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Sachin Karadgi

A Reference Architecture for Real-Time Performance Measurement

An Approach to Monitor and Control Manufacturing Processes

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To my daughter Sanvi

Foreword

The region around Siegen has many metalworking enterprises (e.g., Gontermann-Peipers GmbH) and machine builders (e.g., Achenbach Buschhütten GmbH). The metal working enterprises belong mostly to the class of Small- and Medium-sized Enterprise (SME) that caters to automotive and machine builders. Due to globalization, these enterprises are facing stiff competition, especially over costs, from the developing world, like Brazil, India, and China. Additionally, these enterprises have to adhere to stringent requirements imposed by their customers and government regulators. For instance, an enterprise has to support traceability of components so that the costs incurred to a supplier during a recall are minimized. Hence, these enterprises need to enhance their existing monitoring and control of manufacturing processes in order to maintain their competitive advantage.

According to this context, management and control of an enterprise can be hierarchically classified into different levels—strategic, tactical, operational, and resource. Additionally, an enterprise can be viewed from different scientific perspectives—management science, control engineering, and information science. These levels as well as perspectives are crucial for the monitoring and control of manufacturing processes. The research focus at Business and Information Systems Engineering (BISE) is on Enterprise Integration (EI), Real-Time Enterprise (RTE), and Performance Measurement Systems (PMS), especially closing the feedback loop across different enterprise levels in real-time.

There exist numerous concepts (e.g., Event-Driven Architecture (EDA), RTE), technologies (e.g., Manufacturing Execution Systems (MES), Complex Event Processing (CEP)), methodologies (e.g., Resource Consumption Accounting (RCA)), and standards (e.g., IEC 62264, VDI 5600) that address particular issues in the aforementioned research areas. Subsequently, a reference architecture has been developed to integrate and adapt the concepts, technologies, methodologies, and standards at BISE. The architecture encompasses numerous components that elaborate on realizing EI, accomplishing traceability, and performing product analysis, among others.

Manufacturing enterprises employ real-time operational metrics (see VDMA 66412 and ISO 22400) for monitoring and control of manufacturing processes. The same enterprises have issues computing the financial metrics, which are mostly computed offline. Thus, the reference architecture details financial metrics that are close to the shop floor and its computation in real-time. Furthermore, a performance positioning chart has been envisioned that links the financial and operational metrics in real-time, which provides crucial inputs for decision making to plant managers and supervisors.

The reference architecture has been implemented and validated in Ohm & Häner Metallwerk GmbH & Co. KG., a sand casting foundry. The foundry was commissioned in October 2008 and has a state-of-the-art production line supported with numerous automated machines. The implemented system and its functionalities are available to enterprise members based on their roles and responsibilities to monitor and control the production line, especially in real-time.

This book at the crossing of several sciences like business administration, engineering, and information systems may contribute to further understanding and development of the concept of financial and operational metrics, and their linkage in real-time to manufacturing enterprises.

Siegen, April 2014 Manfred Grauer

Preface

Today's manufacturing enterprises cater to multiple customers with necessary competencies—capabilities and capacity. These enterprises must adhere to low volume and high mix production schedules, i.e., mixed model production, especially to fulfill the objectives of Just-in-Time (JIT), and kanban, among others. These enterprises are facing ever-increasing pressure from internal and external environments to maintain their competitive advantage. For instance, enterprises are internally facing increasing pressure to manufacture complex products with high quality, reduced lead times, low cost, and low quantity, and at the same time, increased shareholders' profitability. Likewise, the enterprises' external business environment is highly competitive, volatile, and driven by uncertainties.

To overcome these concerns, manufacturing enterprises need to reinforce their existing monitoring and control of manufacturing processes with the aspirations to achieve a higher degree of transparency, flexibility, and adaptability. In this regard, manufacturing enterprises initiate continual improvement programs. Additionally, decision making is a complex task requiring the right information, at the right time, and in the right context.

Numerous performance measurement systems have been elaborated, especially from a strategic perspective, to satisfy the aforesaid requirements. These systems highlight the importance of non-financial or operational metrics, and linking the financial and operational metrics, among others. However, enterprise members have varying requirements related to performance metrics depending on their roles and responsibilities. The financial reports are generated according to the enterprise reporting cycle, and contain financial jargon, which is difficult to interpret by plant managers. Likewise, accountants have a challenging task to consolidate the real-time operational metrics into financial reports.

The financial and operational metrics are two sides of the same coin—both are essential for monitoring and control of manufacturing processes. In contrast to operational metrics, research to compute the financial metrics in real-time has not garnered the required attention, which has resulted in inadequate linkage of financial and operational metrics in real-time. Subsequently, enterprises will have issues in measuring the effectiveness of process improvement programs, and the decision making will not be based on facts.

The book presents a reference architecture that has been developed at the Business and Information Systems Engineering (BISE), University of Siegen to enable enterprise integration. An integrated enterprise can be considered a building block toward partially realizing the above stated aspirations. The building block shall be fostered to accomplish the computation of financial and operational metrics in real-time. The financial metrics considered are more meaningful from the shop floor perspective. Furthermore, the concept of linking financial and operational metrics in real-time is elaborated with an aim to provide a comprehensive view of an enterprise. The reference architecture and the concepts of metric computation and their linkage are based on interdisciplinary fundamentals, technologies, and standards.

Acknowledgments

This book is a result of my research carried out at Business and Information Systems Engineering (BISE), University of Siegen. I am greatly indebted to my colleagues at BISE and MESA Metrics Working Group, project partners, friends, and family for helping to shape my thinking around the area of Enterprise Integration (EI), Manufacturing Execution Systems (MES), and Real-Time Enterprise (RTE).

I would like to first thank my Prof. Manfred Grauer for providing me with an opportunity to carry out research at BISE. I greatly benefited from his advice in the aforementioned areas. Additionally, I am thankful to Prof. Grauer for allowing me to participate in the activities of MESA Metrics Working Group, and attending numerous international conferences, which enabled me to enrich my knowledge. The research was mainly possible due to the AutoEDA project sponsored by Ohm & Häner Metallwerk GmbH & Co. KG., Olpe, Germany. I am indebted to the management and employees of Ohm & Häner, especially to Ludger Ohm, Georg Dieckhues, and Jürgen Alfes, for going ahead with the AutoEDA project even during the financial crisis of 2008.

I would like to thank Walter Schäfer for his guidance during the formative years at BISE and during the execution of the AutoEDA project. I cherish my collaboration with Daniel Metz while working on AutoEDA and MOLD-CONTROL projects and writing research articles. Along with Daniel, I had a wonderful association with Ulf Müller, who introduced me to similarity search algorithms. Apart from work, I had a wonderful time with Daniel and Ulf. Daniel and Ulf helped me and my family to adjust to the German way of life, especially dealing with bureaucracy.

I would like to acknowledge Matthias Dietrich from Heinrich Wagner Sinto Maschinenfabrik GmbH for his guidance and support during the execution of the AutoEDA and MOLD-CONTROL project. I would like to thank Almat Reusch for his valuable contribution in writing EPL statements to compute different types of costs. Finally, I am grateful to my current and former colleagues at BISE who supported me in my research activities directly or indirectly, including Annette Wiebusch, Anke Schüll, Dominik Seiler, Frank Thilo, Julian Reichwald, Michael Seiler, Ralf Drier, Thobias Pontz, and Thomas Barth.

I am a member of Manufacturing Enterprise Solutions Association (MESA) International. Since October 2011, I have been actively participating in the activities of MESA Metrics Working Group and its subgroups, especially ISO TC 184/SC 5/WG 9 and Metrics Maturity Model. During my association with MESA Metrics Working Group, I was able to learn and test my knowledge, and get a totally different perspective on many of the sub-tasks of my research. I am grateful to my colleagues at MESA Metrics Working Group, especially David McKnight, John Horst, John Jackiw, and Julie Fraser.

I would like to thank my friends for their logistic support, especially Bharat Karanth, Sachin Arora, Saju Adayapurath, and Sudhir Neginhal. The research and subsequent book would not be possible without the indispensable and unconditional support, motivation, and love provided by my family, especially my parents and brother. I am forever grateful to my wife, Abhilasha, for making suitable adjustments in her life so that I could pursue my research. Finally, I would like to thank my little daughter, Sanvi, for forcing me take a break from work, thereby helping me to relax and think more clearly.

Siegen, April 2014 Sachin Karadgi

Contents

Acronyms

6σ	Six Sigma
ABC	Activity-Based Costing
ABC/M	Activity-Based Cost Management
AI	Artificial Intelligence
API	Application Programming Interface
ARIS	Architecture for Integrated Information Systems
B2MML	Business to Manufacturing Markup Language
BatchML	Batch Markup Language
BISE	Business and Information Systems Engineering
BOM	Bill of Material
BOR	Bill of Resources
BPR	Business Process Reengineering
CAD	Computer Aided Design
CEN	European Committee for Standardization
CEO	Chief Executive Officer
CEP	Complex Event Processing
CFO	Chief Financial Officer
CIMOSA	Computer Integrated Manufacturing Open System Architecture
COPQ	Cost of Poor Quality
CQL	Continuous Query Language
CRM	Customer Relationship Management
CSR	Corporate Social Responsibility
DCS	Distributed Control System
DFD	Data Flow Diagram
DIN	Deutsches Institut für Normung/German Institute for Standardization
DMAIC	Define-Measure-Analyze-Improve-Control
DPMs	Dynamic Performance Measures
EAI	Enterprise Application Integration
EDA	Event-Driven Architecture
EFQM	European Foundation for Quality Management
EI	Enterprise Integration
EMA	Environmental Management Accounting
EP	Event Processing
EPA	Event Processing Agent

EPC	Event-Driven Process Chain
EPL	Event Processing Language
EPN	Event Processing Network
ERD	Entity Relationship Diagram
ERP	Enterprise Resource Planning
FA	Financial Accounting
FASAB	Federal Accounting Standards Advisory Board
FIFO	First In, First Out
GAAP	Generally Accepted Accounting Principles
GERAM	Generalized Enterprise-Reference Architecture and Methodology
GHG	Greenhouse Gases
GIM	GRAI Integrated Methodology
GMP	Good Manufacturing Practice
GPK	Grenzplankostenrechnung/Marginal Planned Cost Accounting
GUI	Graphical User Interface
HMI	Human Machine Interface
HMS	Holonic Manufacturing Systems
IASB	International Accounting Standards Board
ID	Identification
IDE	Integrated Development Environment
IDEF	Integrated Definition for Function Modelling
IEC	International Electrotechnical Commission
IFAC	International Federation of Accountants
IP	Internet Protocol
ISA	Instrumentation, Systems and Automation Society
ISO	International Organization for Standardization
IT	Information Technology
JIT	Just-in-Time
KDD	Knowledge Discovery in Databases
KPI	Key Performance Indicator
KRI	Key Result Indicator
MA	Managerial Accounting
MAS	Multi-Agent Systems
MES	Manufacturing Execution Systems
MESA	Manufacturing Enterprise Solution Association
MFCA	Material Flow Cost Accounting
MOM	Manufacturing Operations Management
MRP	Material Requirement Planning
MRP II	Manufacturing Resource Planning
OCS	Open Control System
OEE	Overall Equipment Effectiveness
OEM	Original Equipment Manufacturer
OFE	Overall Factory Effectiveness
OLE	Overall Line Effectiveness
OPC	OLE (Object Linking and Embedding) for Process Control

OTE	Overall Throughput Effectiveness
PAF	Prevention-Appraisal-Failure
PAS	Public Available Specification
PDCA	Plan-Do-Check-Act
PERA	Purdue Enterprise Reference Architecture
PI	Performance Indicator
PLC	Programmable Logic Controller
PLM	Product Lifecycle Management
PMS	Performance Measurement System
PRM	Purdue Reference Model
RBS	Rule-Based System
RCA	Resource Consumption Accounting
RI	Result Indicator
ROA	Return on Assets
ROI	Return on Investments
ROQ	Return on Quality
SCADA	Supervisory Control and Data Acquisition
SCM	Supply Chain Management
SCOR	Supply Chain Operations Reference
SME	Small- and Medium-sized Enterprise
SMED	Single-Minute Exchange of Die
SOA	Service-Oriented Architecture
SOAm	Service-Oriented Architecture in manufacturing
SPC	Statistical Process Control
SQL	Structured Query Language
STEP	Standard for the Exchange of Product Model Data
TDABC	Time-Driven Activity-Based Costing
TQM	Total Quality Management
UML	Unified Modeling Language
VDI	Verein Deutscher Ingenieure/The Association of German Engineers
VDMA	Verband Deutscher Maschinen- und Anlagenbau/The German Engineering Federation
WCF	Windows Communication Foundation
WIP	Work-in-Progress
XML	eXtensible Markup Language

Abstract

Today's manufacturing enterprises cater to multiple customers with necessary competencies—capabilities and capacity. They must adhere to low volume and high mix production schedules. Nevertheless, these enterprises are facing ever-increasing pressure from internal and external environments to maintain their competitive advantage. To overcome these concerns, a manufacturing enterprise needs to reinforce its existing monitoring and control of manufacturing processes, with aspirations to achieve a higher degree of transparency, flexibility, and adaptability.

Decision making is a complex task requiring the right information, at the right time, and in the right context. Furthermore, enterprise members have varying requirements depending on their roles and responsibilities. Numerous performance measurement systems have been elaborated to satisfy the aforesaid requirements. These performance measurement systems stress the importance of financial and non-financial/operational metrics. The financial reports and corresponding financial metrics are generated according to the enterprise reporting cycle (i.e., offline), and contain financial jargon, which are difficult to interpret by plant managers. Likewise, accountants have challenging tasks to consolidate the real-time operational metrics into financial reports.

The financial and operational metrics are two sides of the same coin—both are essential for monitoring and controlling manufacturing processes, but from different perspectives. Research to compute and link the financial and operational metrics, especially, in real-time, has not garnered the required attention. The presented research attempts to integrate the enterprise across different enterprise levels and departments, which can be considered as a building block toward partially realizing the stated aspirations. The building block will be fostered to accomplish the computation and linkage of financial and operational metrics in real-time, and to provide a comprehensive view of an enterprise.

Keywords Complex event processing · Managerial accounting · Manufacturing execution systems · Performance measurement · Resource consumption accounting

Chapter 1
Introduction

Manufacturing enterprises, especially those categorized as Small and Medium-Sized Enterprises (SMEs), play an important role in the economy and society. These enterprises need to constantly innovate to sustain their competitive advantage. However, they are facing threats from internal and external environments. Subsequently, it is crucial to monitor and control their manufacturing processes; to this end, performance measurement plays an important role.

1.1 Motivation

Today's enterprises are internally facing an increasing pressure to manufacture complex products with high quality, reduced lead times, low cost and small lot size, and at the same time increase shareholders' profitability. The product portfolio offered by the enterprises has broadened, i.e., through variety and customization [109], with the introduction of build-to-order, engineer-to-order, one-of-a-kind or mass customization strategies. Consequently, the product lifespan has been drastically reduced [109]. This has forced the enterprises to design modular products, which can be used across different product variants [43], with an attempt to realize high volume and low mix production schedules.

Likewise, the enterprises' external business environment is highly competitive, volatile and driven by uncertainties [127, 141]. Customer preferences, desires and loyalty to products are changing rapidly (see ISO 9000 [127]). The government regulatory and standards bodies impose stringent legislations and legal regulations that are difficult to comply with, and these legislations and regulations often change according to the whims and fancy of a selected few people or a selected small group. Additionally, the availability of raw material and the corresponding cost is subjected to a lot of volatility and unpredictability. The enterprises in the developed world

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are facing stiff competition from enterprises in the developing countries. Finally, the political indecisiveness and instability amplifies the previously mentioned volatilities and uncertainties.

The above challenges lay emphasis on the enterprises to achieve a greater degree of transparency, flexibility and adaptability in their manufacturing processes [220, 97]. This necessitates enterprises to initiate continual improvement programs [139], especially incremental, and/or if necessary innovative improvements [172]. Process improvement programs consist of "all the strategies, policies, goals, responsibilities and activities concerned with the achievement of specified improvement goals" (see ISO/IEC 15504-1 [129]). Subsequently, performance measurement within and across an enterprise is vital to monitor and control the success and effectiveness of process improvement efforts [170].

1.2 Problem Description

During the era of mass production, the set of performance metrics mainly pointed to financial metrics, especially the unit cost of a product, that are computed according to enterprise reporting cycle, i.e., offline. Traditional accounting techniques were employed to derive these metrics [14]. These techniques assigned direct costs and allocated aggregated indirect costs based on a pre-determined allocation rule [25]. Subsequently, these metrics had their own share of drawbacks. For instance, it was hard to distinguish between the profitable products and the ones that are incurring losses [25].

The operating scenarios of enterprises have changed internally and externally during the last decades. For instance, direct costs shrank, indirect costs increased drastically, and the product portfolio has more variants [109]. As a result, the traditional performance metrics were inadequate to monitor and control the manufacturing processes [211]. Numerous Performance Measurement Systems (PMSs) have evolved, which stress the importance of financial and non-financial/operational metrics, and the alignment of financial metrics and operational metrics with the enterprise objectives [12]. Overall, these systems provide a comprehensive view of an enterprise to sustain competitive advantage.

Along with the advances in PMSs, the tradition accounting techniques have evolved from pure allocation of costs to trace and assign costs based on causal relationships [25]. In this regard, the notable accounting techniques are Activity-Based Costing (ABC) [25] and Resource Consumption Accounting (RCA) [225]. Headway has also been made to calculate the operational metrics in real-time [141]. Research, with support from standards and nonprofit organizations, has been carried out extensively in isolation; this has resulted in the standardization of operational metrics, such as production Key Performance Indicators (KPIs) (see ISO 22400-2 [125], VDMA 66412-1 [150], VDMA 66412-2 [151], VDMA 66412-3 [152]) and Supply Chain Operations Reference (SCOR) KPIs [146].

The progress in development of financial metrics and operational metrics has been carried out in complete isolation and is diverging. The operational metrics are indispensable for operators, supervisors and managers, among others. These enable them to react promptly to the situations on the shop floor [140]. Similarly, financial metrics are crucial for Chief Executive Officers (CEOs), Chief Financial Officers (CFOs) and accountants, and so forth. These metrics are necessary for planning and controlling of enterprise strategies and objectives [140]. These financial and operational metrics can be considered as lagging and leading metrics respectively based on the trends to compute them [17].

The operational metrics are treated as leading metrics as they are computed in real-time or online [139], which enable to take necessary reactive or proactive actions to minimize deviations from planned values/objectives, and support future planning and decision making based on facts. Manufacturing Execution Systems (MES) support in automated collection and aggregation of process data, computation of operational metrics, and timely display of operational metrics to enterprise members to initiate, if necessary, suitable actions [141]. Subsequently, this assists to realize a real-time or online monitoring and control of manufacturing processes employing shorter closed loop feedback cycle. In comparison to the offline monitoring and control of manufacturing processes, this will result in around 10–20 % improvements in performance via increased throughput, reduced cycle time and improved quality, and so forth [119, 141, 187].

