) along the product's value stream equal to the summation of all processing-state' costs:

$$\mathrm{P_c} = \sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{P_{c-ws1} + P_{c-ws2} + P_{c-ws3} + P_{c-ws3} + \cdots P_{c-ws_n}} \qquad [7]$$

Note that the VA product-states are not 100% pure VA because there are some hidden wastes which should be uncovered and eliminated.

Since specific resources (e.g. material handling equipment, logistic labors, etc.) may be shared among different products' value streams, 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's cost-rate is 20 ct/minute, and he supplies different workstations with sub-assemblies using forklift, there are many ways to incur his cost-rate directly on the main product, one of these methods is to include his cost-rate in the total transport cost-rate to be incurred on the transported sub-assemblies which will be mounted on the main product, in this case the cost of each sub-assembly part becomes equal to its initial purchased cost in addition to the cost of transport.

For sure there are previous costs related to warehousing costs, and some costs incurred later on the sub-assemblies like the cost of WTM-state. The same fashion is also applied to convert all conventional manufacturing overhead costs which pertain 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's 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 is important to note that the cost-drivers vary from business to business, thus the nature of the production environment determines which methodology should be followed to track each cost-driver along the value stream and how waste could be correctly identified. 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 production parameter and conditions or payrolls.

In material usage-driven manufacturing costs, the costs of consumed materials along the value stream (e.g. raw materials, subassemblies and components) are similarly incurred on individual products as shown in the next section.

6.4.3. Material Usage-driven Manufacturing Costs

The second main cost-driver beside time-driven costs is the material consumption along the value stream. The product's value stream of material costs are calculated based on the direct and indirect material consumed by the product along the value stream. The real-time manufacturing cost tracking process starts with incurring the cost of the main direct material used at the first production-stage. After that and during the production run, material-cost is incurred once a material (e.g. component or sub-assembly) is added onto 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 value stream including individual 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. oil, lubricant, etc.). However, both direct and indirect materials will be converted into direct cost. Accordingly, the material cost which is incurred on individual products over the value stream processes T_{mc} is defined as:

$$T_{mc} = \sum_{i=1}^{n} [RM_i + DM_i + (IM_i)] \qquad [8]$$

Where:

RM_i: *The* main raw material used at the first workstation in the product value stream.
DM_i: The components and sub-assemblies usage over the product value stream.
IM_i : The indirect material used for production activities.

Normally (IM_i) 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, etc.). In this case, the cost of the components and sub-assemblies will be updated on their RFID-tag and on a relevant database in DVSM after each state; this cost will be incurred on the semi-finished product's cost once it is mounted with it.

6.5. Working Logic of RT-MCT in DVSM and the RT-CTP Construction

This section discusses the working principles of real-time allocation of manufacturing costs to individual products based on time-unit (i.e. second, minute) and material usage rate.

The real-time information of operations and machining progress events is one of the important key functional factors of RT-MCT. While the operations are producing and the products pass through their value stream on PSF; the resources and materials are being consumed where the manufacturing cost is growing. Meanwhile, RFID tracks all manufacturing operations on PSF and maps their information to the DVSM using RT-CEP system, and then the cost-relevant information is mapped to the corresponding real-time costing rules in RT-MCT module. RT-MCT 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 in order to estimate the total manufacturing cost of the entire value stream of each product.

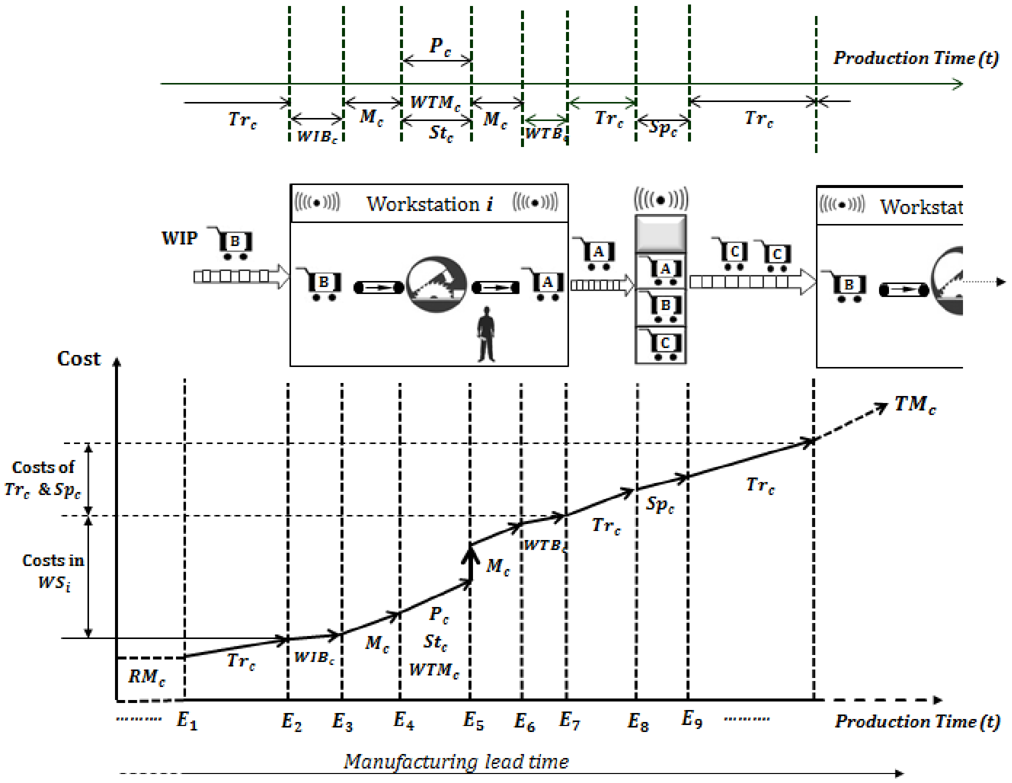


Figure 6.5a. Real-time Product Cost-time Development.

The time and material usage driven costs which contribute to the gradual cost development during the flow of products along the value stream are shown in figure 6.5a. 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.

If a product's value stream consists of sub-streams, then the costs of these sub-streams are estimated identically to that in the main value stream. The costs belonging to these sub-streams must be incurred on the product's cost pool.

Figure 6.5b describes the working logic of the real-time manufacturing cost tracking module in the DVSM and how the cost–time development in figure 6.5a can be constructed.

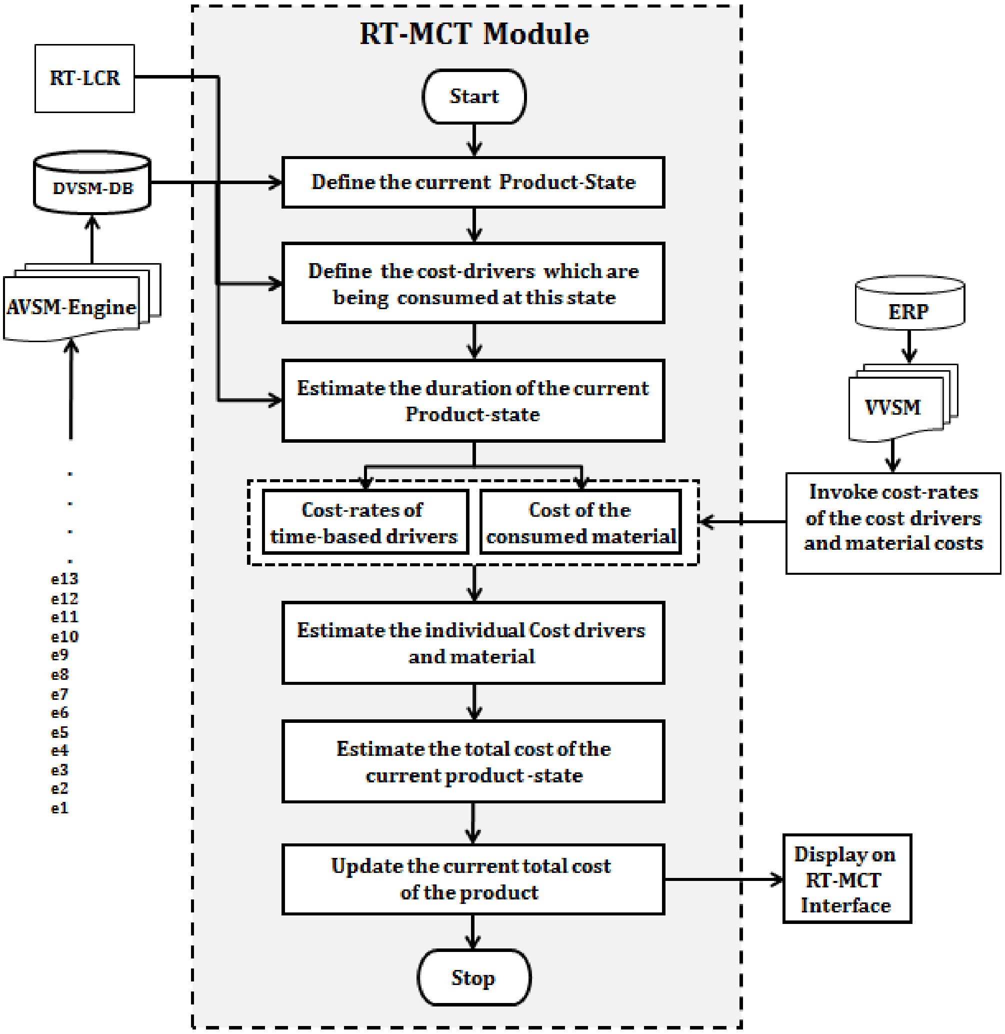


Figure 6.5b. The Working Logic Flow Chart of the RT-MCT Module in DVSM.

6.6. Real-time Cost-based Lean Performance Monitoring

Since the traditional accounting systems are not concerning themselves with the classification of production activities in terms of VA and NVA activities, the NVA activity costs cannot be separately estimated. For example, the cost of overproduction, inventory handling and space utilization cannot be separately recognized and estimated to evaluate its impact on the total manufacturing cost.

This section addresses how the monetary impacts of waste on the total manufacturing cost can be automatically recognized and estimated. Real-time lean-cost performance measures are integrated with RT-MCT to monitor the monetary impacts of a waste elimination process through continuous-improvement or via the “Kaizan” lean tool. RT-MCT supports real-time performance analysis in terms of cost through distinguishing between the VA and NVA activities that are cost-based (either necessarily or unnecessarily). RT-MCT aims to translate the applied performance of actualized VVSM activities to cost (e.g. processing cost, transport cost, waiting cost, etc.). Since the cost of VVSM of each product is determined and predefined during product development and the production process design phase; this standard cost will be compared with the cost of the actualized VVSM. Generally, the difference between these two costs represents the cost of the wastes and the NVA activities which include for example usage of excess materials, consuming more resources' time, and subsequently increasing the NVA costs (i.e. exceeding the standard processing time, excess waiting time due to machine breakdown and therefore more space utilization). On the other hand, there are "abnormal costs" which refer to the non-regular and unexpected occurrences like unexpected heavy breakdown of machinery. The abnormal costs are not considered to be incurred on the individual products in this module. Similarly, any penalty costs resulting from production delay due the inherent waste are not considered in this report as NVA costs.

The RT-MCT enhances continuous improvement efforts, where the lean cost analysis aims to create some kind of benchmark for comparing the actual performance with the target performance, where the deviation between them will be displayed in terms of cost to demonstrate for the managers how big the adverse impacts of the NVA activities, however trivia they may be, are on the value stream cost pool.

In figure 6.6, the graphical structure visualizes how the production value stream costs are identified and tracked. It shows a real-time cost analysis of the VA and NVA activities through the live tracking of a product through its value stream. The associated costs are then estimated and displayed simultaneously once the product-state is changed to either a time-consuming state (time-driven costs) or a material-consuming state such as a component being assembled with the main semi-finished product (material-driven costs). Figure 6.6 is summarized in the following two questions which explicitly describe the operational performance of the production system's state: How much costs are designated to each product-state along the value stream and how the costs are actually required (actual cost)? This kind of detailed analysis helps to localize the most costly and wasteful state or work-stage over the value stream.

As shown below, box 1 & 3 in figure 6.6a presents the product-states based on time-driven and material-driven costs. The actual cost of each product state as shown in box 2 in figure 6.6a is estimated and incurred simultaneously during the production progress on the product's value stream cost pool. In order to estimate the activity-associated waste costs; the actual manufacturing costs (AMC) shown in box 4 in figure 6.6a are subtracted from the standard manufacturing costs (SMC) which are predefined already in VVSM; therefore we are able to see for example the impact of extra processing time at workstation (i) in terms of money and the weight of its impact on the manufacturing cost. Therefore the manufacturers become able to identify the inefficiencies in the manufacturing process that are contributing towards extra costs. This means, through this module, the critical NVA activity which ultimately increases the manufacturing cost will be detected and targeted with the highest priority so it can be eliminated. The cost of the activities (VA/NVA) can be represented as vertical values along the production time line as shown in figure 6.6b.

Because the total manufacturing lead time plays a critical role in the lean environment, where spending more time means more costs are incurred on the cost pool. Figure 6.7 shows a horizontal-distribution of the costs over the total manufacturing lead time. Therefore, if any lean improvement is applied to decrease the total manufacturing lead time; its monetary impact will be monitored through one of these time-splits.