On the contrary, the financial metrics are considered as lagging metrics as they are calculated according to the enterprise's reporting cycle, i.e., offline [84]. The computed metrics are delivered late, i.e., performance evaluation, and planning and decision making processes are temporally delayed and will not be based on facts. Consequently, this will lead to realizing a sluggish closed loop feedback cycle [98]. The aforementioned improvement associated with the real-time or online monitoring and control of manufacturing processes can be enhanced if the closed loop feedback cycle consists of real-time financial metrics. Furthermore, the real-time financial metrics must be linked with the corresponding operational metrics in real-time, and plant managers and supervisors have access to these metrics in reasonable amount of time, especially in real-time.

The requirements of different audiences are contradictory [140]. For instance, the operational metrics are communicated as an index, which represents efficient and effective use of raw materials and resources, among others [140, 197]. Accountants have difficulties to consolidate these operational metrics. Likewise, the financial metrics are expressed using currency that is extremely aggregated and conceals the operational details [140]. Furthermore, the financial metrics, in most of the cases, cannot be easily traced to products and productions orders. In short, the audiences' requirements and their interpretation make it difficult to link and align the financial and operational metrics [11].

Research to link financial and operational metrics, especially in real-time, has not garnered the required attention [226]. MESA[1] (Manufacturing Enterprise Solutions Association) Metrics Working Group has identified linkage of financial and

[1] For more information, refer to http://www.mesa.org.

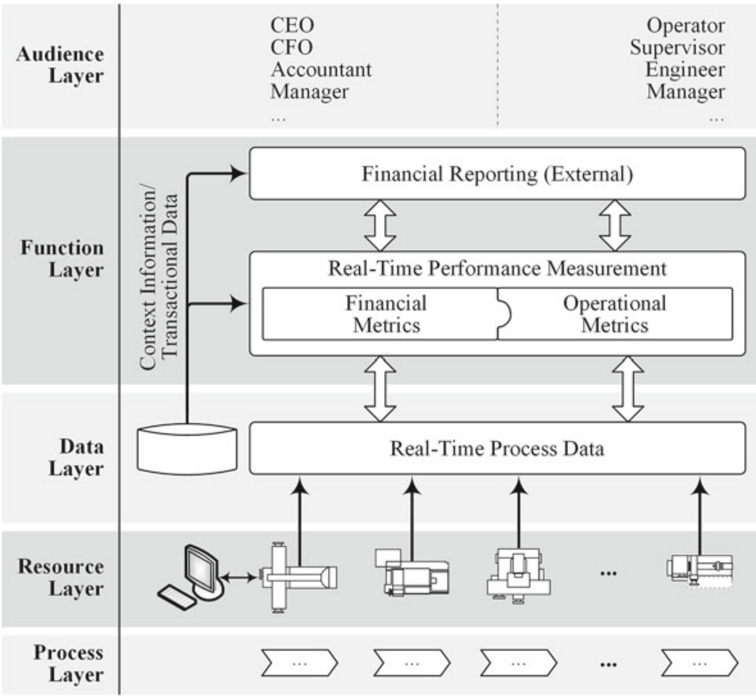

Fig. 1.1 Computation of performance measurement, i.e., financial and operational metrics, using real-time process data from the shop floor and corresponding context information from enterprise applications, especially from the Enterprise Resource Planning (ERP) System

operational metrics in real-time, as one of the challenges yet to be realized [140]. Few attempts have been made to integrate the contradicting metrics. For instance, the concept of Dynamic Performance Measures (DPMs) was introduced to measure the financial and operational metrics, and to connect the shop floor with the strategic level of an enterprise [113, 114, 115]. Nonetheless, the information and details are scare regarding DPMs.

1.3 Structure of the Research

The financial and operational metrics are two sides of the same coin—both are essential for monitoring and controlling manufacturing processes. A resource is an entity that is common between the financial and operational metrics [141]. A resource has well defined processing capabilities and throughput capacities (see IEC 62264-1 [121]). These capabilities and capacity of a resource are employed during the execution of manufacturing processes generating process data in real-time.

The process data provides awareness about different enterprise entities including products, resources and production orders, customers, and so forth. Likewise, enterprise applications, especially Enterprise Resource Planning (ERP) System, store context information or transactional data about enterprise entities [11, 175]. The acquisition of process data in real-time and the corresponding transactional data can be used to simultaneously compute the financial and operational metrics in real-time, as depicted in Fig. 1.1. Consequently, a comprehensive view of an enterprise can be presented to different audiences, convert the lagging financial metrics into leading financial metrics, and link the financial and operational metrics in real-time.

A reference architecture has been developed at the Business & Information Systems Engineering (BISE), University of Siegen to enable Enterprise Integration (EI) and address the aforementioned issues. An integrated enterprise can partially enhance existing monitoring and control of manufacturing processes within and across the enterprise boundary, with aspirations to achieve a higher degree of transparency, flexibility and adaptability. The integrated enterprise needs to be exploited and fostered to accomplish the functionality of real-time performance measurement, i.e., computation of financial and operational metrics.

The remaining part of the presented research is structured as follows. Chapter 2 elaborates constraints and goals of the presented research. The reference architecture and the methodology for realizing real-time performance measurement involve different fundamentals, technologies and standards, which are presented in Chap. 3. The reference architecture and the envisaged methodologies are elaborated in Chap. 4. The reference architecture has been validated in an industrial scenario, as discussed in Chap. 5. Finally, Chap. 6 presents the conclusion and identifies future activities.

Chapter 2
Research Description

The previous chapter laid down the basic road map of the presented research. This chapter builds on the previous chapter, and elaborates the constraints and goals of the presented research. In the presented research, different time notations are used. Section 2.1 presents these notations and their meaning. Based on the previously mentioned descriptions, Sect. 2.2 elaborates the constraints and goals of the presented research. Finally, a summary of the chapter is presented in Sect. 2.3.

2.1 Time: Classification and Definition

In recent years, different technologies and computing power have made advances by leaps and bounds. The technologies and computing power can be employed in numerous ways. Nevertheless, there are different definitions of time that influence the meaning and outcome of the aforementioned technologies and computing power. These definitions of time are defined from the perspective of how the systems respond to situations and user interactions.

A real-time system is defined as a "system which is required by its specification to adhere not only to functional requirement, but also to temporal requirements, often also called "timing constraints" or "deadline" [199]. A real-time system is characterized by speed—rate of execution of intended tasks, responsiveness—ability of the system to adjust to the external changes in the environment and remain alert to incoming events, timeliness—ability of the system to react within the time constraints or deadlines, and graceful adaption—ability of the system to adjust to the internal changes in workload and resource availability [36].

Real-time systems can be classified as hard and soft real-time systems [99]. A hard real-time system has to produce a response to a situation before a specified deadline, usually in a matter of a few milliseconds or less and without human intervention [99, 199]. For the computer science community, a real-time system is a hard real-time system. The response is mostly concerned with maintaining the safety of operators,

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and resources, among others [99, 199]. Furthermore, a hard real-time system is located very close to its environment and is tightly coupled with it [99].

A soft real-time system responds to a situation in seconds or more, and can miss the deadline, i.e., the response can arrive after the deadline [99, 199]. The response time is in the order of a few seconds or more [99]. Additionally, the deadline missed by the system is not critical and operators or users can intervene in the working of the system [99]. A soft real-time system is also known as an online system [99]. In contrast to an online system, an offline system consist of processes that are executed over a prolonged period of time (e.g., days, weeks) and is idle most of the time waiting for inputs.

Nevertheless, the manufacturing community does not classify the time precisely the way the computer science community does. For instance, some manufacturing enterprises consider real-time if response happens within a minute or less [141]. Rather, the manufacturing community uses real-time, soft real-time and online interchangeably. Subsequently, the presented research also does not distinguish among real-time, soft real-time and online, rather real-time and offline terms are appropriately used.

2.2 Research: Constraints and Goals

Manufacturing enterprises can be characterized based on employee count, plant layout, manufacturing processes and production quantity, among others. Likewise, performance measurement is a broad field. The presented research considers specific enterprises and attempts to address the requirements of performance measurement concerning the chosen enterprises. In addition, the presented research focusses on processes internal to a manufacturing enterprise as the enterprise has more influence to enhance its internal processes. Consequently, the following paragraphs will outline the research constraints and goals based on the problem described in Sect. 1.2.

2.2.1 Manufacturing: Enterprises, Processes and Taxonomy

The presented research is concerned with manufacturing, and its processes and activities leading to the manufacture of physical products, i.e., discrete products, in discrete industry. Manufacturing is defined as "the application of physical and chemical processes to alter the geometry, properties, and/or appearance of a given starting material to make parts or products; manufacturing also includes the joining of multiple parts to make assembles products" [62].

The manufacturing enterprises referred to here can be represented by suppliers, SMEs and area or site of a bigger enterprise that deals with the manufacturing rather than assembling. The presented research is limited to the manufacturing of products, which can be a crucial strategy for SMEs. Here, a product refers to a physical

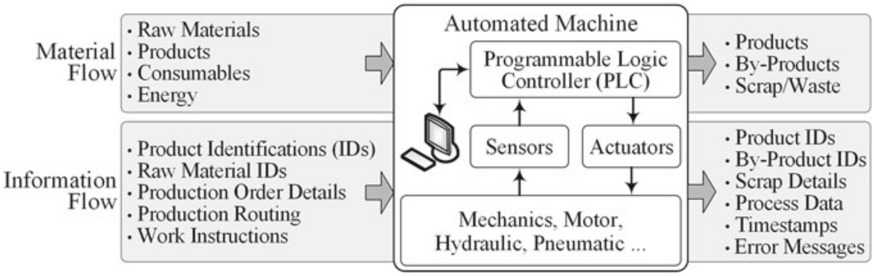

Fig. 2.1 Schematic representation of an automated machine along with the material flow and the corresponding information flow, adapted from [47]

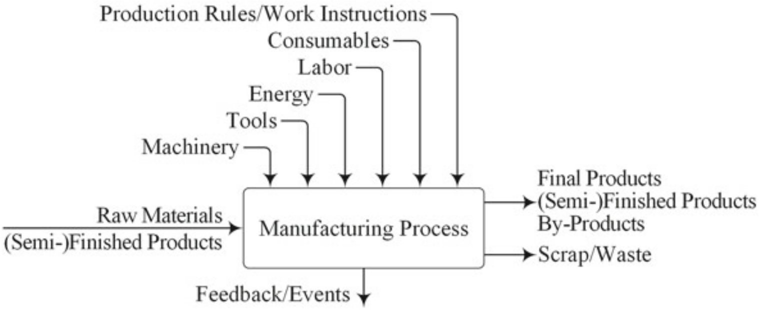

Fig. 2.2 Simplified view of a manufacturing process along with its inputs and outputs, adapted from [62]

individual work unit and not to the assembly of components. These enterprises considered in the presented research rely on automated machines to improve cycle time, reduce manufacturing lead time, improve product quality, and so forth [62]. An automated machine can be schematically illustrated as shown in Fig. 2.1.

The automated machines encompass different degrees of automation—fully automatic and semi-automatic devices [173]. Furthermore, human intervention is required for the control of semi-automatic and manual devices [173]. Nonetheless, the presented research is concerned with machines that are able to provide manual/automatic feedback of manufacturing processes. The feedback can be as simple as denoting the completion of a manufacturing process to a complicated one describing the manufacturing process with the actual process parameters employed.

The conversion of raw materials into (semi-)finished products is realized by a manufacturing process, as illustrated in Fig. 2.2. In contrast to manufacturing processes, there are business processes to manage customers' orders, billing and so forth. In either case, the business and manufacturing processes should consist of value-added activities [37], and should be part of the value-chain [184]. These processes can be belong to discrete, batch processing, and continuous industries [63], and logistic domain (see IEC 62264-3 [123]). A manufacturing process is supplied with product definition information, which specifies the required materials, products and subassemblies; describes the instructions to carry out the manufacturing process; and identifies resources to be employed (see IEC 62264-1 [121]). This information can be part of production routings, manufacturing Bill of Material (BOM) and Bill of Resources (BOR) in discrete industry or recipes in batch processing industry.

Finally, the plant layout of manufacturing enterprises would contain all possible types of resource layouts and material flows, especially in the case of SMEs. The plant layout is dictated by the production variety, production quantity [62] and product specification. There exist numerous plant layouts—fixed-position, process/functional, cellular and product [62]. Nevertheless, the presented research can be employed for different plant layouts.

2.2.2 Enterprise Entities and Identification

Monitoring and controlling of manufacturing processes is indispensable for sustaining a competitive advantage. However from a monitoring and control engineering perspective, the manufacturing processes are imprecise and intangible, which is mainly due to way enterprise members interpret and execute these processes. Thus, it is essential to monitor and control the underlying tangible enterprise entities of manufacturing processes. Resources, manufacturing operations, production/work orders, production schedules, raw materials, products, and quality, among others are a few of the enterprise entities that can be really monitored and controlled.

Nonetheless, it is necessary that the enterprise entities are uniquely identifiable to realize monitoring and control by tagging/labelling them. The unique Identification (ID) and the underlying tagging/labelling can be done virtually or physically using enterprise determined procedures or available standards[1] and guidelines. For instance, a barcode label containing ID can be physically glued onto a product that can be read using the barcode reader attached to the operators' terminals along the downstream processes. Likewise, an automation device can assign a virtual unique identification to enterprise entities, especially (sub-)products and raw materials, which can be communicated with its upstream and downstream machines.

2.2.3 Enterprise Perspectives

A manufacturing enterprise can be viewed from different perspectives—management science, control engineering and computer science. Nonetheless, there exist additional perspectives (e.g., functional and infrastructure), which are considered under previously mentioned three perspectives. These perspectives are essential to address

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[1] For more information, refer to GS1 at http://www.gs1.org and Association for Automatic Identification and Mobility at http://www.aimglobal.org.

the challenges existing in the enterprise's internal and external environments, and to assist different enterprise members in performing their duties. The management science perspective is concerned about the health of an enterprise in the short-, medium- and long-term. This might involve strategic planning and the management of operations, and so forth [39].

The strategic plans and objectives are realized by executing the business and manufacturing processes. Here, the strategic plans and objectives are rolled down to the shop floor [109]. Likewise, the feedback in terms of performance metrics is rolled up to top management after the execution of manufacturing processes [109]. In this regard, the management science perspective should be assisted with the control engineering perspective as presented by the (control) engineering community. The feedback loops are based on the concepts of cybernetic controls to monitor and control the manufacturing processes [32, 112, 207], especially by comparing the actual performance metrics and the planned enterprise objectives.

Additionally, the computer science community has proposed the computer science perspective, which is crucial for both the management and control engineering perspectives. This perspective provides necessary information for monitoring and control, and subsequent decision making. Here, an enterprise employs different enterprise applications, like the ERP System, Supply chain Management (SCM) System and Customer Relationship Management (CRM) System.

The monitoring and control of manufacturing processes based on multiple feedback loops stress the importance of financial and operational metrics [112, 207]. Thus, the control engineering perspective is the focus of the presented research, and elaborates methodologies to compute financial and operational metrics during the execution of manufacturing processes. However, it does not address the decision making, i.e., action or reaction component (see Sect. 2.2.6).

2.2.4 Performance Metrics

Manufacturing enterprises are influenced by internal and external situations. However, the enterprises are in a position to effectively control their internal situations [109]. The performance metrics vary from enterprise to enterprise in a specific industry as well as from industry to industry, especially concerning discrete and batch processing industries. Thus, the research addresses the computation of basic financial and operational metrics internal to a manufacturing enterprise, especially concerning manufacturing processes, in real-time. On the other hand, the research does not delve into selection of performance metrics and PMS.

2.2.5 Linkage of Financial and Operational Metrics

Today's manufacturing enterprises compute operational metrics in real-time. In contrast, the financial metrics are calculated offline, which presents a snapshot of a manufacturing enterprise at a particular instant in time. The manufacturing enterprise with a stable high volume and low mix production schedules can afford to use the lagging financial metrics to monitor and control the manufacturing processes. In the aforementioned situation, the manufacturing enterprises are in a position to link the operational and financial metrics. For instance, Overall Equipment Effectiveness (OEE), an operational metrics, can be linked to financial metrics (e.g., profitability) [213].

On the contrary, the manufacturing enterprises are mainly represented by suppliers/SMEs that adhere to low volume and high mix production schedules, and would like to employ leading metrics to monitor and control manufacturing processes. In this situation, many of the operational metrics cannot be easily aggregated/transformed and linked with financial metrics, i.e., requires huge effort and many assumptions to assign information to production orders. Subsequently, aggregation of operational metrics might result in deceptive financial metrics.

The presented research attempts to compute the financial and operational metrics in real-time from the acquired real-time process data and link them, resulting in the conversion of lagging financial metrics into leading financial metrics. For instance, the improvement steps introduced on the shop floor should increase the operational efficiencies and effectiveness, and instantaneously suitable changes should be observed in the financial metrics. Likewise, any managerial decision should suitably influence the financial as well as the corresponding operational metrics.

2.2.6 Performance Management

Performance management should complement performance measurement, and is crucial for sustaining competitive advantage. Performance management is identified as “systematic, data-oriented approach to managing people at work that relies on positive reinforcement as the primary means to maximize performance” [80]. Likewise, performance management, according to IEC 62264-3 [123], is defined as “the collection of activities that systematically capture, manage and present performance information in a consistent framework. This includes utilizing corrective actions to affect operational improvement.” The presented research attempts to compute financial and operational metrics in real-time, and present a comprehensive view of a manufacturing enterprise.

Nonetheless, enterprise members need to initiate corrective actions, if necessary, when the manufacturing processes deviate from the planned objectives as indicated by the financial and operational metrics. In addition, the computed metrics can be used to provide feedback to upstream processes, like engineering and sales. Overall, it is necessary to realize multiple performance feedback loops [109], especially within and across the enterprise boundary.

The corrective actions can be reactive or proactive [59]. Furthermore, these actions can be fully automated, semi-automated, or manual. However, it is beneficial to have a semi-automated approach in which few types of actions are automated and remaining actions are initiated by enterprise members. For instance, the action component can also be partially automated based on an event processing paradigm (see [157]). Likewise, improvement, either incremental or innovative, can be initiated to enhance the processes. Apart from the process corrections, efforts might be needed to invest in training of employees to realize higher performance. However, the presented research is concerned with the quantification of financial and operational metrics in real-time, and does not deal with the performance management and the corresponding action components, training of employees, and so forth.

2.3 Summary

Manufacturing enterprises need to monitor and control their manufacturing processes to sustain a competitive advantage. In this regard, performance measurement and management are crucial. Since the mid-1980s, several PMSs have been elaborated. These systems have emphasized the importance of financial and operational metrics, alignment of financial and operational metrics with the enterprise objectives, and inclusion of stakeholders, among others. Nonetheless, PMS are seen from a strategic perspective and do not elaborate about selection and computation of performance metrics. Subsequently, the presented research attempts to address the performance measurement component of PMS.

Section 2.2 elaborated research constraints and goals based on the problems associated with performance measurement presented in Sect. 1.2. The research goals can be summarized as following:

- computation of financial and operational metrics internal to a manufacturing enterprise in real-time;
- linkage of financial and operational metrics in real-time.

Chapter 3
Fundamentals, Concepts, Technologies and Standards

The previous chapter delineated the constraints and goals of the presented research work. The goals should fulfill the criteria of a good PMS—comprehensive, causally oriented, vertically integrated, horizontally integrated, internally comparable and useful [17]. Subsequently, it is crucial to exploit inter-disciplinary fundamentals, technologies and standards. The following content is based on extensive literature review of books, journal articles, conference articles, standards, and whitepapers, and interaction with numerous experts.

The chapter is structured as follows. Section 3.1 introduces an enterprise. An integrated enterprise is crucial to manage its external and internal challenges. Thus, Sect. 3.2 elaborates enterprise engineering, modeling and integration. Section 3.3 introduces MES, a tool for realizing vertical integration, and monitoring and controlling manufacturing processes. Next, the state-of-the-art in performance measurement is described in Sect. 3.4. The concept of event processing is introduced in Sect. 3.5, which can be exploited to compute real-time performance metrics necessary to monitor and control the manufacturing processes. Finally, a summary about various fundamentals, technologies and standards is presented in Sect. 3.6.

3.1 Enterprise

An enterprise is defined as "one or more organizations sharing a definite mission, goals and objectives to offer an output such as a product or service" (see ISO 15704 [124]). The presented research focusses exclusively on products and subsequently, the terms manufacturing enterprise and enterprise will be used interchangeably. An enterprise has a well identified "set of functions that carry a product through its entire life span from concept through manufacture, distribution, sales and service" [228]. Furthermore, the enterprise has to deal with its suppliers, and satisfy its internal and external customers, shareholders and stakeholders.

S. Karadgi, *A Reference Architecture for Real-Time Performance Measurement*, Progress in IS, DOI: 10.1007/978-3-319-07007-0_3,

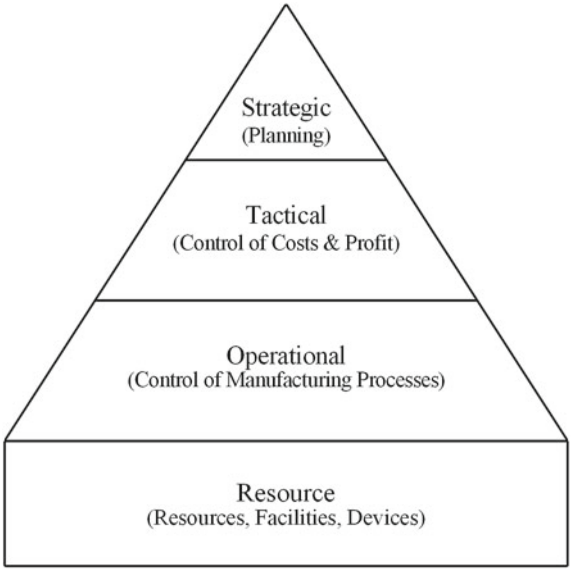

Fig. 3.1 Hierarchical classification of an enterprise into different levels, adapted from [56]

An enterprise operates in a highly constrained environment. For instance, an enterprise has to adhere to various government laws and regulations that deal with the products (e.g., food safety and traceability [178]) and environmental concerns (e.g., emission of carbon dioxide by light commercial vehicles [179]). In addition, an enterprise has to address social responsibilities that are defined in its Corporate Social Responsibility (CSR) objectives (see ISO 26000 [126]).

An enterprise needs a consistent decision making mechanism, enhanced flexibility, and increased transparency, supported with necessary context information to address the aforesaid challenges. Subsequently, an enterprise can be hierarchically classified into different levels, as illustrated in Fig. 3.1. This classification is not always valid and depends on myriad factors, like employee count, enterprise type, and process structure.

The strategic level is concerned with monitoring and defining the enterprise's long-term objectives, which are rolled down to the subordinate levels [109]. Next, the tactical level is concerned with the (tactical) planning toward realization of objectives. Finally, the operational level manages and controls the plans, which in-turn interacts closely with the manufacturing processes located on the resource level. The resource level is supported with numerous resources, consisting of (automated) machines, materials, automated guided vehicles and labors, and so forth. The feedback, i.e., performance metrics/reports, of executed manufacturing processes are aggregated and communicated back to the higher enterprise levels [109]. The feedback is used by higher management levels to make amendments to the existing objectives and employed as inputs to define new objectives.

Nonetheless, the aforementioned enterprise levels are associated with distinctive characteristics and requirements, which necessitate viewing the enterprise from different perspectives—management science, control engineering and computer science. The management science perspective is indispensable for managing an enterprise, which has number of characteristics and requirements [56, 58, 81, 97, 103, 109, 140, 154, 183], as depicted in Fig. 3.2. Here, an enterprise can be hierarchically classified into top, middle and supervisory management levels [56, 103], with clear definitions of roles and responsibilities.

The management science perspective should be supported with a mechanism to monitor and control the manufacturing processes. In this regard, the (control) engineering community has presented a control engineering perspective of an enterprise, which complements the management science perspective, as illustrated in Fig. 3.3. This perspective leads to multiple feedback loops based on the concepts of cybernetic controls for realizing the monitoring and control of processes [32, 112, 207]. Furthermore, this perspective has certain characteristics and requirement (see [97, 109, 230], IEC 62264-1 [121], IEC 62264-3 [123], VDI 5600 Part 1 [148]).

In the presented research, the monitoring and control of manufacturing processes will adhere to the multi-part IEC 62264 standard, which is further based on the concepts of system theory (see Annex F of IEC 62264-1 [121]). IEC 62264 logically classifies an enterprise into a functional hierarchy consisting of five levels. Level 0 represents manufacturing processes supported with numerous resources. These processes are monitored using a number of sensors at Level 1. The processes are controlled manually or automatically with the assistance of supervisory control systems at Level 2. These levels have a narrow view of an enterprise and processes, i.e., aim to keep the processes under control. However, Level 4 and Level 3 have wide views of an enterprise, i.e., need to manage multiple orders, and customers, and consider future activities, and so forth. The activities of Level 4 are establishing basic plant production schedule and capacity planning, among others whereas Level 3 is concerned with the activities such as dispatching of production orders and production performance analysis.

The enterprise activities, like decision making, can be complex and spread across different enterprise levels, and depend upon the quantity and quality of context information. Subsequently, the computer science community has presented the computer science perspective of an enterprise. This perspective consists of different characteristics and requirement [56, 68, 97, 173, 230], as illustrated in Fig. 3.4. The different enterprise levels are supported with numerous systems. The tactical level is supported with enterprise applications such as the ERP System, CRM System and SCM System. Similarly, the activities of the operational level are performed using the manufacturing management systems, such as MES. Finally, the resource level contains resources, sensors and special terminals, which can be used to maintain the stable state of manufacturing processes using applications like Supervisory Control and Data Acquisition (SCADA), and Human Machine Interface (HMI).

The top management is mainly concerned with the health and progress of the enterprise [13]. Thus, top management relies heavily on the financial reports, and follows Generally Accepted Accounting Principles (GAAP) to generate external

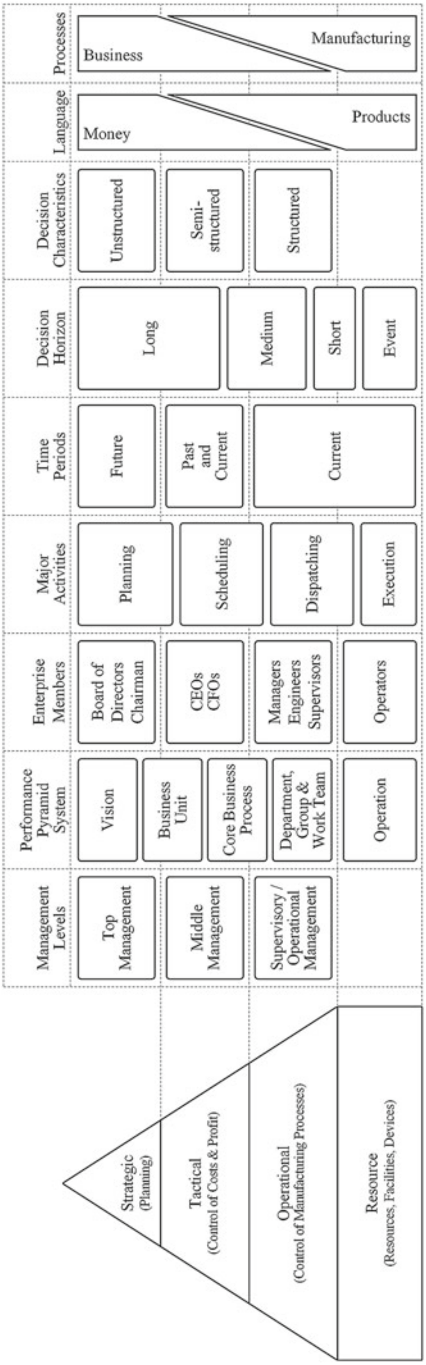

Fig. 3.2 Management science perspective of an enterprise along with its characteristics and requirements, adapted from [56, 103] and et al.

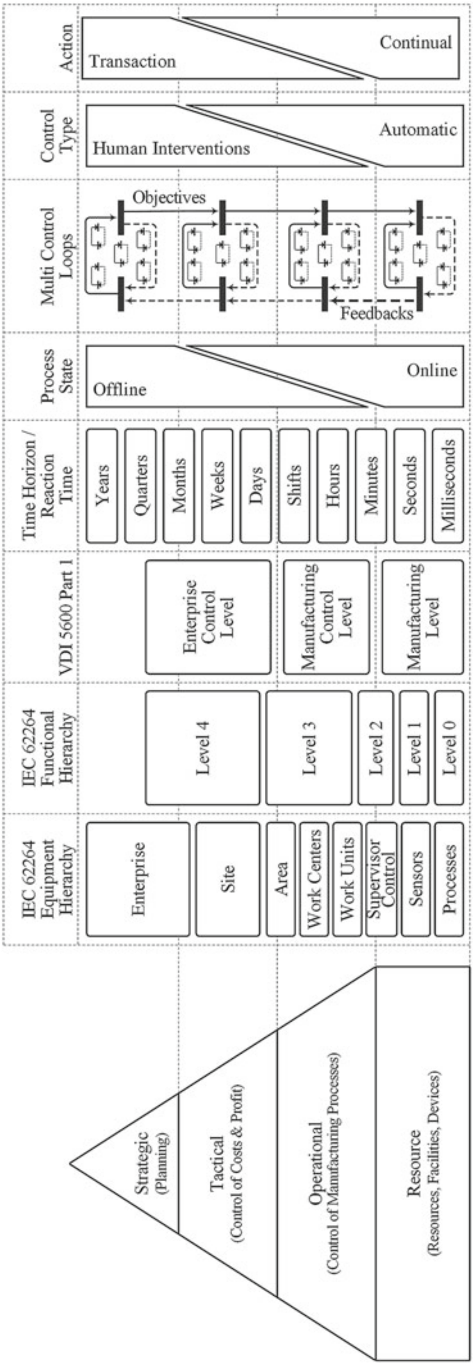

Fig. 3.3 Control engineering perspective of an enterprise along with its characteristics and requirements, adapted from IEC 62264-1 [121], IEC 62264-3 [123] and et al.

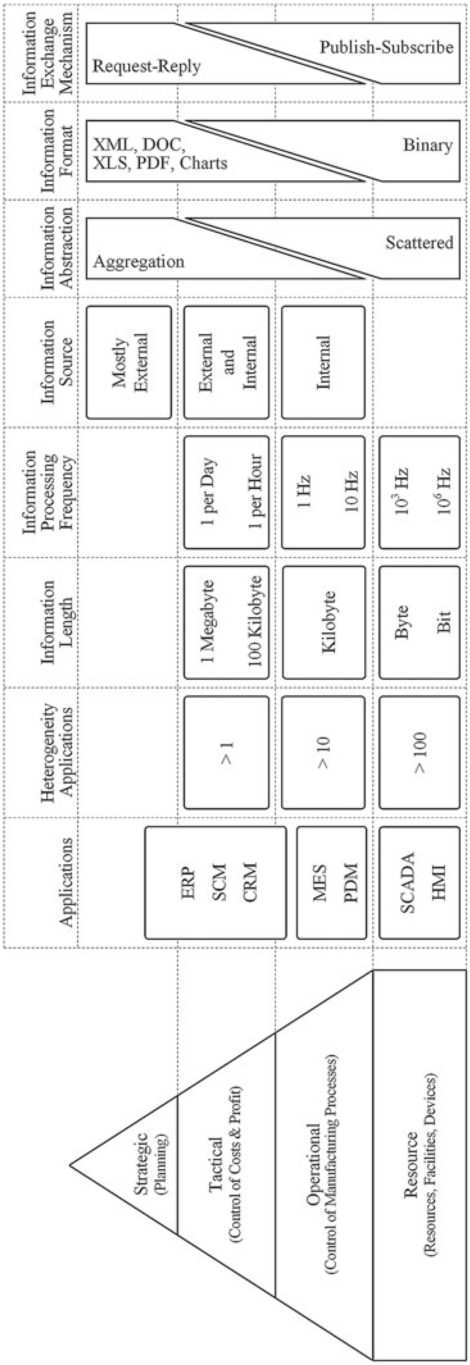

Fig. 3.4 Computer science perspective of an enterprise along with its characteristics and requirements, adapted from [68, 173] and et al.

financial reports [25]. This is crucial to satisfy its stakeholders, legal regulations, government legislation, financial institutes, customers, and so forth [25]. In addition, the financial reports are used to derive financial metrics [25]. Overall, the external financial reports and the corresponding financial metrics provide a retrospective view of an enterprise. In contrast, other management levels rely on the operational metrics to monitor and control the manufacturing processes. However, it is necessary to employ managerial accounting techniques to derive financial metrics that are critical for middle and supervisory management [25].

3.2 Enterprise: Engineering, Modeling and Integration

An enterprise's internal and external environments are rapidly changing due to reasons mentioned previously. Furthermore, an enterprise operates as an element of a multi-site enterprise, extended enterprise, or virtual enterprise [162]. Thus, it is necessary to have efficient and effective process management, integration and coordination, and consistent decision making within different enterprise levels and across enterprise boundary.

Since the early-1990s, research has been carried out in the area of enterprise engineering to overcome the previous mentioned requirements [117]. Enterprise engineering is concerned with the "set of methods, models and tools that one can use to analyze, to design and to continually maintain an enterprise in an integrated state" [117]. Furthermore, enterprise engineering constitutes enterprise modeling and enterprise integration. Enterprise modeling is a prerequisite for realizing an integrated enterprise [53].

3.2.1 Enterprise Modeling

Enterprise models is defined as "abstraction of an enterprise domain that represents enterprise entities, their interrelationships, their decomposition and detailing to the extent necessary to convey what it intends to accomplish and how it operates" (see ISO 19439 [128]). Furthermore, enterprise modeling has to be carried out to develop enterprise models (see ISO 19439 [128]).

The modeling can contain different views (e.g., function, information, resource, organization) of an enterprise (see ISO 15704 [124], ISO 19439 [128]) and various levels of details (e.g., coarse grained) [161]. For instance, ARIS (ARchitecture for integrated Information Systems) Toolset supports modeling of business processes based on the concept of ARIS House, which is divided into control, product/service, data, function and organization views [191, 192]. Likewise, Integrated Definition for Function Modelling (IDEF) is used to graphically model processes or complex enterprise systems [2].

Level	Type	Description & Characteristics	Enablers
Business	Coordination	• Business process coordination • Collaboration • Knowledge sharing • Enterprise-wide decision-making	• ISO 15704
Application	Interoperability	• Interoperability of heterogeneous software applications and databases on different platforms	• XML • HTML
Physical	Connectivity	• Physical integration of heterogeneous hardware, machines and devices • Not concerned with the interpretation of sent data	• Profinet • Profibus • Modbus • Ethernet

Fig. 3.5 Different integration levels within an enterprise starting with the physical integration on the lower level, proceeding with the application integration and finally realizing business integration, adapted from [51, 162]

Enterprise modeling will constitute reference and partial models that can be applied across numerous enterprises, and particular models that can be used for a specific enterprise [100]. These models are used to characterize the different life-cycle phases of an enterprise's activities/processes (see ISO 15704 [124]).

3.2.2 Enterprise Integration

Enterprise Integration (EI) can be identified as the ability to "provide the right information at the right place and at the right time and thereby enable communication among people, machines and computers and their efficient cooperation and coordination" [101]. EI concerning a single enterprise, i.e., inter-enterprise integration, can be widened to include integration encompassing multiple enterprises, i.e., intra-enterprise integration [162].

EI has to address different levels of integration within an enterprise [51, 162], also known as enterprise information integration [51]. These levels of integrations—physical, application and business are elucidated in Fig. 3.5. The supreme goal of an enterprise is to realize business integration [162]. This goal can be fulfilled starting with the physical integration on the lower level, proceeding with the application integration and finally realizing business integration [162]. Nonetheless, in reality, EI will remain an elusive vision because of continual changes in the enterprise's environment, such as technologies, government legislation and enterprise strategies, among others [162].