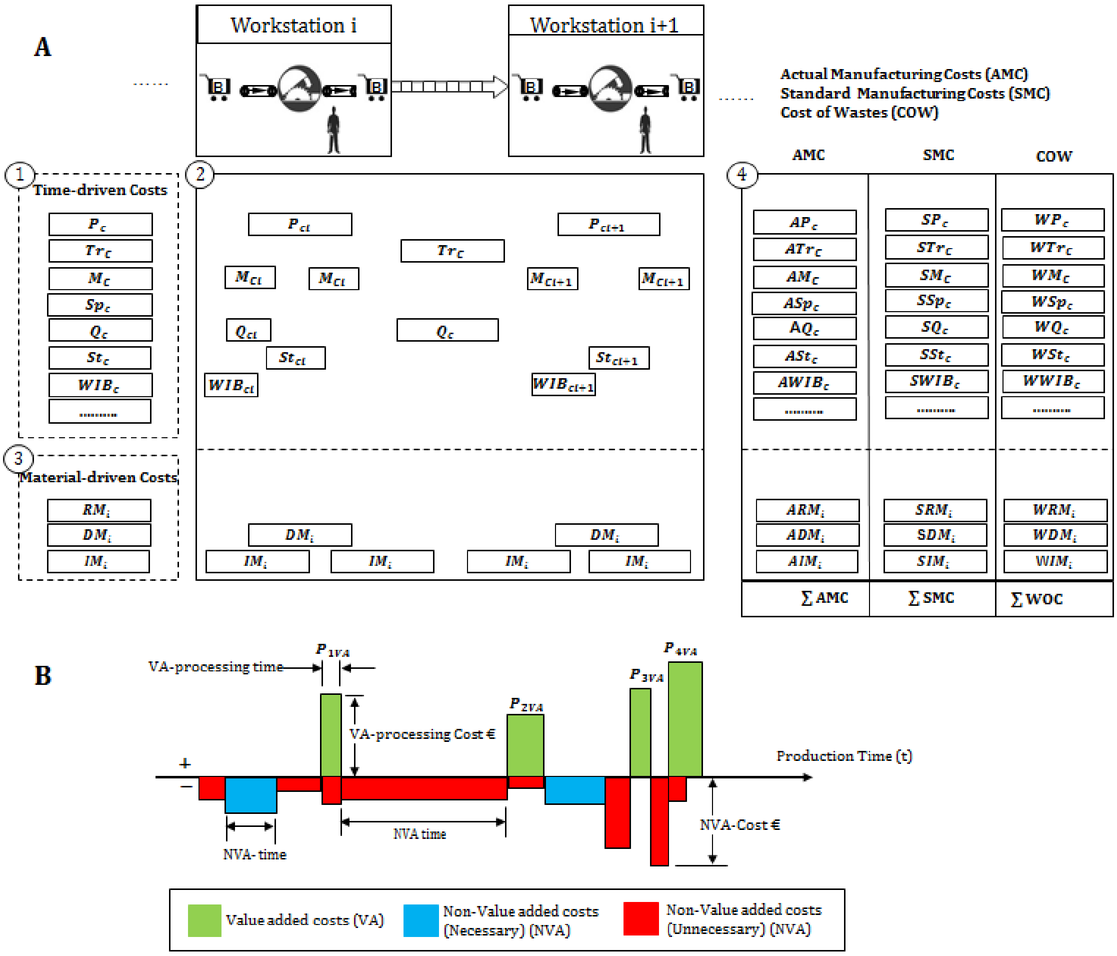


Figure 6.6. Activity-based Costs Analysis along the Value Stream.

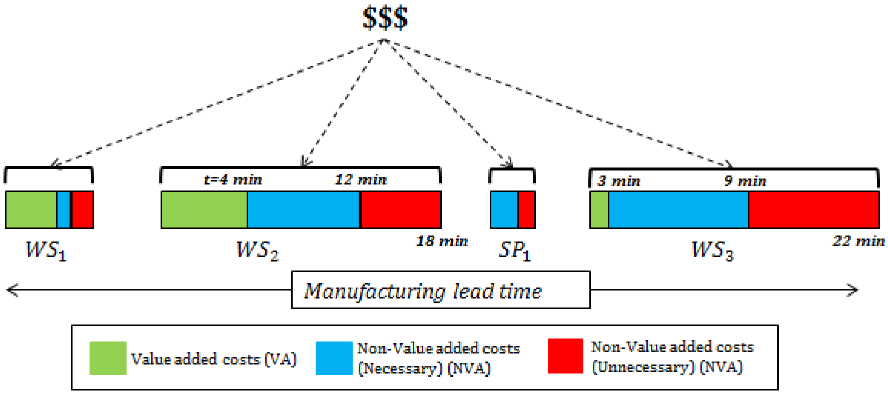


Figure 6.7. Time-based Costs of Value Steam Activities.

To estimate the cost of waste in the AVSM based on the VVSM, we subtract the cost of both AVSM and VVSM as seen in figure 6.6a.

Now, the average cost of AVSM products is presented in equation 9:

$$\text{Average cost of AVSM product} = \frac{\sum_{\mathrm{i}}^{\mathrm{n}} \text{exact cost of individual product}}{\text{final AVSM produced products}} \qquad [9]$$

This cost includes three types of costs (i.e. VA costs, NVA-Necessary costs, and NVA-unnecessary costs). The cost of waste is hidden within the operational production activities represented in the deviation from VVSM. However, there are also additional costs that refer to the non-incurred costs during product flow like the cost of the unused capacities (e.g. Free labor or unused running machines).

6.7. Simulation Model

The simulation model represents an example to demonstrate the feasibility of the developed real-time manufacturing cost tracking method in this chapter and shows how RFID could be used to support its functionality. A hypothetical manufacturing environment is created through ProModel simulation software. Based on the developed costing method, this model shows how RFID real-time data helps track the actual manufacturing costs and measure the monetary impact of the implemented lean tools.

The cost-rate of each cost-driver (e.g. machines, equipment, materials, labors, etc.) which is being utilized during each product-state should be predefined. Practically, this information should be predefined in the VVSM-database. For model configuration in ProModel, the sum of cost-rates of each product-state and other information is presented in figure 6.8 and Table 1. Table 2 presents the operational flow of different types of products (i.e. A, B, C, D, E) passing through several workstations and their processing times.

Table 6.1. Information about the Process Flow and Cost-rates.

Mc_X :	Initial material cost[€ / Item]
Mc_SA :	Sub-assembly cost [€/ Item]
Pc	The cost-rate of the processing at each workstation
T	Transport-state [N(4, 0.1)min]
CR_Tc	25 Ct./min [Cost Rate of Transportation events between workstations]
CR_Mc	2 Ct./min [Cost Rate of the Moving events inside the workstations]
CR_Wxy	0.2 Ct./ min [Cost Rate of all types of waiting, WIB, WTB,WTM, WIQ, etc.]

The impact ratio of lean improvements on the time-segments of MLT (i.e. product-states) is based on a real manufacturing process in an international switchgear manufacturer in Germany; table 3 shows the percentages of reduction in MLT after specific lean improvements have been implemented on the production system of this manufacturer. The SMED and TPM have an indirect impact on the MLT as shown in the results.

Table 6.2. Processes Data for Model Configuration.

Process Parameters for Model Configuration						**Demand rate /min (assumed)**
Product Type	**Processes Flow /Processing time-Random Distributed**					
A	**WS1** N(14,4)	**WS2** N(11,3)	**WS3** N(11,2)	**WS4** U(16,18)	**WS5** T(16,18,20)	Takt = 50 minutes
B	**WS1** N(10,1)	**WS2** T(7,10,12)	**WS32** N(12,2)	**WS4** N(11,2)	**WS5** T(10, 0.5)	Takt = 50 minutes
C	**WS21** N(12,1)	**WS2** N(10,2)	**WS3** U(13,17)	**WS4** T(6,8,10)	**WS5** N(8,1)	Takt = 60 minutes
D	**WS31** N(12,1)	**WS3** U(9,11)	**WS4** N(25,1)	**WS5** U(10,12)		Takt = 30 minutes
E	**WS21** N(6,1)	**WS2** U(9,13)	**WS32** T(7,13,15)	**WS4** N(14,1)	**WS5** N(18,2)	Takt = 45 minutes

For model simplicity, the duration of the product's moving-state inside the workstations is fixed and equal to one minute, the cost rate of the moving-state is 2 Cent/minute. To see the monetary impacts of lean improvements, the simulation includes several scenarios:

- Push system: the model works according to push principles-initial scenario.
- Pull system: the model is configured to work according to pull principles including kanbans, JIT replenishment, line balancing, takt time, heijunka, small lot size and one piece flow.
- Lean tools improvement: a series of lean improvements have been configured in the model according to the real manufacturing process in an international switchgear

manufacturer in Germany, the impact of these improvements on the system performance is considered in terms of time.

The cost-rates can be reduced through lean improvements and cost reduction programs (e.g. minimizing the used materials through implementing design-to-cost concepts, reducing labor time after simplifying the process or utilizing cross-trained operators, etc.). These issues are not discussed in our study.

To represent the functionality of RFID in the simulation model; different variables have been defined to track each product-state along the value stream, for example, the variable (CycleTimeWS_P1A) tracks the duration of the processing-state for product A at the first workstation, (CycleTimeq1_A) tracks the waiting duration in queue at workstation one, the same fashion is followed for the rest of the workstations and product types. The variables (Transport_counter_WTB1_WIB2_B, Transport_time_WTB1_WIB2_B) track the product's transport-state and its duration according to the event's start and end time using the RT-CEP method, in order to incur the corresponding predefined cost-rates on the total cost so far.

For pull system and to meet the customer demand; the load-leveling box is created and assigned at the beginning of each product route. The sequences of the production are as follows: A & B = [A B A B A B A B A B A B.....], D = [DDDDDDDDDDDD.....], C & E = [CCC EEEE CCC EEEE CCC EEEE CCC EEEE...], all products pass through WS4 and WS5. The complete cycle of the load-leveling box for products C and E is 360 minutes.

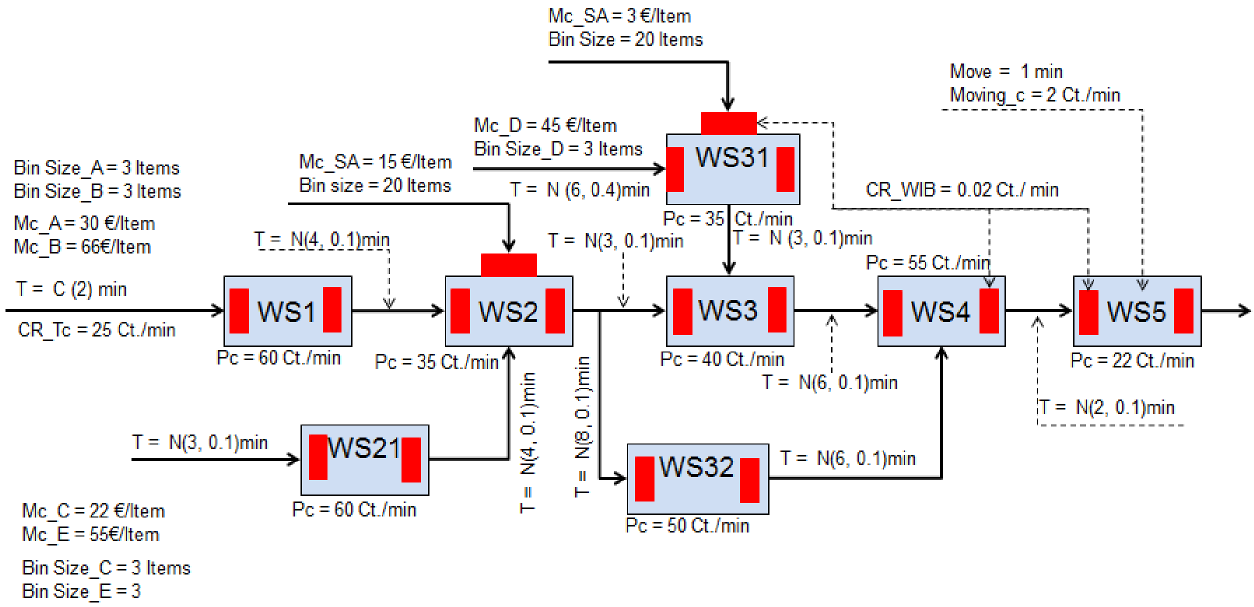


Figure 6.8. Flow Structure of Manufacturing Processes.

Table 6.3. The Impact of Lean Improvements on the MLT.

	Product-state	**Lean improvements ratio in terms of time**		
		Pt	**Tt**	**WIB/WTB/Qt/etc.**
Lean Tools	5S	*20%	20%	These values are changed accordingly in the simulation model
	Andon	10%	20%	
	Standard work	*40%	10%	
	SMED	50% reduction in Setup time		
	TPM	50% Improvement in Availability		
	Poka-Joke	*20%	10%	
*Other product-state are spontaneously reduced like repair-time, rework-related time.				

The simulation model is configured to run 16 hours with a 5 hours warm-up period, the results show how the cost gradually increases while the product flows to the downstream workstations. Figure 6.9 shows how the RFID is able to track the cost developments during the production progress and show it in RT-CTP. ProModel is configured to incur the associated cost-rate once a product-state is detected, then the accumulative costs have been summed and drawn in the RT-CTP.

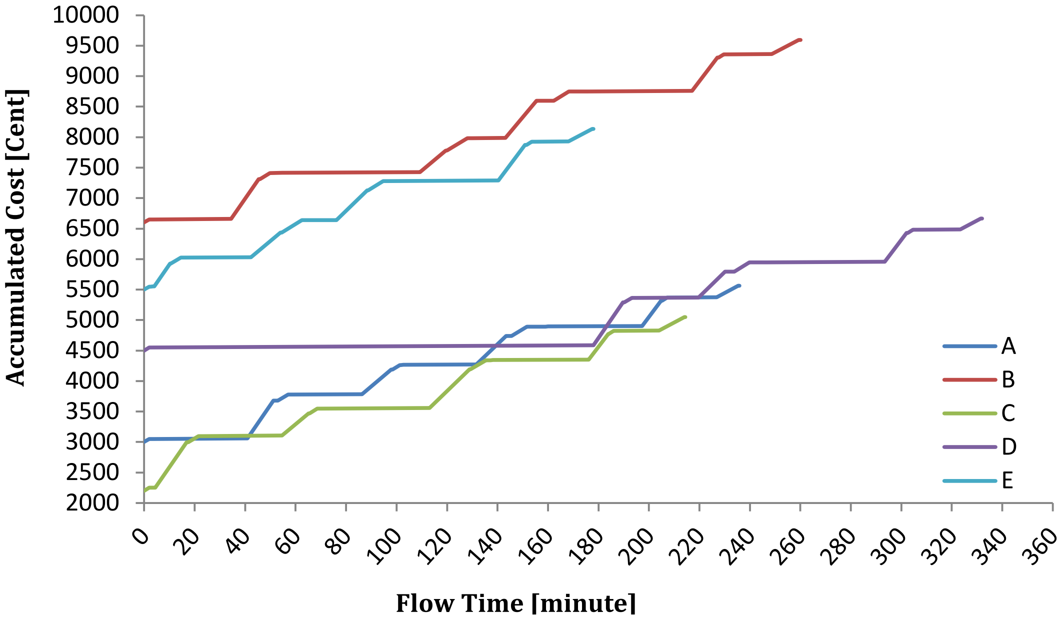


Figure 6.9. Real-time Cost-tracking Using RFID in the Simulation-[Pull Scenario].

To show the monetary impact of individual lean tools; the different lean tool scenarios have been configured in ProModel to represent their accumulated impact on the time and subsequently on the cost. Figure 6.11 shows how RFID can track and measure the monetary impact of each lean tool in the total cost of the product B. The difference in the accumulated impact between the second scenario i.e. 5S scenario and the last scenario i.e. poka-yoke is estimated to reduce 101.09 minutes in the MLT and subsequently reduce 14.20 € in the cost of each part from product type B. Other analysis can be done to evaluate the lean effectiveness from the financial side.