Research has been carried out to use different architectures, standards and models to realize an integrated enterprise. For instance, Fig. 3.6 illustrates integrated enterprise system framework reference architecture. As stressed earlier, an enterprise can be classified into different hierarchical levels. Hence, EI of a single enterprise needs to address the integration within and across different enterprise levels. Subsequently,

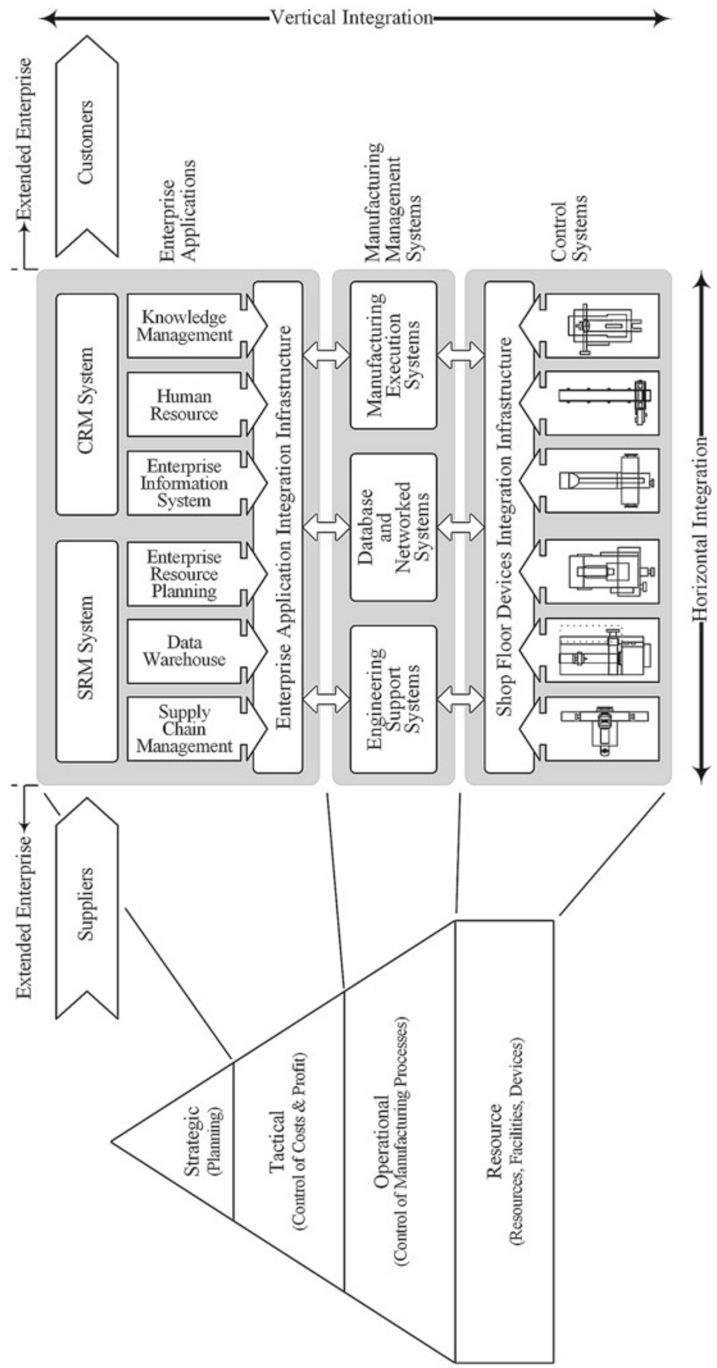

Fig. 3.6 Integrated enterprise system framework reference architecture depicting horizontal and vertical integration, and different (enterprise) systems, adapted from [68]

EI can be split into horizontal integration to address the integration of different systems within an enterprise level and vertical integration to confront the integration challenges across different enterprise levels, as displayed in Fig. 3.6.

3.2.2.1 Horizontal Integration

The horizontal integration at the tactical level has received enormous attention, which is represented as Enterprise Application Integration Infrastructure in Fig. 3.6. The integration between applications during the early days of application integration was legacy point-to-point integration, which was complex when introducing new applications and managing the existing integration [72, 136]. By the late-1990s, the situation started to change with the introduction of Enterprise Application Integration (EAI) [72, 136].

Enterprise applications, such as ERP Systems, CRM Systems and SCM Systems, communicate using the hub-and-spoke method of application integration supported by EAI [136]. The Service Oriented Architecture (SOA) paradigm is suitable for realizing the horizontal integration of different enterprise applications [72]. Furthermore, PAS 1074 [144] describes the data standard and process to initiate exchange of data among ERP Systems, and the coordination across multiple enterprises to manage production orders. The exchange of information is critical to support business networks with the aim to serve customers employing (business) processes within and across the enterprise boundary [175].

The horizontal integration at the remaining enterprise levels has received the least amount of attention. For instance, the development of STandard for the Exchange of Product model data (STEP) led to the possibility of a manual transformation of product related data among different engineering support systems [51], especially among Computer Aided Design (CAD) Systems and Product Lifecycle Management (PLM) Systems. The manufacturing environment is about a complex interaction of processes and their corresponding resources [200]. Consequently, the physical integration of resources is extremely vital, as illustrated by Shop Floor Device Integration Infrastructure in Fig. 3.6. However, the physical integration is still far from realizing a solution similar to the EAI solution. Nonetheless, there exists vendor specific point-to-point based integration among automated machines on the shop floor.

3.2.2.2 Vertical Integration

The vertical integration across different enterprise levels is indispensable to realize EI. Nonetheless, vertical integration has its own set of issues—semantics and temporal, because of the characteristics and requirements of different enterprise levels (see Figs. 3.3 and 3.4).

The semantic vertical integration gap exists while exchanging data among different enterprise levels [67, 176]. The data model can be employed to overcome the semantic gap. This model can be defined in different ways—defining a data model prior to the exchange of data, defining only a meta-level structure of the data model before data exchange, and defining a dynamically accommodated data model during data exchange [162, 176]. In addition, ontologies have been recommended to define the semantics [162]. Overall, standardization activities have taken place to address the issues of data sharing [22].

Enterprise levels are associated with different decision and reaction time horizons, which lead to temporal vertical integration gap [98, 176]. MES provides the capability to deliver the information about the shop floor to the managers on tactical levels in real-time [98, 177]. In other words, MES enables to overcome the temporal vertical integration gap by aggregating data from heterogeneous data sources or applications associated with different time horizons, and provides a closed loop feedback between enterprise applications and resources on the shop floor [98, 177]. This can be addressed by exploiting the system theory, automatic control and automation engineering, especially by integrating the event-driven and time-driven components [164].

The interface between enterprise applications on the tactical level and MES located on the operational level has received considerable attention [161, 162]. IEC 62264-2 [122] has defined the necessary interfaces between the tactical and operational levels for discrete industry. Furthermore, Business to Manufacturing Markup Language (B2MML) contains necessary XML (eXtensible Markup Language) schemas to enforce the aforesaid interfaces [136], with an intention to overcome the semantic vertical integration gap. Likewise, IEC 61512-2/ISA-88 defines interface between tactical and operational levels for batch processing industry, and there exist corresponding XML schema known as Batch Markup Language (BatchML) [185].

Nonetheless, as mentioned previously, the interface between the operational level and resource level is not well defined. Numerous equipment manufacturers have employed Object Linking and Embedding (OLE) for Process Control (OPC) communication specifications to connect their controllers with the MES [142]. Furthermore, The Association of German Engineers(VDI) guideline VDI 5600 Part 3 [149] has attempted to address these issues by standardizing the data content to be exchanged among automated machines on the shop floor and MES, and vice versa in a discrete industry scenario. In reality, there exist various communication protocols, control devices and their programming languages, and manufacturing processes, among others that need to be addressed with specific solutions.

Research has been carried out to realize vertical integration based on the SOA paradigm, which is a de facto standard underlying EAI. The European-funded projects SIRENA and SOCRADES aim to exploit the SOA paradigm to integrate heterogeneous resources located at the resource level with business processes at the tactical level [79, 203]. Furthermore, Gartner has introduced two concepts that are interconnected. Firstly, the Service-Oriented Architecture in manufacturing (SOAm) approach has been introduced that considers the manufacturing requirements of SOA [136]. Secondly, the Manufacturing 2.0 reference model is presented based on the SOAm approach and the IEC 62264 [50, 136]. Here, Manufacturing 2.0 "leverages service and collaboration based architectures for manufacturing—right first time and on-demand—across dynamically reconfigurable sensor and mobile worker enabled supply networks" [50].

3.2.2.3 Architecture and Standards

ISO/IEC/IEEE 42010 [130] identifies architecture as "fundamental concepts or properties of a system in its environment embodied in its elements, relationships, and in the principles of its design and evolution." The definition of architecture expresses a number of ideas—"fundamental or unifying system as a whole," "conception of a system," "understood in context," and "not merely the overall structure of physical components that make up a system" (see ISO/IEC/IEEE 42010 [130]).

EI has received extensive attention, which has led to the development of various reference architectures, and standards. By the mid-1990's, several EI reference architectures had been developed in isolation addressing certain requirements of an enterprise (see ISO 15704 [124]). These reference architectures, like Computer Integrated Manufacturing Open System Architecture (CIMOSA), Purdue Enterprise-Reference Architecture (PERA), GRAI Integrated Methodology (GIM), contributed in the development of Generalized Enterprise-Reference Architecture and Methodology (GERAM) (see ISO 15704 [124]). Later on, GERAM was standardized as ISO 15704—Requirements for Enterprise Reference Architecture and Methodologies (see ISO 15704 [124]).

Likewise, standardization work has been carried out to define reference, particular and partial models based on ISO 15704 [124]. For example, IEC 62264 [121] defines a reference model for discrete industry. The standardization activities have been spearheaded by standardization bodies, like International Standardization Organization (ISO), International Electro-technical Committee (IEC), and European Committee for Standardization (CEN). In addition, research institutes and nonprofit organizations provide guidance and support to establish standards.

The aforementioned standards guide in realization of an integrated enterprise. Nonetheless, they do not mention realization in terms of technologies. There exist in different technologies that assist to realize and maintain an integrated state of an enterprise. The modeling of an enterprise from different viewpoints can be considered as a first step in realizing an integrated enterprise. Furthermore, the concepts of MES and event processing need to be exploited to realize an integrated enterprise, especially its abilities to realize a closed loop feedback between enterprise applications and resources on the shop floor in real-time. In short, the integrated enterprise provides a foundation to compute real-time performance measurement necessary to monitor and control the manufacturing processes.

3.3 Manufacturing Execution Systems

Manufacturing enterprises have invested in manufacturing management systems to enhance their operation execution [132]. The manufacturing management systems have evolved from Material Requirement Planning (MRP) in the late-1960s to Manufacturing Resource Planning (MRP II) in the early-1980s to ERP in the early-1990s [132]. In addition, CRM Systems and SCM Systems have evolved along with MRP II Systems and ERP Systems [132].

Enterprise applications, like the ERP System, are mostly transactional systems, i.e., operating in offline mode [97]. These systems are mostly concerned with planning and other administrative functionalities, and real-time reactions to events are not offered by these systems [159]. In addition, as mentioned in Sect. 3.2.2, temporal and semantic integration gaps exist between the planning systems located at the tactical and resources levels. To overcome these shortcomings, MES was introduced in the early-1980s, which tried to take a few of the responsibilities of planning systems of tactical level and control systems of resource level.

Since the early-1990s, MESA International, a worldwide nonprofit community, has been involved with the development and promotion of Manufacturing Execution Systems (MES[1]), and guiding standards organizations. MESA defines MES as "systems that deliver information that enables the optimization of production activities from order to launch to finished goods" [138]. Likewise, MES is defined as "information systems that reside on the plant floor between the planning systems in offices and direct industrial controls at the process itself" [135].

MES supports different functionalities. The functionalities of the MESA MES model are shown in Fig. 3.7 and described as follows [133, 137]:

1. Product Tracing and Genealogy: This functionality provides support in associating the collected data with identifiable products and production orders. The data acquired can be related to a machine operator, machine parameters and quality inspection, among others. Apart from using the data to monitor the manufacturing processes, the data can be used to perform forward and backward traceability.
2. Resource Allocation and Status: The resources should be monitored to check their status—idle, production, and maintenance; this is necessary to schedule/dispatch new production orders. Further, the history of resource can be recalled, especially the production order allocated and status (e.g., unavailable).
3. Performance Analysis: The executed manufacturing operations need to be analyzed and display up-to-the minute performance results via dashboards, e-mails, and other means. Additionally, in-depth analysis needs to be performed to analyze the completed production order at the end of the shift to calculate performance and identify abnormalities.

[1] MES is also known as Manufacturing Operations Management (MOM), especially with the introduction of IEC 62264-3 [123]. Nevertheless, the presented research will use the term MES only.

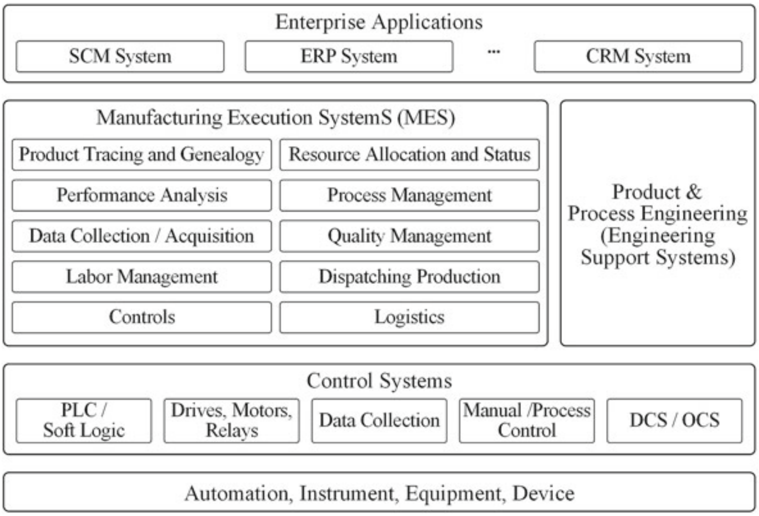

Fig. 3.7 Listing of MES functions, and their relationships with different systems, adapted from [133]

4. Process Management: The aforementioned outcome of performance analysis can be used to manage manufacturing processes. For instance, the abnormalities identified can be used to enhance the existing production routings. In addition, the functionality supports monitoring and control of manufacturing processes by responding automatically and/or alerting machine operators whenever an exception occur.
5. Data Collection/Acquisition: The functionality provides an interface to collect process data from control systems, either manually or automatically. The data can be stored as records associated with the product. The stored data can be exploited in multiple ways, as described in other functionalities.
6. Quality Management: Real-time management and analysis of product quality is necessary to identify any deviations, which in turn should influence the current, upstream and downstream processes.
7. Labor Management: The functionality provides the status of personnel (e.g., education qualifications). Nonetheless, it is mainly concerned with personnel attendance and tracking of main and support activities performed by personnel, which are critical for cost accounting.
8. Dispatching Production: The sequence of products through its production routing is managed by this functionality. In addition, it has to monitor resources, which might require assistance of other functionalities, and subsequently adapt the production sequence.
9. Controls: The functionality includes managing the numerous control systems (e.g., Distributed Control System (DCS) and Open Control System (OCS)), especially available on the shop floor.

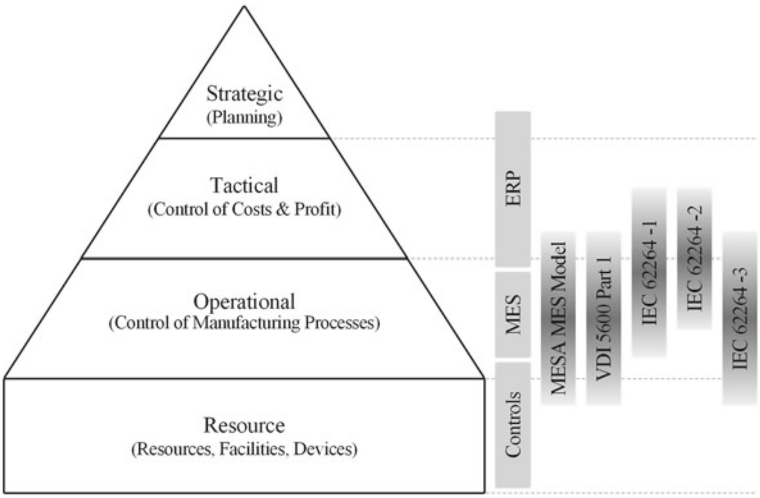

Fig. 3.8 Mapping of MESA MES model [133, 137], VDI 5600 Part 1 [148], and IEC 62264 [121–123] on different enterprise levels, adapted from [145]

10. Logistics: The functionality, as part of inventory management tasks, involves managing the movement of raw materials, Work-in-Progress (WIP) and finished products.

VDI defines VDI 5600 Part 1, especially for the German speaking community, for the introduction of MES in discrete industry [145]. VDI 5600 Part 1 is based on the MESA MES model and maps the aforementioned functionalities into 8 MES tasks. Furthermore, these tasks are mapped onto business processes and sub-processes (see VDI 5600 Part 1 [148]). Overall, the different MES standards and models cannot be mapped completely as there are differences in their functionalities [145], as illustrated in Fig. 3.8.

Nonetheless, the de facto MES standard is IEC 62264—Enterprise Control System Integration. Instrumentation, Systems and Automation Society (ISA) has developed the multipart IEC 62264 standards, which are based on the initial MESA model and functionalities, and subsequently have been enhanced with the data model and activity model (see IEC 62264-1 [121]). IEC 62264 is also known as ISA-95 or ANSI/ISA-95. In addition, Purdue Reference Model (PRM) has also influenced the IEC 62264. IEC 62264 presents a reference model in accordance with ISO 15704 (see IEC 62264 [121, 123]).

MES has manifold advantages. In many industries (e.g., automotive, food and pharmaceutical) traceability is absolutely necessary to satisfy the stringent legislations and legal regulations. Product tracing and genealogy assist in the realization of this requirement. In addition, real-time monitoring and control of manufacturing processes can be achieved that contributes in reduced cycle time, lead time, and WIP [134]. Furthermore, MES supports the attainment of increased quality and efficiency and effectiveness of manufacturing process. The previously mentioned improvement can be around 10–20 % in comparison to monitoring and controlling processes without MES [119, 187]. Overall, MES support process improvement efforts, especially by revealing what is happening.

3.4 Performance Measurement

Performance measurement within and across different enterprise levels is critical to monitor and control of manufacturing processes. Researchers, practitioners, standards organizations and nonprofit organizations highlight the importance of financial and operational metrics.

The financial and operational metrics can be computed using the process data generated at the resource level along with the necessary financial information. In this regard, DPMs was introduced to measure the operational performance, and to connect the resource level with the higher levels of an enterprise [113, 114]. The concept of DPMs was to combine operational performance measurement and accounting, and compute the cost per unit product in real-time using the data acquired directly from resources, sensors and input devices [115]. The researcher introduces the real-time accounting phrase, but lacks details for wide-spread adoption of DPMs.

3.4.1 Performance Measurement Systems

Since the mid-1980s, extensive research has been carried out in the area of performance measurement and management [49]. The research has emphasized the importance of financial and operational metrics, alignment of financial and operational metrics with the enterprise objectives, and inclusion of stakeholders, among others. The following paragraphs present a brief background of PMS, and its characteristics.

3.4.1.1 Background

Post World War II, the market was branded as a seller's market, which was mainly because of high demand for products [109]. Enterprises employing mass production strategies, selling products with marginal quality at high prices and longer lead times, and so forth were the characteristics of the seller's market [109]. The financial metrics were derived through traditional accounting techniques [12]. The traditional performance metrics were adequate to realize the necessary economic scale of production [220].