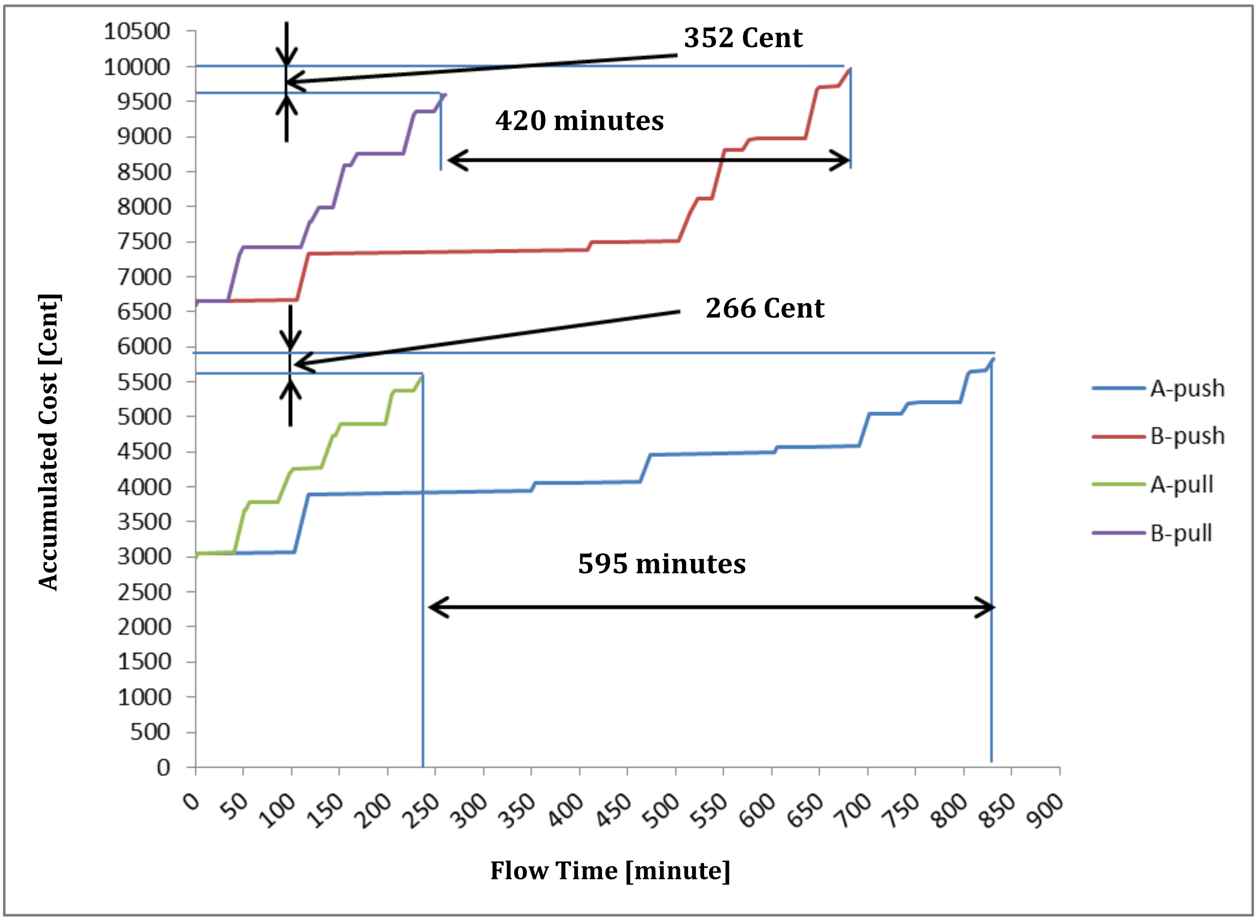


Figure 6.10. Differences between Push-Pull Systems for A and B in Terms of Time and Cost.

For this part of research, the primary goal of the simulation was to prove that the real-time costing method according to event-instances is possible through using RFID data. Moreover, show the monetary impact of lean improvements on the total cost of the products under different scenarios. The average cost of the products can be estimated to monitor the general monetary impact of lean on the overall production system.

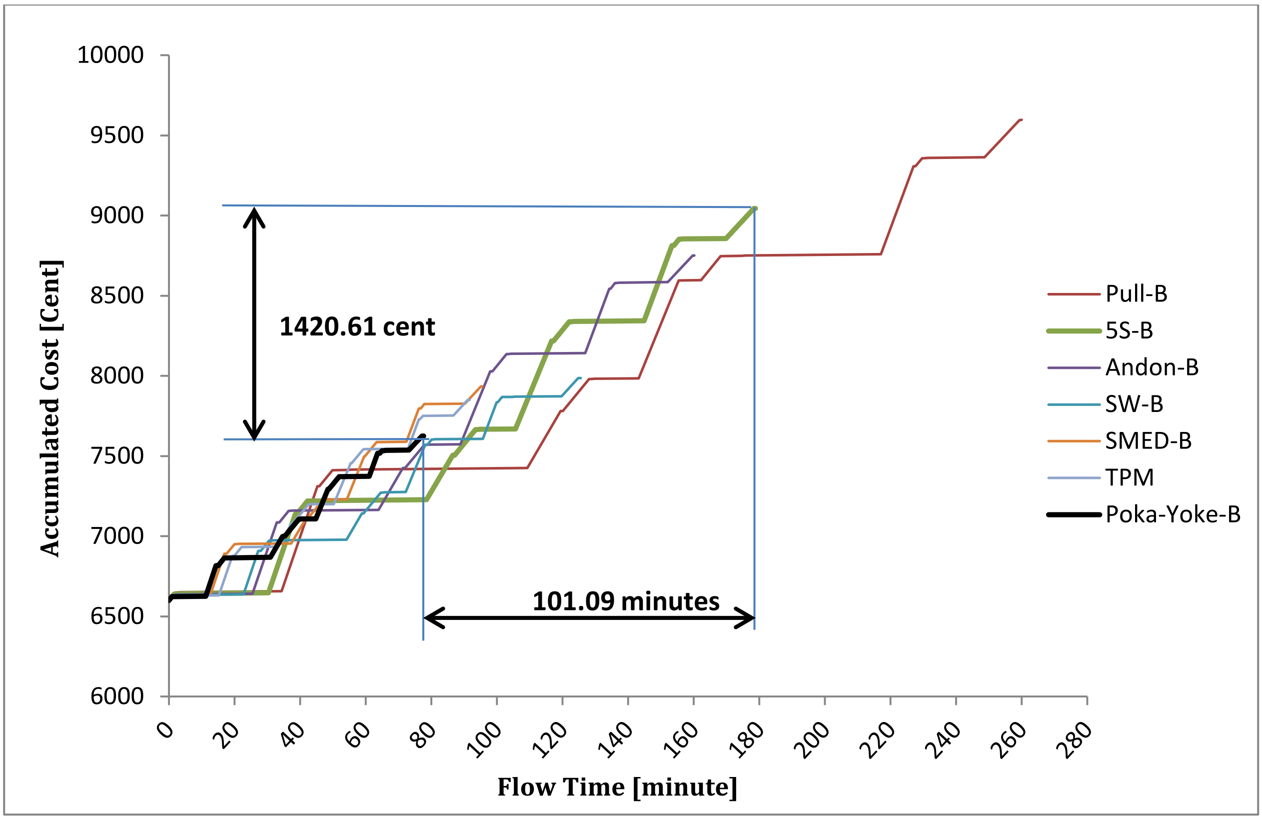


Figure 6.11. The Impact of Gradual Lean Improvements in Terms of Time and Cost.

6.8. Waste-related Cost Analysis and Reduction Methods

In the traditional accounting system, the cost of waste cannot be tracked and usually remains hidden in the overhead costs. This means that a major portion of the product cost is not traceable, and, therefore, the manufactures cannot understand why and where the extra costs are coming from. In this context, the cost of this waste should be estimated to identify its ratio/impact on the total product cost with respect to VA costs. Thus, a complementary framework for a real-time waste cost tracking tool is introduced as part of the RT-MCT module for tracking, analyzing and quantifying the cost of the waste associated with the manufacturing processes. This analysis aims to measure the monetary gap between the current performances and the desired one represented in VVSM.

The cost estimate of waste depends mainly on identifying the causes of each waste which has been discussed in chapter 4, where the waste causes, such as operational incidents and failures, are automatically defined. After that the associated cost of these indecencies and failures will be estimated based on the predefined cost-rates and considered as waste costs.

We proposed to classify the cost of wastes into two types: the first cost is the cost of deviation between the standard cost in VVSM and the actual cost in AVSM represented in the excess consumption of time, material, quality costs and scraps costs; the second cost type is the non-incurred costs where the product does not pass through but it costs money during the production run and its represented in the cost of the unused capacities. The first type can be estimated from this formula: The total cost of waste = (standard Cost of VVSM – actual Cost of AVSM); however, the cost of individual waste is still not specified separately! This is explained in the discussion below showing how RT-MCT can pinpoint which waste type stands behind the extra costs at each time point along the value stream; these waste-related costs are based on operational causes.

6.8.1. Overproduction-related cost

In fact, overproduction causes the major portion of the other types of waste especially excess WIP-inventories. The created inventory utilizes more spaces and spends more time in the waiting-state; it needs more labor and equipment for handling and transporting which may lead to more defects in addition to the hidden defective parts. Moreover, the excess inventory leads to unsmooth material flow which may cause unused capacities, and so on. These NVA states absorb more costs. In traditional accounting systems, these costs are hidden in the overhead costs thereby they are not recognized as extra costs which are incurred due to the NVA activities.

Therefore, the costs of the extra-activities resulted due to the overproduction are tracked through RT-MCT and their cost is estimated and considered as overproduction costs. In other words, the RT-MCT classifies the extra costs as overproduction-related costs if the DVSM detects that excess WIP-products have been produced more than the planned quantity as in the load-leveling schedule in DVSM. Sometimes, if excess inventories accumulate and waiting in front of a workstation is caused due to machine breakdown; in this case the cost of the waiting-state is not related to overproduction. This means that the cost of each waste is separately estimated and the actual monetary impacts are measured and targeted for reduction. Thus, lean improvements aiming to eliminate overproduction should be reflected into additional reduction in the total manufacturing cost.

In the above discussion, we focused on the operational costs resulting from overproduction, but there is another cost associated with overproduction such as the investment-cost where the manufacturers' capital is tied with the inventories (RM, WIPs, and FG) caused by overproducing for a long time, this part is not discussed in this thesis.

6.8.2. Quality/Defective-related costs

Because DVSM is able to recognize the actual status of each product either in its rework-state or its totally defect/scrap-state, the cost value of quality checks and rework activities can be defined and incurred on the product value stream cost pool of the reworked products. This methodology supplies the manufacturers with the rework-related costs. But in case of a totally defective WIP; DVSM is able to track the WIPs up to the point that it becomes defect, and then the cost up to this point is estimated to be considered in the average product cost in equation 9. In this way, the manufacturers can accurately estimate the costs of defective products and the impact those costs have on the other products, which depend on the financial strategy of the manufacturers and how they report and incur these losses on their accounting system.

6.8.3. Over processing - related costs

The product's VVSM includes detailed information about the production processes such as specifications, durations, parameters, BOM, work instructions, and other information which is uploaded from the ERP level before the product's VVSM is released to PSF. Therefore, any deviation in processing-state durations implies unnecessary utilization of resources or that excess materials are being consumed (i.e. exceeds the standard processing time at a specific machine or perform an undefined process) which means machining or processing beyond the required standards. This status will be captured, quantified, and translated into costs to be incurred as over-processing-related cost.

6.8.4. Moving/transportation–related costs

Normally, the routes and destinations of each product are pre-defined in the VVSM on DVSM. Thus, during the VVSM actualization any WIP transporting process to the wrong destination will be captured and a warning signal will be sent to the LO from DVSM. But in this case more time and thus cost is wasted and incurred into the cost pool as waste-related cost. Moreover, any implementation of lean improvements to reduce the total transportation distance travelled by the product along the value stream will be evaluated directly through RT-MCT. However, any excess material moving and transporting (i.e. material handling) due to excess in WIP inventory is considered as inventory or overproduction-related costs not as transporting-related costs.

6.8.5. Inventory-related costs

The monitored excess WIP-inventories at different locations along the value stream lead to more costs on the products. The inventory-related costs that are incurred while in the waiting-state include excess transportation and movement cost-rates, facility cost-rates, container cost-rates, cost of the caused damage and losses that occur during transportation, and so on. Based on the type of business, the inventory related cost-rates can be summarized for instance under the WIP holding cost-rate.

This cost will demonstrate for the manufacturers how the high inventory/WIP level significantly affects their total products' cost directly in addition to its costly consequences (e.g. hidden quality problems). The recognition of this cost will encourages them to continuously monitor their buffer spaces and reduce the amount of occupied space used by each value stream in order to reduce the WIP turnover period.

As mentioned above, the waiting-state contributes to extending the freezing time of the capital in terms of materials before it is recovered through sales, which shows the value of time.

6.8.6. Unused capacity -related costs

The resources idleness-state (i.e. unproductive-state) occurs when the available capacities/resources under certain circumstances such as unbalanced lines continue to consume money and generate more costs while they do not add value to the product (e.g. starvation of running machines like a furnace in a metal industry, labor, under-utilization, etc.), this cost is called unused capacity related-cost and it is 100% waste. The traditional accounting system fails to identify the cost of the unused capacity and its impact on the individual products. This cost remains hidden in the overhead costs, since managers do not have sufficient information to see where the extra costs originated from [RFC13].

According to the developed framework, the RT-CES detects which object is in an idleness-state during the production run. The event data set will then be sent to the RT-MCT system to separately estimate the cost of the unused capacity of each tracked object based on its cost-rate.

Based on RT-MCT system; the costs of activities are allocated based on the product-states along the value stream; while the unused capacity related-costs remain unallocated to the product because no product benefits from their cost-drivers. Therefore, this cost will be incurred according to the financial policy of the manufacturers on the products of the released VVSM to estimate its impact on the total product cost and for pricing issues.

This cost quantifies the monetary value of the wasted unused-capacities to demonstrate for the manufacturers how the under-utilization of resources will impact the product cost and their prices.

6.9. Lean Improvements for Cost Reduction Based on DVSM

Lean manufacturing aims to increase profits by reducing manufacturing costs through applying lean tools and practices to eliminate waste [SS11]. As discussed in the previous chapters, DVSM possesses powerful features that are able to support the lean tools and practices to eliminate waste; here we briefly discuss how DVSM modules contribute to reduce the costs, for examples:

- DVSM through RT-SPC module supports the production according to the TAKT-time and load-leveling schedule, which in its turn prevents the overproduction and thus excess inventories and the resulting costs (i.e. excess transport, moving, waiting and holding costs beside space utilizations costs).
- DVSM through the RT-TPM system is able to track and monitor the status of the machines and equipment. Furthermore, it is able to reduce the average downtime and thus the resulting costs (i.e. waiting time and space utilization costs)
- DVSM through RT-SPC module and RT-DPG module supports JIT replenishment and release of the required materials/components /subassemblies to the point of use for the manufacturing process, this is accomplished (i.e. the right material at the right place and the right time with the right quantity) through real-time synchronization between production activities which enhance the JIT practices at all levels, reduce the needed spaces and side line inventories, and thus the resulting cost.
- DVSM through the kaizen module is able to detect the improvement opportunities, in this case the manufacturers are able to continuously track the duration of the processing-state of the products because it is the most costly state and see if any PO frequently finishes in less time, then standardize his work movements for others. This will reduce the cost of the processing-state as well as reduce the materials' investment time.
- In general, DVSM through all its modules reduce the incidence and failures which are considered as the variability causes and lead to production disturbances like unused capacity and thus an increase in the cost.