Around the 1980s, the internal and external operating scenarios of enterprises started changing. The internal environment was transformed for the better with the introduction of management concepts like Just-in-Time (JIT) [109]. The external environment began to change, especially challenging the existing business practices. This resulted in a shift from a seller's market to a buyer's market. Thus today's enterprises have a bigger product portfolio with shorter life spans to address the buyer's market [109].

The traditional financial metrics were insufficient to manage the changes in the external and internal environments [211]. Firstly, these metrics solely concentrated on internal processes with the objective of minimizing the unit cost of a product and variance [14, 116]. Secondly, managers had a retrospective view of an enterprise as the financial metrics were derived offline (e.g., monthly, and quarterly) [109], and hence these metrics are considered as laggards [17]. Next, the metrics did not provide any valuable insight into the processes that can be used as inputs for decision making and process improvement programs, among others [14]. Finally, the financial metrics greatly encouraged the achievement of short-term objectives, did not guide in the realization of the enterprise's strategic, and favored local optimization of processes [102].

The aforesaid drawbacks of financial metrics and the new operating scenarios of an enterprise were addressed with the elaboration of new PMSs. PMS is identified as the "set of metrics used to quantify both the efficiency and effectiveness of actions" [12, 14]. The systems include Performance Pyramid System [109], Balanced Scorecard [85], Performance Prism [12, 169] and European Foundation for Quality Management (EFQM) Excellence Model [40], among others. The PMSs have been adapted in various enterprises [49, 186, 211].

A PMS provides a comprehensive view of an enterprise. Also, research has been extended to foster a collective PMS that includes all enterprises along the supply chain, i.e., in a collaborative setting [8, 16]. However, a PMS does not elaborate about the realization nor does it suggest which performance metrics should be employed, i.e., PMSs are purely considered from a strategic viewpoint [12].

3.4.1.2 Characteristics of Performance Measurement Systems

Numerous characteristics associated with PMSs have been identified [24, 49, 54, 171]. For instance, the desirable features of PMS are: derived from strategy, clearly defined with an explicit purpose, relevant and easy to maintain, simple to understand and use, provide fast and accurate feedback, link operations to strategic goals, and stimulate process improvement initiatives [71]. Likewise, the characteristics of a PMS are as follows: strategy alignments, strategy development, focus on shareholders, balance, dynamic adaptability, process orientation, depth and breadth, causal relationships, and clarity, simplicity and accuracy [49].

The aforementioned listed characteristics of a PMS can be summarized to define the criteria of a good PMS, which can be identified as comprehensive, causally oriented, vertically integrated, horizontally integrated, internally comparable and useful [17]. The comprehensive criteria stress the importance of balanced metrics, which is mentioned in various PMS literature. Next, the performance metrics should

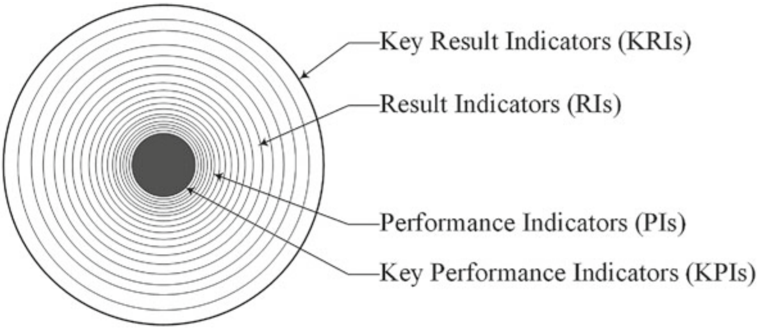

Fig. 3.9 Representation of different types of performance metrics using onion analogy and the relationship among them, adapted from [180]

be modeled to define the causality that assists to navigate, i.e., drill-down or drill-up, and to determine the root causes for performance deviations [17].

The metrics across different enterprise levels should be linked, i.e., vertically integrated, and at the same time the metrics at a particular level should be linked along the manufacturing processes, i.e., horizontally integrated [17]. Further, the metrics should be internally comparable among different metrics, which support decision making by enabling to carry out sensitivity analysis [17]. Finally, the metrics should be useful and trustworthy [17] and install a sense of confidence among the enterprise members in a PMS [204].

Apart from the aforementioned characteristics and criteria of PMS, it is necessary to address the issues of timeliness of computed metrics. The data quality is characterized by multiple attributes—accuracy, completeness, consistency, and timeliness [11]. These attributes have to be given equal weightage during the computation of metrics. Nonetheless, timeliness stands out among the attributes that define the usefulness of data and its computed metrics. The metrics should be computed and presented to enterprise members within a given time frame. Otherwise, the presented metrics do not serve any purpose.

3.4.2 Performance Metrics: Types, Characteristics and Validation

An enterprise employs numerous performance metrics, which depend upon objectives, enterprise level, and enterprise members' roles and responsibilities. Henceforth, metrics, measurements and indicators are used interchangeably. These performance metrics can be classified as Key Result Indicators (KRIs), Result Indicators (RIs), Performance Indicators (PIs) and KPIs, which can be related using an onion analogy, as illustrated in Fig. 3.9. In most of the cases, the performance metrics employed in an enterprise are simply known as KPIs [180].

The outer most layer of the onion consists of multiple KRIs [180]. These indicators are periodically computed for a longer period of time—week, month, or quarter, i.e., backward looking, and indicate if the enterprise is moving in the right direction to realize its planned objectives [180]. The set of KRIs is useful to top management. Thus, financial metrics can be classified as KRIs. Overall, KRIs can be characterized as a closed loop feedback cycle with long cycle times [180]. Next are numerous RIs and PIs. RIs indicate what has been done whereas PIs will inform what has to be done [180].

KPIs exclusively focus on critical indicators that will indicate the current and future direction of an enterprise to realize its planned objectives [180], i.e., forward looking and predictive [141]. KPIs are computed regularly—event-driven, minute, hour, shift, or day, and indicate how to significantly increase the performance [180] via suitable process improvements and optimization (see IEC 62264-3 [23]). Overall, KPIs can be judged as closed loop feedback cycle with short cycle times for operational influence of manufacturing processes (see VDI 5600 Part 1 [148]).

At a given time, enterprise members' can handle only a few metrics [12]. In addition, enterprise members associated with a specific level and department require a unique set of performance metrics. In any given circumstance, the performance metrics must be aligned with the planned/strategic objectives. Accordingly, it is suggested to employ a performance metrics mix in the following ratio: 10 KRIs, up to 80 RIs and PIs, and 10 KPIs [180]. In reality, short-term and medium-term objectives of an enterprise keep on evolving to address its internal and external challenges [13]. Consequently, it is necessary to profile the existing performance metrics mix, and revise it to reflect the current situations and anticipated situations [13, 109].

The aforementioned different types of metrics can be tagged as actionable or reportable metrics [141]. Actionable metrics denote those metrics that need to automatically generate responses from a system (e.g., MES) or inform concerned enterprise members of situations to initiate a corrective action in a timely fashion [141]. For instance, send an e-mail to managers and supervisors about the manufacturing situation when a performance metric crosses its predefined lower or upper threshold limits. Likewise, reportable metrics are used to communicate the trends as reports [141]. According to their description, KPIs and a few PIs can be categorized as actionable metrics whereas the remaining PIs, RIs and KRIs can be classified as reportable metrics.

Today's systems generate voluminous amounts of (raw) data (see IEC 62264-3 [123]). The probability of getting lost in the data is high. Consequently, it is necessary to classify the data and the corresponding metrics in a hierarchical model, and identify the dynamic interplay of factors influencing the performance metrics [209]. Overall, the hierarchy model assist in root cause analysis by performing navigation, i.e., drill-down or drill up.

3.4.3 Production Performance Analysis and Operational Metrics

Non-financial metrics are crucial. These metrics can be related to customers (e.g., customer satisfaction index [109]), logistics (e.g., delivery item accuracy [146]) and production (e.g., cycle time [109]), and so forth. In the presented research, emphasis is on the operational metrics.

According to IEC 62264-3 [123], production performance analysis is one of the core functionalities of MES, which is defined as "the collection of activities that analyze and report performance information to business systems." The production performance analysis is supported by quality performance, maintenance performance and inventory performance analyses (see IEC 62264-3 [123]). Apart from been made available to enterprise members (e.g., operators), the metrics are communicated to enterprise applications (e.g., ERP System) for product cost accounting (see IEC 62264-1 [121]).

There exist different standards and reference models that guide the establishment of aforesaid performance analysis and computation of corresponding operational metrics. Furthermore, different software vendors assist in determining a subset of operational metrics, either as a part of MES or as a standalone system [189]. In addition, many equipment suppliers provide software tools to support the activities of production and maintenance performance analysis.

The operational metrics include resource utilization, resource availability, cycle time, production schedule attainment, production variability and procedure efficiencies, among others [123, 133]. However, OEE has gained tremendous popularity, especially in discrete industries, among researchers, enterprise members and MES software vendors. As a quantitative tool, OEE is an index encompassing three factors—availability, performance and quality [153] and provides a comprehensive view of a single resource. The previously mentioned factors are associated with six big losses—breakdowns, setup and adjustments, small stops, reduced speed, startup rejects and manufacturing rejects [153]. These losses must be identified and eliminated to improve resource effectiveness [153].

A manufacturing enterprise will have multiple resources arranged in different configurations (e.g., series, parallel) and interact with each other [70, 167]. The concept of OEE for a single resource has been extended to determine plant-wide OEE [165]. For instance, production equipment effectiveness can be determined by employing straight or weighted average of OEEs of individual resources [165]. Likewise, research exist to determine Overall Factory Effectiveness (OFE), Overall Line Effectiveness (OLE), and Overall Throughput Effectiveness (OTE) [70, 165, 167, 168, 174].

Nonetheless, OEE and other aforesaid performance metrics have shortcomings in the long run. OEE is appropriate for use in discrete industry that adheres to high volume and low mix production schedules [33, 165, 189]. OEE is indispensable during the initial stages of manufacturing [197]. In order to reduce the six large losses, the enterprise might face other issues [197]. For instance, enterprise members might miss training to maintain high availability of resources [197]. Further, high utilization indicates that the resources are not available for other tasks, like maintenance [197].

The OEE score conceals the information about production orders, product complexity, costs, and so forth from decision makers [153, 197]. Moreover, the score does not suggest improvements and probability exists to misinterpret the scores [153]. The shortcomings of OEE and OTE, among others can be realized by providing enterprise members with multiple operational metrics. In addition, the enterprise

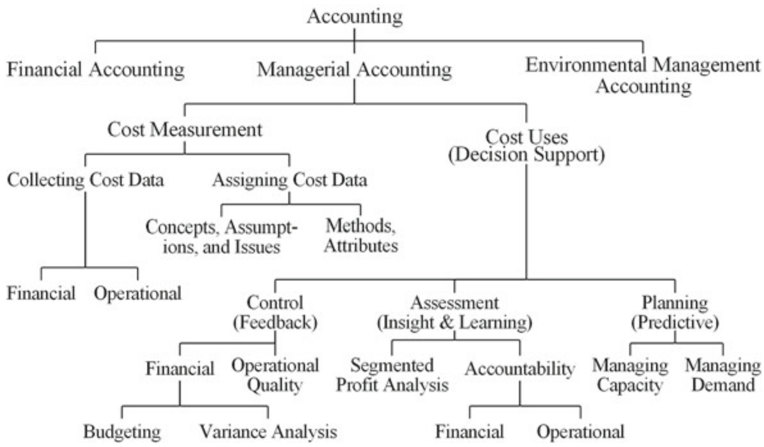

Fig. 3.10 Classification of accounting techniques and their purpose, adapted from [25]. The classification has been extended to include Environmental Management Accounting (*EMA*)

members should be supplemented with financial metrics [229], especially, highlighting the cost effectiveness of manufacturing processes [159]. Thus, this will enable to link the financial and operational metrics in real-time.

3.4.4 Product Cost Accounting and Financial Metrics

IEC 62264-1 [121] lists the functions of product cost accounting as part of Level 4 and interacts with the functionalities of MES, especially with production control functionality. These functions include reporting cost objectives for production, calculating and reporting total production costs, and so forth. Product cost accounting function is carried out with the support of accounting module of an ERP System (see IEC 62264-1 [121]), may be, in interaction with a CRM System and a SCM System. Similarly, there is also a possibility to perform product cost accounting and financial metrics using standalone cost accounting systems [201].

Financial metrics are indispensable for enterprise members belonging to strategic and tactical levels of an enterprise, which helps to identify the health of an enterprise [13]. The financial metrics can include earnings per share, price per earnings ratio, operating profit margin, Return on Assets (ROA), Return on Investments (ROI), among others [13, 55, 109]. Nonetheless, in the presented research emphasis is on manufacturing and related aspects of financial metrics.

The chapter is organized as follows. Section 3.4.4.1 defines cost, lists different types of cost and explains cost behavior. The accounting techniques can be classified into financial and managerial accounting, as illustrated in Fig. 3.10. This classification can be further augmented with the environmental management accounting.

Subsequently, financial-, environmental management- and managerial-accounting are elaborated in Sects. 3.4.4.2, 3.4.4.3 and 3.4.4.4 respectively.

3.4.4.1 Cost: Definition, Types and Behavior

Cost is defined as "the monetary value of resources used or sacrificed, or liabilities incurred, to achieve an objective, such as acquiring or producing a good or performing an activity or service or making resources available but not using them" [74]. The cost term has been prefixed with different names/adjectives; a few of these costs in the context of presented research are listed.

1. Actual cost is the cost incurred, treated as past or historical cost [69]. Actual cost assists to compute the actual costs incurred which are more realistic and might be useful in short-term [84]. On contrary, the incurred costs are difficult to compare with the costs from different period of time.
2. Standard cost is "a carefully determined cost of a unit output" [69]. This cost is established for a given period and updated by considering outputs for a given time interval [84]. This cost assist to compare costs incurred during different period of time [84].
3. Direct cost represents "costs that can be specifically identified with an output" [74].
4. Indirect/overhead cost is stated as "costs of resources that are jointly or commonly used to produce two or more types of outputs, but cannot be specifically identified with any individual output or traced to a given cost object in an economically feasible way" [74].
5. Fixed cost is identified as "costs that remains unchanged in total for a given time period, despite wide changes in the related level of total activity or volume" [69]. Similarly, it can be defined as "costs that do not vary with the volume output" [201].
6. Proportional cost is the "costs that vary with the volume of consumer output" [201]. This cost is based on the principle of responsiveness [225].
7. Variable cost is the "cost that changes in total in proportion to changes in the related level of total activity or volume" [69]. In contrast to proportional cost, this cost is based on the principle of variability, i.e., the total cost varies in accordance to total volume [225].
8. Unit cost is "computed by dividing total cost by the number of units" [69].

The costs incurred are assigned to cost objects [25, 74], which represent enterprise entities that need to be monitored and controlled. The cost object or cost information is composed of fixed costs and/or variable/proportional costs, which can constitute assigned direct costs and allocated indirect costs. From a manager's viewpoint, it is indispensable to highlight the cost behavior, especially, the fixed and variable/proportional costs [69].

Cost behavior can be stated as "determining how inputs (and hence their costs) change with changes in output. Cost may increase proportionally with increasing activity (the usual assumption with variable cost), or it may not change (a fixed cost)" [74]. The cost behavior is influenced by the way the resources are acquired [69]. For instance, the cost of a resource owned by a manufacturing enterprise can be treated as a fixed cost. Likewise, the costs associated with renting a resource can be treated as variable costs.

3.4.4.2 Financial Accounting

Financial accounting (FA) provides a retrospective view of an enterprise. It is mainly concerned with the external reporting that adheres to the laws and regulations of various government regulatory bodies [73]. An enterprise, in most cases, follows accounting standards, like GAAP [25]. Furthermore, the external financial reports are generated following enterprise reporting cycle [84]. Overall, FA provides a tool to check the health of an enterprise regularly, which assists in gaining confidence of financial institutes, customers, shareholders, and so forth.

Nonetheless, FA and its external reports are inappropriate as inputs for planning and decision making by production managers. The external reports are passed to managers, i.e., employing the top-down approach, who must be capable of understanding the jargon of financial terms and statements [84]. The reports are delivered late, well past the completion of the accounting period [84], i.e., the decisions will not match the current manufacturing situations. The reports are highly aggregated, which makes it difficult to recognize the source of problems, and profitable and non-profitable products, among others [84]. Additionally, the upstream processes (e.g., product development) receive misleading product cost information [84]. Overall, the managers find these reports inapt for planning and decision making.

3.4.4.3 Environmental Management Accounting

Environmental Management Accounting (EMA) is identified as one of the components of environmental accounting, defined as the "management of environmental and economic performance through the development and implementation of appropriate environment-related accounting systems and practices" [73]. EMA is concerned with the identification, collection, analysis and use—the physical flow of materials, energy and water, and the associated monetary information [73].

DIN EN ISO 14051—Material Flow Cost Accounting (MFCA) has been introduced to complement EMA [117]. MFCA is based on the principle of material balance. MFCA assists in tracking the quantified flows and stocks of materials and energy within an enterprise. Additionally, the costs associated with the material flows and stocks are also quantified. MFCA is suitable to enterprises involved in manufacturing as well as service. Furthermore, the concept of MFCA can be extended to include all the enterprises across the supply chain.

Nonetheless, MFCA has certain limitations. MFCA data collection is carried for a specified time period (see DIN EN ISO 14051 [117]). In the author's opinion, MFCA is highly useful during the initial stages of manufacturing, where the values can be used as feedback to optimize the upstream processes by identifying wastes, and design constraints, among others. Likewise, MFCA is highly suitable in the scenario of mass production.

3.4.4.4 Managerial Accounting

Managerial Accounting (MA) is also referred as management accounting or managerial cost accounting that attempts to address the shortcomings of FA. According to Federal Accounting Standards Advisory Board (FASAB), managerial (cost) accounting is defined as "the servant of both budgetary and financial accounting and reporting because it assists those systems in providing information. Also, it provides useful information directly to management" [46]. Apart from integrating with FA systems, MA needs to be integrated with other enterprise applications [46].

Managers as well as concerned (front-line) employees require both financial and operational information for internal decision making in a timely fashion. The decision making can be related to production planning and budgeting, initiating process improvement programs, training and learning, what-if analysis, and future investments, and so forth [25, 73, 84]. This information can be basically summarized into quality, time and cost [84], which are highly interconnected. MA attempts to address these requirements, especially from the cost perspective. Subsequently, MA attempts to provide accurate and reliable cost information about the utilization of resources that have monetary value [26, 46]. MA should also provide a platform to investigate the cause-and-effect relationships between inputs and outputs of past and present manufacturing processes, and simulate future manufacturing scenarios [26].

Cost measurement, i.e., collecting cost data and assigning costs, tends to be challenging, especially in scenarios where low volume production and high mix production schedules are employed, products with varying complexity are manufactured, and new processes are frequently introduced [25, 84]. Collecting cost data is split into financial and operational data collections, which are combined to generate cost information [25]. Likewise, cost assignment methods "traces the consumption of "source" expenses (i.e., cash outlay expenditures) to a destination (i.e., cost object) that is of interest to management" [25].