The cost of materials represents a big challenge for many manufacturers; the reduction of the material cost is supported also in the DVSM during the VVSM-phases where the Design-To-Cost concepts should be taken into consideration to reduce the cost of the material under the same performance and quality level, such as replacing the expensive materials with cheaper material and searching for cheaper suppliers.

The impact of lean improvements on the total cost can be estimated and monitored; figure 6.12a shows an example of the reduction in the cost of waste separately, while the impact of this reduction on the total product cost is visualized on the RT-CTP, figure 6.12b shows this based on the simulation model.

Finally, if the causes and their associated costs are defined and improvements are applied; a cost reduction due to the improvements should be mirrored on to the value stream cost pool, otherwise the improvements are invalid.

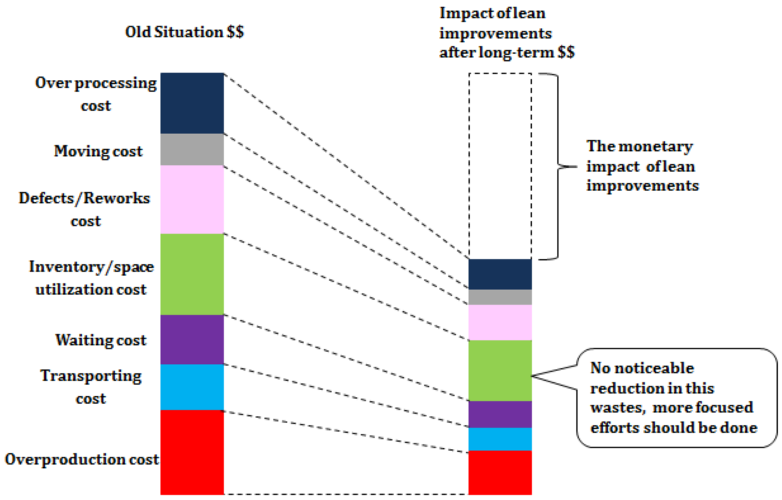


Figure 6.12a. Impact of Lean Improvements on the Costs of Individual Waste Types.

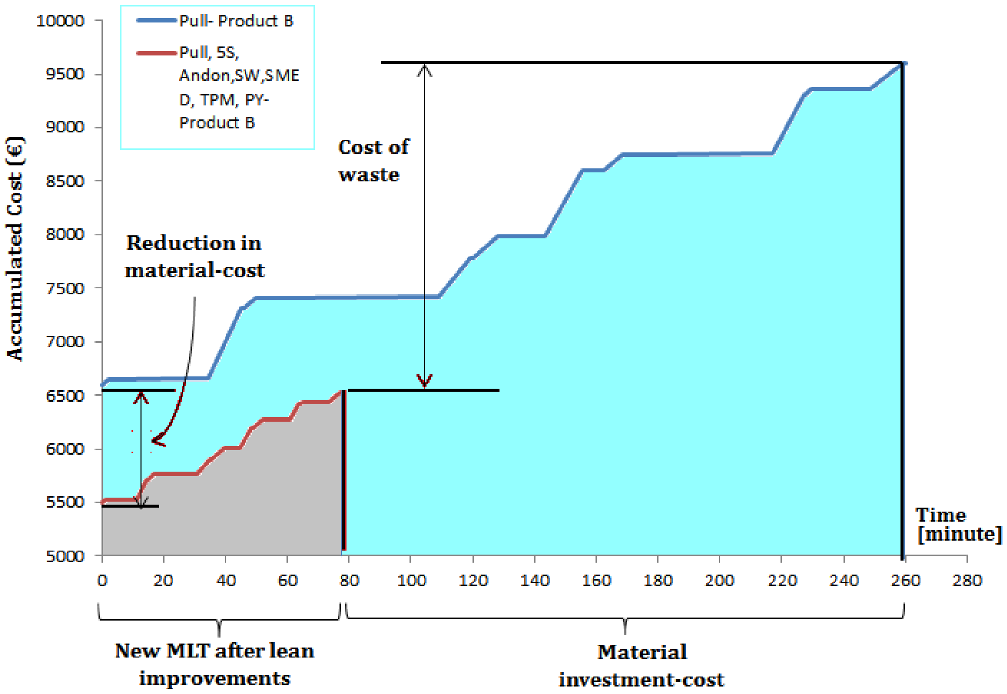


Figure 6.12b. Impact of Lean Improvements Displayed on the RT-CTP.

6.10. Conclusion

Because today's global markets force the manufacturers to work in a high customization production environment, the cost tracking of the individual product becomes a very important key element of lean manufacturing measurements.

This part of research highlighted the financial setbacks in a traditional VSM which does not contain any details about manufacturing costs of individual products and its accumulation during the product flow. This chapter has discussed the concept of real-time manufacturing cost tracking system for lean purposes. The framework addressed how the RFID data is used to track the cost development of individual products in real-time during the progress of the production operations.

RT-MCT module enable the manufacturers to identify the root causes of redundant costs and pinpoint the most costly root causes and locations , so they are targeted with the highest priority to be eliminated. Finally, the impact of implementing any lean tool can be checked, evaluated and mirrored in terms of a cost-time profile.

As a result, RT-MCT adds a new powerful feature to the DVSM through bridging the operational and financial views in one pool; the potential benefits of this module are listed below:

- Monitoring the costs of individual processes and the entire processes included in the value stream as well as identifying and distinguishing between the VA and NVA costs.
- Monitoring the current operational performance in terms of cost during the production progress.
- Monitoring the impact of individual and gradual lean improvements on the financial performance using cost-benefit analysis.
- Monitoring the costs of the defective WIPs up to the point of becoming defect.
- Monitoring the costs of the reworks of non-conforming products.
- Enhance manufacturing daily operational decisions depending on cost-benefits analysis.
- Monitoring the financial consequences due to any necessarily adjustments or changes in the production either technical or operational.
- Help to create financial scenarios for custom orders' bidding based on actual value stream cost analysis (the old cost analysis could help determine the cost of new products during the process design).

- Contribute to involving the accounting personnel in lean enterprises. This will create a weather of integration between the people working in operational areas and accounting personnel.
- Accurately determine production labor costs and the costs which are hidden in the overhead costs. This refers to incorrect accounting systems where the unseen costs by accounting personnel are classified under overhead costs.
- Identify the most costly activities as well as the most wasteful NVA activities so they are targeted with the highest priority to be corrected or eliminated.
- The manufacturers will realize the power of time and its impact on the total cost.
- For strategic and competitive goals, RT-MCT helps the manufacturer to precisely split the product total cost in terms of individual processes; materials, components, labor, tooling, and other drivers. The previous products cost-splitting data are very helpful during the development and design phases of new products as well as process design phase to meet the market prices and to answer the core question *"what is the maximum allowable cost of our product?"*
- Estimate the ratio of materials-usage cost to time-driven cost along the value stream.
- Prepare the financial statements precisely by allocating all manufacturing costs to the AVSMs' products in the period in which they have been produced.