The cost assignment, according to FASAB, employed in MA should follow certain assignment preferences [46], as illustrated in Fig. 3.11. Firstly, directly tracing costs to products based on the (actual) consumption. For instance, materials and (sub-)products costs can be directly traced to the products. Secondly, costs should be assigned to products based on cause-and-effect relationships between resources/operations, and products or between inputs and outputs [46]. For example, labor and energy costs can be assigned to products based on cause-and-effect relationships after the actual consumption. Finally, allocating accumulated indirect costs should be applied proportionally to products based on a predefined cost allocation rule [46].

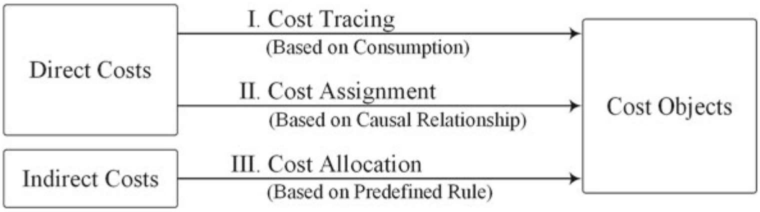

Fig. 3.11 Illustration of different cost assignment preferences, adapted from [46]

Operational data and financial data are two sides of the same coin; they influence the characteristics, including accuracy, reliability, and timeliness, of cost information. MES and accompanying standards place high importance on operational data collection from the resource level. In the same way, numerous accounting techniques have evolved. International Federation of Accountants (IFAC) has identified a costing levels continuum maturity model [75]. In the following paragraphs, a few important accounting techniques are elaborated. Nonetheless, enterprises need to employ multiple accounting techniques to manage their business and manufacturing processes.

Job-Order Costing and Process Costing

Job-order costing and process costing are the managerial accounting techniques that can be placed at the beginning of the costing levels continuum maturity model [75]. Further, an enterprise can employ both job-order and process costing, i.e., hybrid costing [69].

The costs are accumulated in job-order costing for a specific quantity of products that are processed on different resources and are uniquely identifiable [188]. Job-order costing is also known as job costing [69] and project accounting [75]. Job-order costing is initiated after the receipt of the customer's order [188]. The material requisition cards, direct labor time ticket and predetermined overhead rate associated with products are used to determine the costs [188]. In most of the cases, quantity is usually a single unit (e.g., construction of a special purpose machine) [69]. Nevertheless, job-order costing can also be employed to measure costs of identical units of a distinct product [69, 188].

In contrast, process costing is used to calculate costs of products manufactured in a continuous process through a series of manufacturing activities [188]. Process costing is also referred to as lean accounting [75]. Here, the costs are measured periodically for processes, rather than products [188]. The manufactured products are identical, i.e., units require the same input, technology and effort [188], and are produced in high volume [69]. Since costs are measured for processes, process improvement programs can be initiated to improve the product quality and process performance, and subsequently, reduce the costs [75].

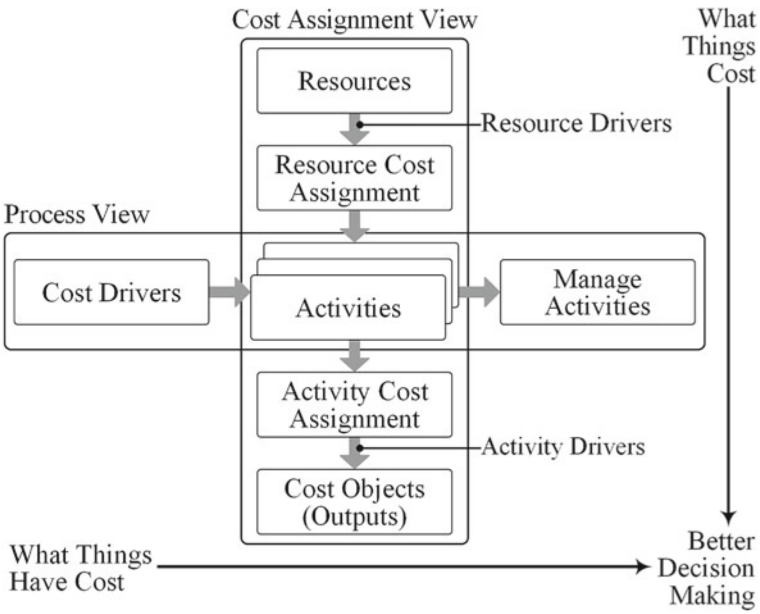

Fig. 3.12 Activity-Based Cost Management (*ABC/M*) framework, adapted from [25]

Activity-Based Costing

Activity-Based Costing (ABC) was an important step forward to address the shortcomings of tradition accounting techniques. ABC concentrates mainly on activities performed in an enterprise [182]. An activity is identified as "work performed by people, equipment, technologies, or facilities" [35]. Since the mid-1980s, extensive research has been performed on ABC. Consequently, Activity-Based Cost Management (ABC/M) framework has been developed [25], as shown in Fig. 3.12. In layman's language, resource costs are assigned to activities depending upon the consumption of resources by the activities, and these activity costs are reassigned to cost object (e.g., products, processes) based on cause-and-effect relationships and proportional use of activities [25, 35].

ABC/M framework consists of the process view and the assignment view along horizontal and vertical directions respectively [25]. The activities are horizontally linked as processes and sub-processes along the process view that are necessary to fulfill the requirements of production orders [25]. The cost assignment view consists of three cost drivers: resource; activity and cost object, and two assignments: resource cost and activity cost [25]. A resource driver "trace expenditures (cash outlay) to work activities" [25]. It quantitatively measures the amount of a resource used by an activity [25, 84]. Furthermore, resource cost assignment is used to link a resource and the activities performed by it [25].

Likewise, an activity driver "trace activity costs to cost objects" [25]. For example, machine hours, production runs, maintenance hours, setup hours are activity drivers. It quantitatively measures the output of an activity [84]. Furthermore, the activity cost assignment is employed to assign activity costs to a cost object based on the consumption of an activity [25, 35]. Finally, the cost objects can be combined along the horizontal process view via cost object drivers, which are identified as "trace cost object costs to other cost objects" [25].

The ABC System can be employed in an enterprise manufacturing heterogeneous mix of products—standard and custom products, low volume products, high volume products and mature products, among others [84, 182]. Nonetheless, it has not been adapted widely, primarily because of its complexity [182, 183, 201]. The definition of activities and associated cost drivers, in most cases, is subjective based on the enterprise members' role, responsibility and experience [201]. Furthermore, managing the activity list is expensive and difficult as the model size increases exponentially [84, 201]. Consequently, it is absolutely necessary to trade off the accuracy of the generated cost information against the effort to maintain the ABC System [84].

Additionally, ABC Systems consider all costs as variable [182, 183, 201], which might be useful for the long-term planning decisions [182]. Nonetheless, the cost information might be irrelevant in the short-term [182]. Furthermore, ABC fails to differentiate the behavior of fixed and variable costs on excess capacity [182], which hinders performance analysis, and planning and decision making. Finally, the ABC concept is a unidirectional step-down approach, i.e., costs flow from resources to activities to (final) cost objects [201]. Accordingly, fully burdened resource costs, i.e., true interrelationships between senders and receivers of activities, and resources are not realized [201].

Time-Driven Activity-Based Costing

ABC was an important step in overcoming the drawbacks of traditional cost accounting. Nonetheless, there are inherent issues with ABC as previously mentioned. The aforementioned ABC was simplified by employing time-based activity drivers [75]. This simplified ABC concept is known as Time-Driven Activity Based Costing (TDABC) [82, 83]. TDABC requires two input parameters for an activity—the capacity cost rate of supplying a resource and the capacity usage of the resource by products, service and customers, which are multiplied to derive the cost information [82, 83].

TDABC has several advantages in comparison to ABC. TDABC stresses rough accuracy instead of precision [82]. Using two input parameters, the model size of TDABC tends to increase linearly in comparison with ABC [83]. However, TDABC can be employed in an enterprise with highly repetitive transactions and fewer indirect costs [75].

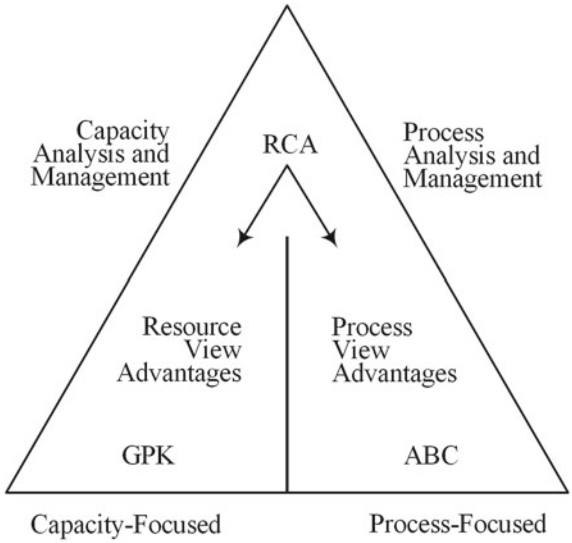

Fig. 3.13 Resource and process view of Resource Consumption Accounting (*RCA*), adapted from [225]

Resource Consumption Accounting

The shortcomings of ABC that impede the decision making process have been addressed with the introduction of Resource Consumption Accounting (RCA). RCA stresses the importance of resources, the nature of costs and a quantity-based approach to cost modeling [156]. RCA encompasses a resource and process view of costs [201], as depicted in Fig. 3.13. The resource view provides robust functionalities to analyze the resources' capacities and their costs [201]. In this regard, RCA is based on Grenzplankostenrechnung (GPK) or marginal planned cost accounting. GPK has been successfully employed since the late-1940s by manufacturing enterprises in German speaking countries and German companies [202, 201, 225].

RCA stresses the importance of the process view to manage the activities and complement GPK [225]. The process view incorporates the best practices of ABC [201, 225]. The concept of activities is applied in a limited and disciplined fashion to avoid the complexity of activity models [225]. Similarly, the cause-and-effect relationships assist in tracing the flow of resource outputs and their costs [225].

RCA technique is built around recourses and not activities [225]. The capacity, capabilities and costs reside in resources [225]. The resources with similar characteristics and outputs, among others, are grouped together in a resource pool [93, 225], as depicted in Fig. 3.14. Furthermore, the cause-and-effect relationships are realized by resource drivers and activity drivers. In contrast to ABC, these drivers are quantity-based indicating quantity of resource (pool) output consumed, with the understanding that costs follow quantity [201]. In contrast to quantity-based assignment, value-based assignment is the allocation of costs as ratios or percentages for consumed resources/activities [201]. In addition, the costs are tagged as primary and secondary costs [182].

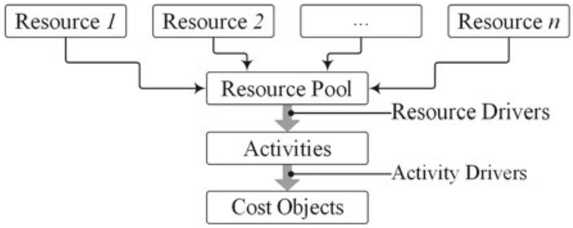

Fig. 3.14 Schematic overview of Resource Consumption Accounting (*RCA*), adapted from [224]

The primary costs originate in a resource and are assigned to the corresponding cost objects [182]. Likewise, secondary costs are assigned to a resource that originates from another resource [182]. Furthermore, these costs are modeled as fixed and proportional costs [93, 182, 201, 225]. Here it is important to note that there is difference between variable and proportional costs (see Sect. 3.4.4.1). The modeling of aforesaid costs depends upon relationship between resource inputs and its outputs [225].

The fixed costs are computed based on the theoretical capacity of a resource pool and are not assigned (purely) based on the consumption of resource outputs [182, 201]. Furthermore, the fixed costs will exist as long as the resource is available [93]. In contrast, proportional costs are assigned based on the consumption of resource outputs [182]. Likewise, there are quantities that can be treated as fixed and proportional [201]. Overall, the aforementioned costs and quantities along with the resource output quantity are used to derive the resource unit rate, as illustrated in Fig. 3.15.

RCA stresses the importance of the inherent nature of cost [93, 155]. This initial nature of cost is reflected in primary fixed and proportional costs, which are incurred at a resource [93]. Likewise, the changing nature of cost is reflected in secondary fixed and proportional costs during the consumption of resource outputs [155]. Overall, the interrelationships between resources and the corresponding quantity flows, i.e., underlying nature of costs, are crucial.

RCA presents managers with detailed and accurate information about resource quantity consumption with the ability to carry out variance analysis at the resource level [94]. This assists in managing planned and theoretical capacity [182], especially the identification of excess/idle capacity. For instance, analysis of secondary, fixed and proportional costs assist in making decisions on outsourcing of manufacturing activities [93]. Furthermore, RCA assists managers by providing predictive resource planning capabilities [75], by simulating different planning scenarios. Finally, RCA has been integrated with ERP Systems, especially SAP R/3 [201].

Nonetheless, there are shortcomings with RCA that are comparable with ABC drawback [182]. RCA introduces new levels of complexity [93, 182]. For instance, the managers have problems initially in classifying the fixed and proportional costs for a resource pool [182].

Resource *XYZ*	Resource Output: *XXXX* Machine Hours				
	Quantity		Expenses (Eur)		
Primary Expenses	Fixed	Proportional	Fixed	Proportional	Total
Supervisor Salary	-	-	XXXX	-	XXXX
Labor	-	-	-	XXXX	XXXX
Depreciation	-	-	XXXX	-	XXXX
Energy	-	-	-	XXXX	XXXX
Secondary Expenses	Fixed	Proportional	Fixed	Proportional	Total
Maintenance	XX	XX	XXXX	XXXX	XXXX
Total			XXXX	XXXX	XXXX
Resource Output Unit Rate: Euro/Machine Hour			*XXXX*	*XXXX*	*XXXX*

Fig. 3.15 An example depicting the calculation of resource output unit rate in Resource Consumption Accounting (*RCA*) by considering primary and secondary expenses, and fixed and proportional quantity and costs, adapted from [201]

3.5 Event, Event-Driven Architecture and Event Processing

Artificial Intelligences (AI) techniques have been used to solve complex problem. These techniques are composed of different subareas—expert systems, and neural networks, among others [18]. Expert systems stand out among AI techniques and have been employed to solve real-world problems in manufacturing, medical diagnosis, banking and so forth [18]. These systems are expensive to build and require high initial effort [18]. On the contrary, these systems are easy to maintain and use [18].

The Rule-Based System (RBS) is a type of expert system [1, 18]. Numerous interference engines have been developed to provide answers/predictions/suggestions to incoming questions by inferring the knowledge base [1]. The knowledge base is modeled as rules, usually as if-then statements [18], which are acquired from human experts and analytical techniques. Nonetheless, RBSs do not have the capability to handle temporal reasoning [118], which is a significant hurdle in realizing real-time monitoring and control of manufacturing processes. Subsequently, the concepts of Event-Driven Architecture (EDA) and Event Processing (EP) have to be exploited to overcome the previous limitations of RBS.

3.5.1 Events: Definition and Aspects

Events are ubiquitous, which can be defined as "anything that happens, or is contemplated as happening" [108], i.e., represented as change in state [212]. An event is also known as a notification when the event has corresponding data to describe it [166]. Similarly, a notification is treated as a message when it is shared with other components of EDA via a communication channel [166].The computer science scientists perceive events in totally different ways and define them as "object that is a record of

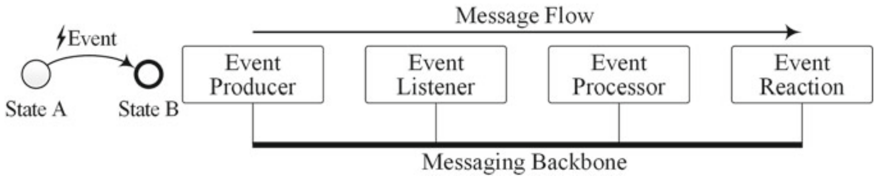

Fig. 3.16 Different components of Event-Driven Architecture (*EDA*), adapted from [212]

an activity in a system" [106], which can be processed by computer systems [108]. An event object encompasses three aspects:

1. Event form indicates the data associated with an event and are also known as an event attributes [108]. The data can be a combination of simple and complex data types, and timestamps [108], which can originate from multiple sources [212].
2. Event significance denotes an activity/operation and the corresponding data associated with the activity is represented by the event form [106].
3. Event relativity describes the relationships with other events [106].

In manufacturing scenarios, an event form can be represented by manufacturing activity parameters (e.g., temperature and spindle speed), event significance denotes manufacturing activity (e.g., milling), and event relativity identifies the relationship of a manufacturing activity with the product and production order.

3.5.2 Event-Driven Architecture

Event-Driven Architecture (EDA) can be defined as "an architectural style in which components are event driven and communicate by means of events" [108]. It contains different architectural elements necessary to broadcast an event immediately to all the interested receivers—human and (semi-)automated systems [160, 212]. Furthermore, identification, broadcasting, processing and utilization of events can be realized employing different components—event producer, event consumers, event processors, event reactions and messaging backbone, as illustrated in Fig. 3.16.

Event producer is a component in which the events originate and are responsible to publish events [166, 212]. Event producers take different forms [212]. For example, event producers can be software programs or temperature sensors in a machine. Further, the event contains data that might or might not originate at event producers [212]. Finally, the events are pushed to multiple event listeners [212] and the event producers are unaware of event listeners [166]. Event listeners receive only subsets of events in which they are interested [212]. Event listeners can also be event producers [166]. Apart from listening to a subset of events, event listeners should be capable of analyzing the incoming events [160, 212].

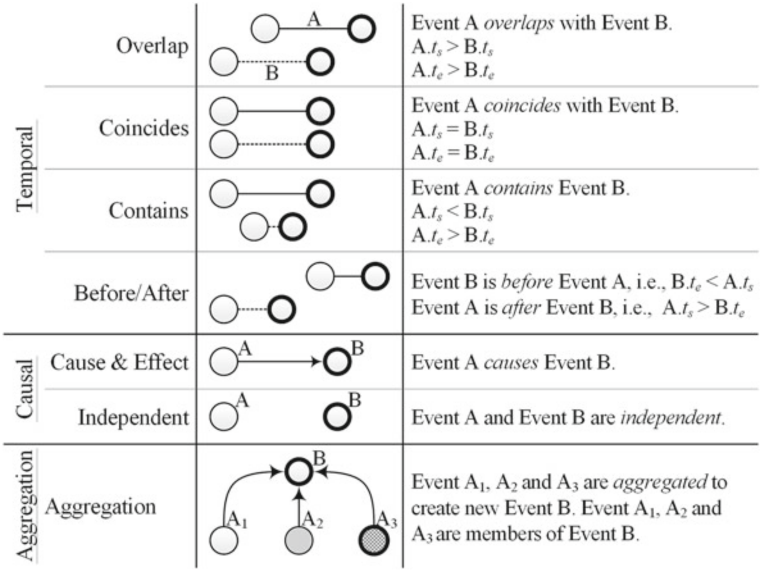

Fig. 3.17 Representation of possible relationships between events based on time, causality and aggregation, adapted from [3, 106]. Here, t_s and t_e denote start time and end time of an event

The analysis of the incoming events will be handled by the event processor [212]. The outcomes of an event processor are event reactions [212]. The event reactions vary from event type to event type, which can be a combination of do nothing, displaying warning messages, initiating pre-defined actions, and triggering new events. The aforementioned components of EDA communicate via a messaging backbone [212], communication mechanism [166], or an event channel [108]. The messaging backbone encompasses multiple hardware components, software modules, network protocols and messaging formats [212].

3.5.3 Event Relationships: Time, Causality and Aggregation

Events are triggered randomly, which necessitates establishing relationships between events to realize real-time monitoring and control of manufacturing processes. There exist different types of relationships between events, which are possibly based on time, causality and aggregation [106], as depicted in Fig. 3.17.

EDA stresses the importance of time and provides capability to handle temporal reasoning. Consequently, there are different temporal relationships, as shown in Fig. 3.17. To realize temporal reasoning and for other processing purposes, it is mandatory for each event to have timestamps, which are based either on the clock of the event producer or event processors [106]. There exist different semantics to

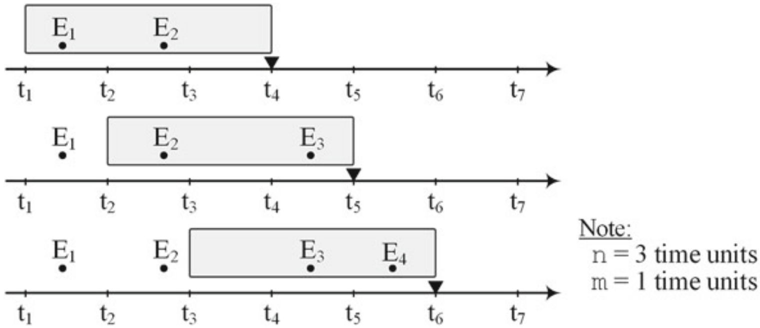

Fig. 3.18 Illustration of overlapping sliding window that assist to realize temporal relationships between events, adapted from [20]

represent timestamps of an event [222]. Firstly, point-based time semantics would assign only a creation time to an event by its event producer or event listener [222]. Secondly, it is possible for an event, especially time consuming, to have interval-based time semantics [222], i.e., event can have start time t_s and end time t_e. Finally, point-interval-based time semantics represent an event with a creation timestamp and also assigns duration, especially to handle the clock's uncertainty and network delays [222].

A window operator is essential to detect temporal relationships [21, 223] and provides a historical snapshot for finite length of time units [20]. There exist numerous types of window operators [20]. The sliding window operator can be demarcated as window length of n time units and advanced by m time units [20]. The sliding (or rolling) window operator can be further classified as an overlapping or as a disjoint sliding window [20]. An overlapping sliding window operator shares its portion of the new window with the old window [20], as illustrated in Fig. 3.18. In contrast, the new window and old window do not share any portion of the window in a disjoint sliding window [20].

Causality is defined as a "dependence relationships between activities in a system" [106]. In contrast, the events are considered as independent events if relationships cannot be established between events [106]. Likewise, aggregation is employed to transform low level events to high level events [106]. The subsets of attributes of low level events are members of high level events [106].

3.5.4 Event Types, Event Hierarchy and Event Cloud

The events can be classified based on event creation, which is subjective [108]. To begin with, a simple event is defined as "an event that is not viewed as summarizing, representing, or denoting a set of other events" [108]. In contrast to simple events, a complex event is defined as "an event that summarizes, represents, or denotes a set

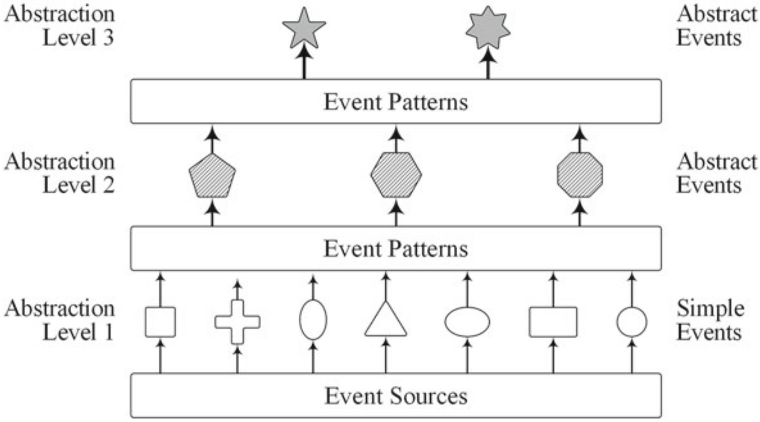

Fig. 3.19 Simplified view depicting event abstraction hierarchy, adapted from [21, 106]

of other events" [108]. The complex events can be further categorized as derived and composite events based on the methods employed to create these events [108].

A derived event can be defined as "an event that is generated as a result of applying a method or process to one or more other events" [108]. For instance, derived events can be generated by performing mathematical computations on events. Likewise, the absence of an event in a given time interval after arrival of a specific event can be considered as a derived event [108]. Similarly, a composite event can be stated as an event "that is created by combining a set of other simple or complex events (known as its members) using a specific set of event constructors such as disjunction, conjunction, and sequence" [108].

In general, the simple and complex events differ according to the level of information made available by these events for decision making. An event abstraction can be defined as the "relationship between a complex event and the other events that it denotes, summarizes, or otherwise represents" [108]. There exist thousands of isolated simple events with low abstraction levels in a system, which most of the time do not make any sense [21, 106]. The simple events need to be aggregated into abstract events with higher abstraction levels, as depicted in Fig. 3.19. These events represent several activities/events that are triggered at different times [106], i.e., support temporal reasoning. Consequently, fewer events with higher event abstractions are available for interpretation [107].

Event patterns are necessary to create events with higher abstraction levels [21, 106, 108]. An event pattern is defined as "a template containing event templates, relational operators and variables" [108]. For instance, an event pattern can be described to select all transportation start events.

Simple events are associated with the lowest abstraction level, i.e., Level 1 [106]. Likewise, complex events can be associated with higher abstraction levels i.e., Level 2 and higher [106]. Furthermore, the events are hierarchically arranged according to their abstraction level—Level 1, Level 2 and so forth, which is known as event

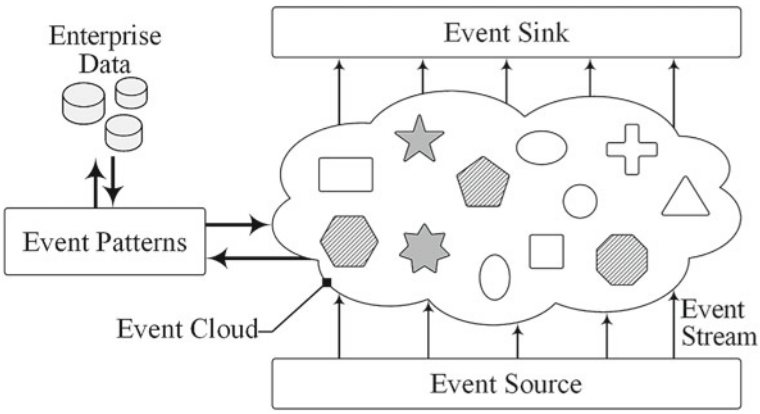

Fig. 3.20 Event cloud containing all events in a system, adapted from [21, 106]

hierarchies [21] or event abstraction hierarchies [106]. The event hierarchies establish vertical causality relationships between events across different abstraction levels [106]. In contrast, horizontal causality determines relationships between events in a particular abstraction level [106].

Numerous different types of events are detected by event consumers [108]. The sequence of incoming events is known as event stream [21], as depicted in Fig. 3.20. An event stream is defined as a "linearly ordered sequence of events" [108], which are usually arranged according to arrival/creation time and causality [21, 108]. Furthermore, different types of events along with their relationships and abstractions are available in an event cloud for processing [108].

3.5.5 Event Processing Agents and Networks, and Complex Event Processing

Event processing is characterized by event capture, event analysis and event response based on sense-analyze-respond paradigm [21], as illustrated in Fig. 3.21. Event processing can be defined as "computing that performs operations on events, including reading, creating, transforming, or discarding events" [108]. Here, event processor and event analysis are synonyms of event processing (see Sect. 3.5.2). Similarly, Complex Event Processing (CEP) deals with complex events [108].

Event patterns, mentioned previously, are critical for realizing event processing, which are encoded in a software module as Event Processing Agents (EPAs) [45, 106]. EPA can be stated as "an entity that processes event objects" [108]. EPAs have the capability to perform different computations on events, like filtering, aggregating and deleting event patterns [106, 108] or filtering, matching and derivation [45]. The aforementioned EPAs can be organized into networks and communicate

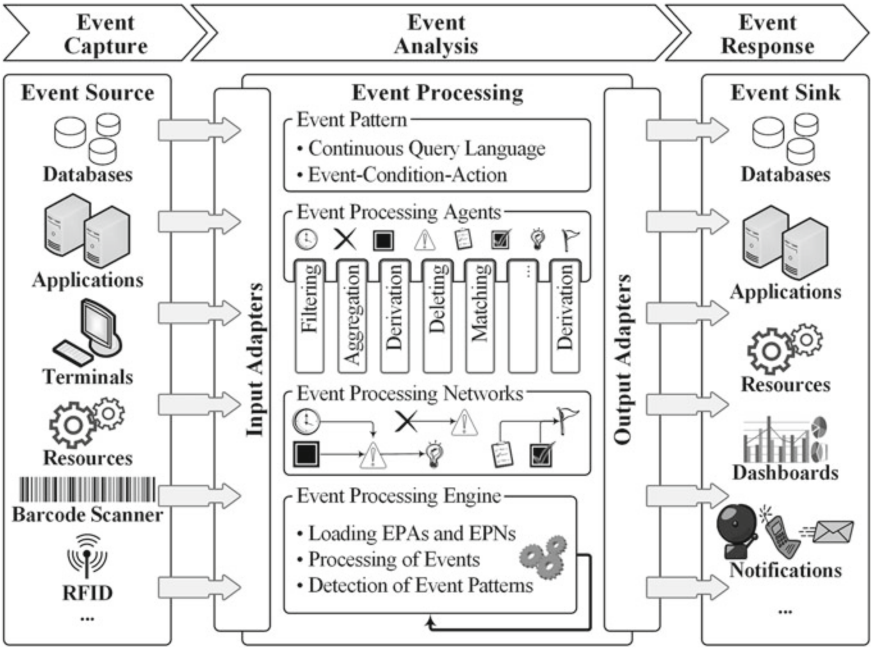

Fig. 3.21 Overview of different components of event processing, which is based on the sense-analyze-respond paradigm, adapted from [21, 218]

with each other using the event channel to form Event Processing Networks (EPNs) [45, 106, 108], which assist in the realization of horizontal and vertical causality [106]. Furthermore, EPNs can be nested and recursive to represent the complex manufacturing processes.

The aforesaid event patterns and the corresponding EPAs are defined using Event Processing Language (EPL) that can be interpreted by the event processing software [45, 106, 218]. EPL can be defined as "a high level computer language for defining the behavior of event processing agents" [108]. There exist different language styles—stream oriented, rule-oriented and imperative/scripting [45, 218]. Nonetheless, each vendor uses a specific language style and there exist no standard language style [218].

Stream-oriented languages are used to identify event patterns from event streams, which the exploit database's Structured Query Language (SQL) [107, 218]. Subsequently, SQL-based language style is referred to as Continuous Query Languages (CQL) [5, 107]. Likewise, rule-oriented languages are identical to the production rule or business rule definition, i.e., if-then notation [218]. Here, the rules are constructed using event-condition-action notation [181, 193].

As mentioned previously, there exist numerous event producers and event consumers. Accordingly, (complex) event processing needs to have necessary input adapters and output adapters that will assist in interpreting the incoming and formatting the outgoing events respectively [218]. Event processing software loads the

EPAs and EPNs into computer memory and processes the incoming events from the event cloud. Event reactions are described as the (re-)action to be taken whenever an event pattern is matched or a predefined situation is detected [108]. These reactions are defined in event pattern rules [106] or event pattern triggered reactive rules [108]. In most cases, the reactions create new events with higher abstraction levels and/or invoke predefined methods.

3.5.6 Event Processing in Manufacturing

Most of the vendors of event processing software focus on financial trading, telecommunication and other related industries [218]. Nevertheless, many vendors specify manufacturing as one of the industry focuses [218]. In reality, event processing in manufacturing has not been adapted extensively.

An extensible event-driven manufacturing system was elaborated [233]. This system was built on the MES platform with a tight integration between the enterprise control level and the manufacturing level, and used CEP engine to manage events. However, the underlying MES platform is unclear (e.g., data collection) as is the case study. Likewise, a unified event management system based on the publish/subscribe paradigm was conceptualized to deal with primitive and complex events for monitoring and controlling manufacturing processes [222]. The system is based on EDA and positioned at the manufacturing control level and integrates real-time data from the manufacturing level.

In contrast to research, event processing has been adapted by commercial MES vendors, especially FORCAM [119] and System Insights [210]. FORCAM's event processing capabilities are unclear as well as the underlying event processing software. However, System Insights employs either JBoss Drools Fusion or EsperTech Esper as the underlying event processing engine [219]. In addition, few event processing vendors focus on manufacturing/production. For instance, TIBCO Business Events are employed to optimize the supply chain [147].

3.6 Summary

A manufacturing enterprise requires performance measurements, which consider both financial and operational metrics. The calculation of operational metrics has been realized in real-time. However, the financial metrics are calculated according to a certain enterprise's reporting cycle and are considered as lagging metrics.

The computation of operational metrics in real-time and the transformation of lagging financial metrics to leading financial metrics require inter-disciplinary fundamentals, technologies and standards. Subsequently, these inter-disciplinary fundamentals, technologies and standards have been elaborated in the current chapter. Furthermore, the timeline and inter-relationships among inter-disciplinary fundamentals, technologies, and standards are illustrated in Fig. 3.22. In short, most of the above activities have been performed in isolation and with a narrow perspective.

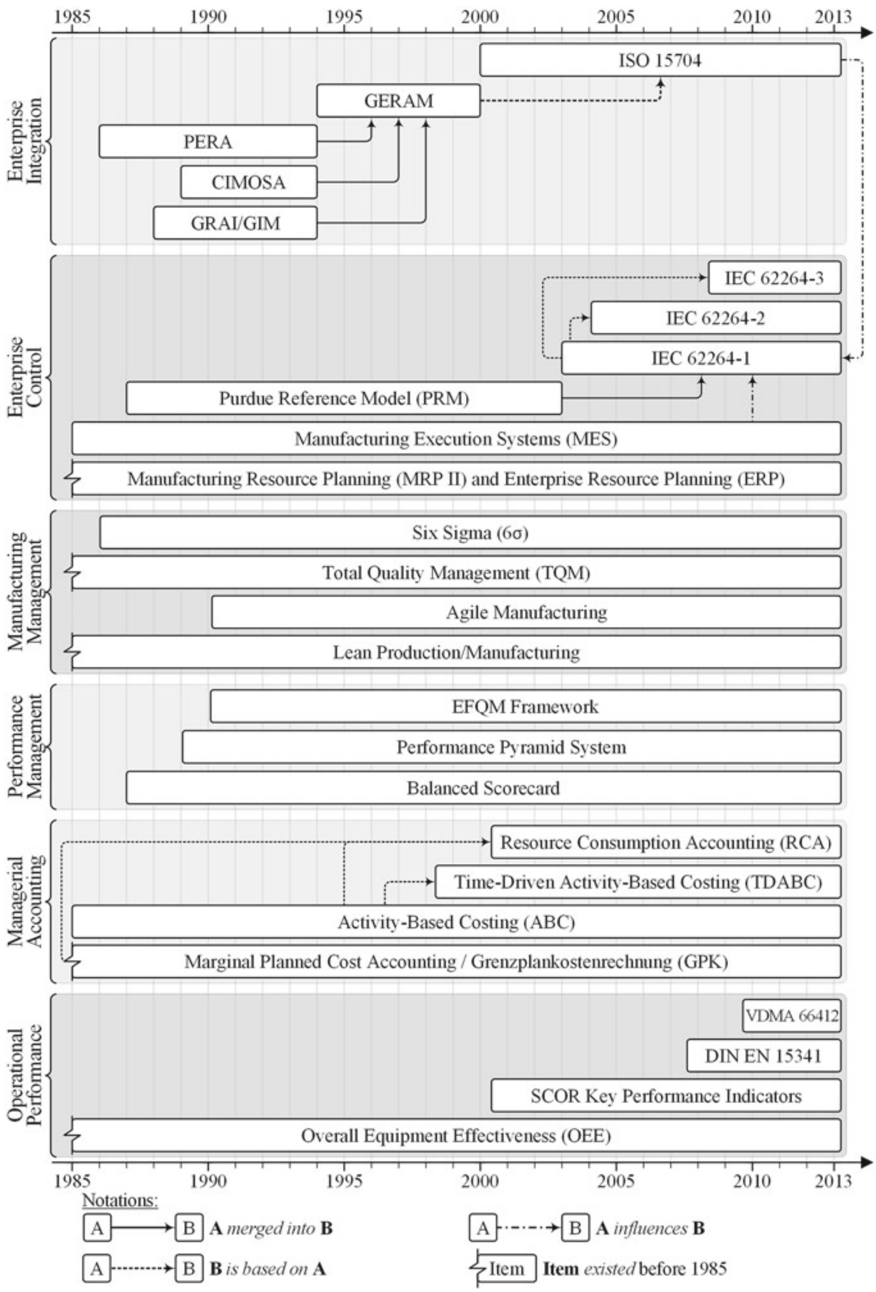

Fig. 3.22 Timeline and relationships among different fundamentals, technologies, and standards

Chapter 4
Real-Time Performance Measurement in Manufacturing

Chapter 3 imparted the necessary foundation to address the research goals. A reference architecture will be presented to address the goals, and reinforce the existing monitoring and control of manufacturing processes. The content of the current chapter is partially based on authors published articles in international conferences and journals [57, 60, 61, 86–89, 158]. The chapter is organized as follows. Section 4.1 describes an overview of the reference architecture for realizing EI and real-time performance measurement. The architecture encompasses multiple components, which are elaborated from Sects. 4.2–4.8. Finally, Sect. 4.9 concludes with a summary.