These measures are used to reflect the lean manufacturing dimensions and hence more reduction in the final manufacturing cost.

CHAPTER 7
Conclusion and Future Research

This dissertation proposed concepts of a smart real-time lean-based IT mechanism for next-generation manufacturing systems.

7.1. Conclusion

The thesis has introduced a systematic explanation on how RFID captured real-time data can be effectively utilized to continuously enhance and support the functionality of lean practices and tools, furthermore, keep them alive and effective in today's high customized manufacturing environments

The dissertation starts with a short overview about lean manufacturing and the major challenges that influence the success of lean transformation in high complex job-shop manufacturing 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, specification, quantities, wide variety of components, smaller-lot size, etc.).

This work also reviewed the importance of real-time IT systems in lean manufacturing, and concluded that an efficient lean manufacturing environment without IT software support has become unthinkable in today's manufacturing systems. In this context, due to the special characteristics and superior capabilities of RFID, it has been suggested to be the major enabler to support such a real-time IT system with real-time production data. However, it has been found that RFID remains questionable and doubtable and manufacturers are still quite hesitant to adopt it in their manufacturing systems.

Therefore, this research addressed a two-dimensional problem; firstly, the challenges and limitations of lean manufacturing in today's manufacturing systems, where lean has become inefficient and difficult to be practiced; and secondly, the adoption of RFID in manufacturing, since there is almost no standard study that comprehensively and systematically discuss the best practices of RFID in manufacturing systems.

The suggested idea to address this problem comes from the fact that Lean boundaries extend to cover all manufacturing aspects through a diversity of powerful practices and tools that are mutually supportive and synergize well together to effectively reduce wastes and maximize value. Therefore, this thesis introduces a solid basis for a standard framework of a digitalized smart real-time lean-based mechanism in order to describe the best practices of RFID technology within lean manufacturing boundaries in order to achieve an intelligent, comprehensive, integrated, and holistic real-time lean-based manufacturing system.

The integration between RFID and lean practices and tools has been derived from the main concepts of traditional VSM, where the time-based flow is greatly emphasized and considered as the most critical success factor of lean.

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

To describe the best practices of RFID technology within lean manufacturing boundaries, several smart real-time lean-based modules concerning lean targets have been developed, including:

➔ Module 1: “Real-Time Analysis of MLT” tracks the manufacturing lead time (MLT) of an individual product along the value stream in real-time, in order to identify its time-components, and accordingly measure the leanness of the production environment in terms of time.

➔ Module 2: “Smart Real-Time Waste Analysis” (RT-SWA) identifies the criticalities, weaknesses and the most wasteful activities in each product-state along the value stream, which influence the duration of the MLT. This kind of mechanism is proposed to make the hidden root-causes of wastes immediately visible through analyzing the event-instances in real-time, so that they can be avoided or treated directly.

➔ Module 3: “Real-Time Dynamic Re-Prioritizing Generator” (RT-DPG) aims to move the manufacturers from a centralized to a decentralized decision-making mode with appropriate levels of intelligence to improve the production performance based on the current status of the interactive smart-objects along the PSF. RT-DPG runs in real-time to avoid a freezed production schedule. Through real-time monitoring of the continuous changes in dynamic production environments, the RT-DPG reprioritizes the waiting products at local storage points along the value stream to mitigate or avoid the impact of sudden disruptions, unexpected incidents and system abnormalities in order to reduce the wastes and NVA activities, as well as, give more flexibility for manufacturers in order release dates, times, and quantities. Therefore, companies become able to achieve higher customer satisfaction and quickly respond to the fluctuation in market demand. The effectiveness of this framework has been validated through a simulation model using ProModel.

➔ Module 4: Real-time Smart Production Control (RT-SPC) smartly controls the material flow between workstations and tightly synchronizes the activities to meet the scheduled production and avoid NVA time. Moreover, in order to support the production system and improve its robustness instead of making it easier to live with the problems; the developed RT-SPC is proposed to be equipped with supplementary RT-LCRs to quickly react or deal with sudden disruptions, incidents and unexpected internal or external disturbances in order to reduce their impacts on the overall performance and keep the material flow smooth.

➔ Module 5: Smart Lean Method Tools (Smart-5S, Smart-Standardized Work, Smart Poka-Yoke), prompt the workers to follow lean standards during daily production runs in order to support the effectiveness of the overall lean system. A framework of smart 5S, standardized work, and poka-yoke has been proposed to be implemented in the switchgear manufacturing company. The smart lean method tools are expected to significantly reduce the MLT through reducing the duration of the individual MLT-time components such as reducing the setup-state, processing-state, transport-state, maintenance-state, etc., through eliminating the time wasted searching for the required tools and equipment for each state, or waiting to solve interruptions.

➔ Module 6: Real-time Manufacturing Cost Tracking System (RT-MCT) module is used to identify the root causes of redundant costs and pinpointing the most costly root causes and their locations, so they are targeted with the highest priority to be eliminated. Furthermore, this costing method mirrors the monetary impacts of implementing lean improvements at various value stream stages in today's mass-customization production environments. The system presented is validated through ProModel simulation software along with extensive calculations, moreover, a demo software using java has been developed.

All modules are running in real-time on DVSM-LPTE and they are equipped with the suitable RT-LCRs, that describe how the RFID captured data can be utilized in the best manner to smartly support LPTs through their modules during daily production runs to keep the lean system alive and effective.

As aforementioned, the concepts of this thesis has been demonstrated through contracting several RT-LCRs algorithms based on CEP have been constructed to prove how the RFID data can be utilized to support lean practices. The feasibility of the constructed RT-LCRs of the modules 3 and 6 have been validated through two simulation models using ProModel as well as to validate the concepts of module 5, a practical case study has been proposed to be implemented in the switchgear manufacturer.

As a result, the DVSM can bring revolutionary improvements in traditional lean manufacturing to face the challenges in today's manufacturing environment. In this regard, the potential results of this framework include the increase in flexibility and adaptability of lean tools and practices in anticipation of the current challenges of lean manufacturing, as well as maintaining lean practices and tools; making sure that they are kept alive and effective for a better level of productivity and effectiveness, regardless of the changes caused under different circumstances.

7.2. Future Research

This dissertation opens a new horizon for future research:

- ➔ This framework could be further enhanced, through standardizing the CEP-rule semantics for constructing the RT-LCRs that can be easily translated into any programming language (code). A complex event compiler could be used to check the validity of a RT-LCRs code according to the information in the meta-data, as well as to conduct syntactical and lexical analysis and corrections of the RT-LCRs expression.
- ➔ Concerning RT-DSG, this work introduced simple RT-LCRs to explain and clarify the concept of this module. Therefore, more detailed RT-LCRs should be addressed in this field, which could be another possible research direction in the area of lean-based smart factories. For instance, the RT-LCRs should consider the interdependencies of queues in a queuing network, since any kind of change in one queue may result in a fully different performance record of the entire queuing network.

➔ Another possible future research is the ability to tie the DVSM with simulation software. Thus, the lean 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.

➔ The elimination of waste in lean manufacturing must not produce other kinds of wastes like extra transportation or movement in production systems. Therefore, there is a need to build RT-LCRs based on optimization tools to avoid the creation of extra wastes.

➔ Another possible extension of this study is to develop further lean-based modules such as TPM, SMED, Kaizen-event modules based on the real-time data.

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