4.1 Reference Architecture: Overview

The previously mentioned issues with the performance measurement (see Chaps. 1 and 2) can be addressed using different inter-disciplinary fundamentals, technologies and standards. Thus, it is indispensable to list and link the previously elaborated inter-disciplinary fundamentals, technologies and standards to elaborate the reference architecture for real-time performance measurement.

Research is carried out at Business and Information Systems Engineering (BISE), University of Siegen to enable EI, which can be considered as a basic building block. The basic building block is exploited to address the previously mentioned goals, and to reinforce the existing performance measurement. This has resulted in development and implementation of a reference architecture that is loosely based on the concept of MES, and considers different characteristics and requirements of a manufacturing enterprise.

The reference architecture encompasses numerous components, as illustrated in Fig. 4.1. The architecture attempts to realize many of the functionalities of MES and further augmented with additional functionalities, like event processing and managerial accounting. Overall, these components can be seen as indispensable for the establishment of closed loop monitoring and control of manufacturing processes. These components are briefly described as follows:

S. Karadgi, *A Reference Architecture for Real-Time Performance Measurement*, Progress in IS, DOI: 10.1007/978-3-319-07007-0_4,

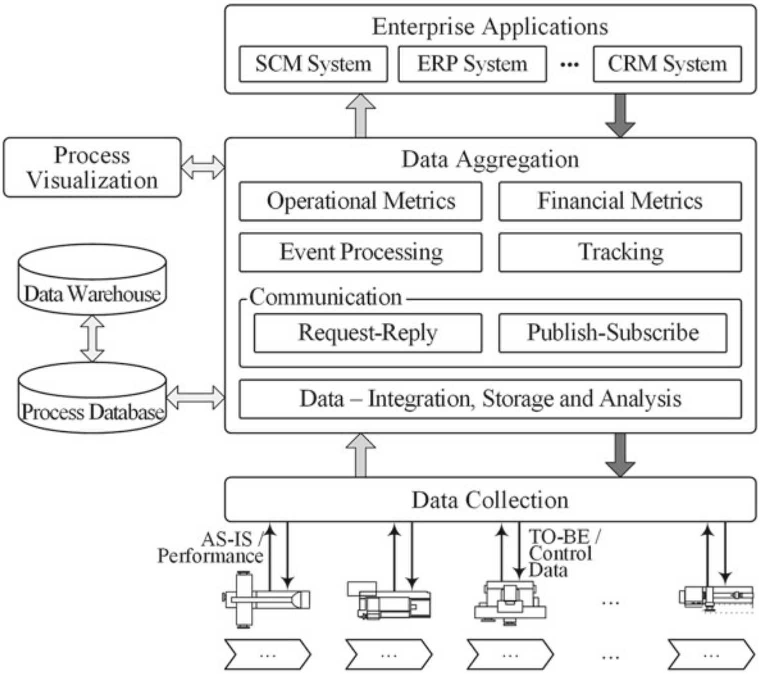

Fig. 4.1 A reference architecture for real-time performance measurement and its components

1. The resources on the shop floor are arranged in different configuration. These resources use different standards and proprietary communication protocols to communicate with other resources and manufacturing management systems, and these protocols are determined by the resource vendors. Subsequently, data collection, at the bottom, provides a modular approach to manage the heterogeneous communication protocols of resources and delivers process data in real time.
2. The real-time process data delivered by data collection is handled by data aggregation. The real-time process data is assigned to suitable enterprise entities along with the corresponding transactional data from enterprise applications, especially from the ERP System. This data would be referred to as integrated process data, which is managed simultaneously in two ways. Firstly, the integrated data is stored in a process database, which is used for offline analysis. Secondly, the sub-set of integrated data is employed to realize tracking of enterprise entities in real-time. Tracking is prerequisite for real-time monitoring and control of manufacturing processes that can be achieved by employing the state-of-the-art event processing techniques. Subsequently, dispatching control data to achieve planned objectives of a manufacturing enterprise. Additionally, tracking information can be employed to determine real-time operational and financial metrics.
3. Numerous process visualization clients communicate with data aggregation based on client-server architecture that employs both publish-subscribe and request-reply mechanisms. The clients provides interfaces, considering the roles

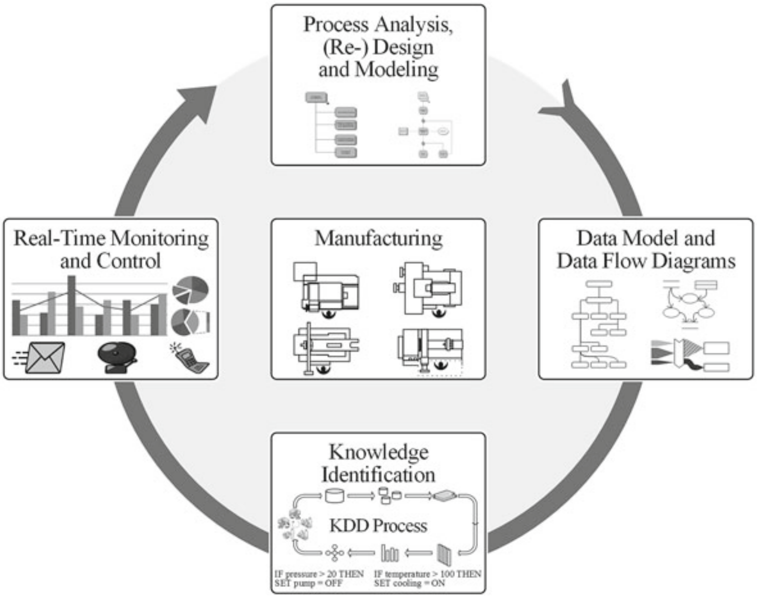

Fig. 4.2 Tasks for realizing the reference architecture for real-time performance measurement, adapted from [158]

and responsibilities of enterprise members, to display real-time process data and tracking information, and to support traceability of enterprise entities, among others.

The reference architecture for real-time performance measurement and underlying real-time monitoring and control of manufacturing processes can be successfully realized by employing additionally tasks, as shown in Fig. 4.2 and listed as follows:

1. Process analysis, modeling and (re-)design are indispensable for monitoring and controlling business and manufacturing processes. EI related standards highlight the importance of process analysis and modeling. Hence, it is necessary from time to time to optimize the processes employed to adapt to the internal and external environments.
2. Data model based on available standards, and Data Flow Diagrams (DFDs) among different resources and Information Technology (IT) Systems have to be created, which assist in the understanding and effective use of the acquired real-time process data, and support root-cause analysis, among others. In addition, it might be required to generate different types of charts depending upon the functionality and problem.
3. Knowledge of real-time monitoring and control of manufacturing processes is (tactically) embedded in the integrated process data, which is stored in a process database. Knowledge Discovery in Databases (KDD) can be employed to determine new knowledge. Additionally, structured interviews with domain experts

can be useful to identify new knowledge, validate new knowledge derived using KDD techniques and update the existing knowledge.

These additional tasks can be positioned around manufacturing processes. Furthermore, these tasks are unique to a manufacturing enterprise and need to be carried out regularly, however, perhaps not sequentially.

4.2 Process Analysis, (Re-)Design and Modeling

Manufacturing enterprises continually evolve/transform for manifold reasons. For instance, an enterprise adapts best practices or good operating practices (e.g., Good Manufacturing Practice (GMP) in pharmaceutical) available in its area of competences. Likewise, an enterprise needs to address the changes in its external environments. The changes can be incremental, discontinuous, organizational, anticipatory, and reactive [19]. Nonetheless, the manufacturing processes executed physically, and the virtual processes that are part of enterprise applications and manufacturing management systems should be in sync and mapped, which is a strict prerequisite to successfully realize real-time monitoring and control of manufacturing processes.

Subsequently, process analysis and (re-)design are indispensable. Process analysis assists in knowing the current/AS-IS situation and suitably (re-)act to address problems, gaps and changes. It deals with decomposition of functions/activities, and construction of logical models of processes and identification of data necessary for the execution of functions [29]. Process analysis can be accomplished by using methods such as questionnaires, structured interviews, observation and auditing documents [19].

In the presented research, processes are viewed from wider sense, which might involve business and manufacturing processes. Business process is defined as a "set of logically related tasks performed to achieve a defined outcome" [34]. Today, these processes are heavily supported by IT Systems and managed as part of business process management [19], and further implemented as services based on SOA concepts [105]. Business processes are relatively easy to re-design to adapt to incremental changes [19]. An enterprise requiring radical transformation to address discontinuous changes must follow the techniques of Business Process Reengineering (BPR) [19].

On the contrary, manufacturing processes are difficult to re-design to address changes via reconfigurability, which is separated into logical/soft and physical/hard reconfiguration [41, 42, 227]. The logical reconfiguration is related to process planning activities, which can be accomplished through re-routing, re-scheduling, re-planning, and/or re-programming [42]. Likewise, the physical reconfiguration is associated with physical reconfiguration of shop floor resources [42]. In either case, the reconfiguration is necessary due to dynamic changes in product development, process planning, investment in new resources, and/or disruptions on the shop floor.

Process modeling, nonetheless, depends on process analysis and assists in significantly enhancing the outcome of process (re-)design. It provides a comprehensive understanding of processes that are employed in an enterprise [2]. However, process modeling is a time consuming activity and effort is required to maintain the process models. Overall, process models are starting points toward successfully implementing IT Systems, especially related to enterprise applications and manufacturing management systems, including the aforementioned reference architecture.

Several modeling languages and methodologies are available to model processes [2], like Event-driven Process Chain (EPC). These modeling languages focus on tangible inputs and outputs. The outcomes of process modeling are (flow) charts, diagrams and dictionaries [29]. Overall, EI related standards have stressed the importance of modeling, which is indispensable during the realization of interoperability and integration of different IT Systems.

4.3 Data Modeling

Today's manufacturing resources are complex; several inputs are required by these resources during the execution of manufacturing processes. In addition, enormous amounts of data are generated on the shop floor by resources in real-time indicating product positions, error messages, and timestamps, among others. Hence, it is necessary to rely on previously mentioned process models and furthermore, construct data models and DFDs.

Data models help to comprehensively understand the manufacturing processes, enhance monitoring and control of manufacturing processes, and support interoperability and integration across different enterprise levels. Data models have been standardized across numerous manufacturing processes and manufacturing types. These standard data models alone are not sufficient, but need to be augmented to suite the existing environment, in terms of IT Systems and resources, of a manufacturing enterprise.

The computer science community represents the data model, especially in a hierarchical structure, with necessary attributes and methods, and preferably modeled using Unified Modeling Language (UML) notation. Likewise, Entity Relationship Diagrams (ERDs) provide a high-level view of enterprise entities and their relationships, without considering the underlying attributes and methods [9]. For example, Fig. 4.3 schematically illustrates different enterprise entities and their relationships, which is necessary to realize tracking and traceability functionalities [38].

The data model provides a static structure of enterprise data. In contrast, DFDs reveal the interdependencies by depicting information flow among enterprise entities, mainly between IT Systems and resources, either in isolation or in combination [92]. In addition, DFDs can also assist in identifying the input and output information of manufacturing processes [9]. There exist different methods and techniques to illustrate data flow between enterprise entities [2]. To address the complexity of machines and IT Systems, DFDs are modeled in hierarchy levels [9]. Coarse-grained DFD, i.e., Level 0, can depict an overview of machines on a shop floor and their intercommunication may be denoted by primary key. Likewise, Level 2 and Level 3 DFDs provide detailed information about a specific process and machine.

Similar to DFDs, Sankey diagrams have been widely used to represent economic value of energy and material flows [195, 196]. Sankey diagram was introduced more

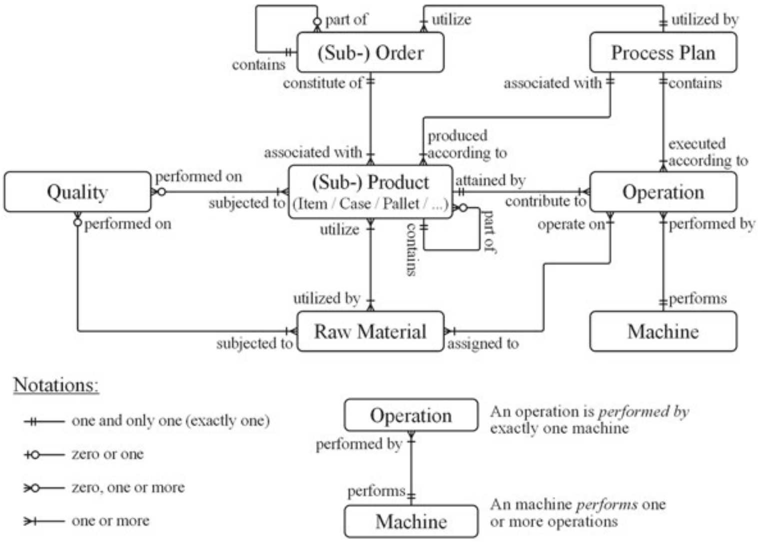

Fig. 4.3 An example of an Entity Relationship Diagram (ERD), adapted from [38, 190]

than 100 years back by Irishman Riall Sankey to measure the energy efficiency of a steam engine [195]. In Sankey diagrams, the flow is represented by arrows and its width denotes quantity of flow [195], expressed either as a number or percentage. These diagrams assist in identifying inefficiencies or losses, and potential savings in terms of cost and material, which are based on the input-output balance [195].

Furthermore, IEC 62264-2 [122] is the de-facto standard for discrete industry to define data interface between enterprise applications, especially the ERP System and manufacturing management systems, particularly MES. Furthermore, the data interface has been codified as XML and is available as B2MML. Similarly, PAS 1074 [144] describes interface, as an XML structure, between ERP Systems and MES for managing production order across multiple enterprise.

4.4 Data Collection and Integration of Resources

There is a proverb "you reap what you sow," which brings data and its quality dimensions into the foreground. There exist different types of data that can be associated with the enterprise entities characteristics or description of enterprise entities, process parameters employed by the manufacturing processes, and so forth [38]. Likewise, the dimensions of data quality are represented by accuracy, completeness, consistency, and timeliness [11]. Nonetheless, the collection of process data from resources on the shop floor and the adherence to data quality dimensions is not straightforward for numerous reasons.

4.4.1 Background

Today's manufacturing resources mostly accommodate Programmable Logic Controllers (PLCs) with dedicated terminals. In the case of manual operated resources, special terminals are made available to the operators of these resources with an intention to assist bi-directional communication between resources, and manufacturing management systems and enterprise applications. These terminals assist operators by providing/selecting necessary inputs (e.g., resource parameters) before the execution of manufacturing processes and later support operators to provide manual feedback. For instance, special terminals are supported with input devices like barcode readers and RFID readers, to identify enterprise entities necessary for the execution of manufacturing processes. Some of these inputs represent planned manufacturing performance, which are known as TO-BE values in the presented research.

The process data, including events, generated by a resource is highly specific to the executed process activity (i.e., operation) and depends upon the measurement capabilities of the resource. The process data representation associated with a process activity does not adhere, most of the time, to any standards, but constrained by machine vendors. A resource can trigger alarms and messages informing its status, products and other enterprise entities. In addition, the operator terminals assist in manually monitoring and controlling the manufacturing processes. In the presented research, the process data, product positions, alarms and messages, and feedbacks are represented as AS-IS values, which denote the actual manufacturing performance.

The process data generated by resources is made available to downstream and upstream resources, and manufacturing management systems by employing different techniques. In many cases, be-spoke solutions are employed to share data between resources and manufacturing management systems. Nevertheless, OPC has been used as the de facto standard to share the process data with the manufacturing management systems. OPC is "open connectivity via open standard" [143]. OPC Foundation supports the development and adaption of OPC standards to achieve connectivity among resources and systems to ensure interoperability [143].

OPC is based on client-server architecture [111]. Subsequently, there can be multiple OPC servers and OPC clients in a manufacturing enterprise. In addition, an OPC server can act also as an OPC client and vice versa. A PLC has a memory, where the PLC program and process data can be stored [64]. Furthermore, the process data can be accessed directly or indirectly, by addressing the corresponding memory location [64]. It is the responsibility of the OPC server, on behalf of OPC clients, to communicate with the PLCs for reading data from or writing data to PLCs [111].

The resources on the shop floor are supplied by multiple vendors. Each vendor implements communication interfaces based on a combination of standards and proprietary network/communication protocols, as illustrated in Fig. 4.4. Most commonly used communication protocols on the shop floor are MODBUS,[1] PROFIBUS,[2] PROFINET[2] and Ethernet. Subsequently, OPC can be mapped onto PLC employing

[1] For more information, refer to http://www.modbus.org.

[2] For more information, refer to http://www.profibus.com.

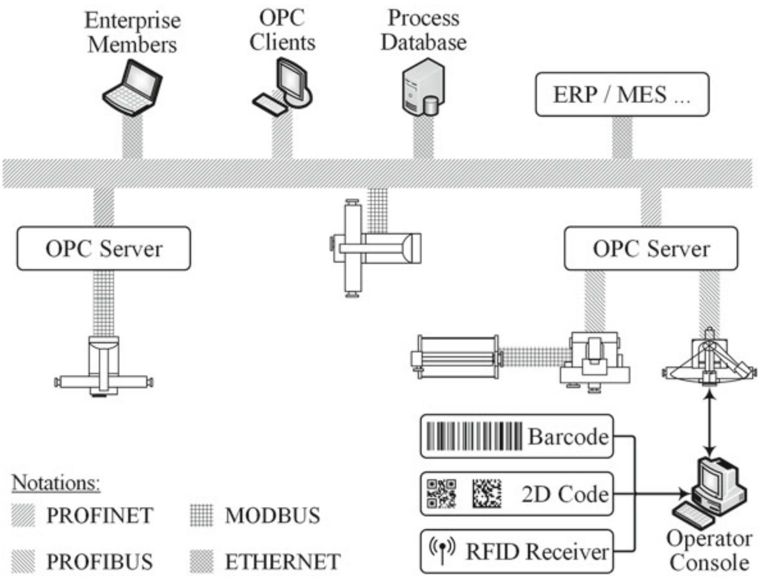

Fig. 4.4 Communication among different manufacturing resources and IT Systems employing standard and proprietary communication protocols

different communication protocols [142]. Furthermore, OPC has been widely adopted by resource vendors [143] and there are a number of OPC software vendors, including Matrikon[3] and Softing.[4]

Nonetheless, there are different resource vendors who rely on a proprietary communication interface. For instance, writing to a shared file on a networked computer. Likewise, a resource interacts by sending process data by employing raw socket communication protocol. In addition, there can be be-spoke solutions to address a specific requirement on the shop floor. Overall, different communication interfaces will create hurdles in achieving interoperability and integration between resources and manufacturing management systems.

4.4.2 Methodology

Data collection functionality is considered as one of the important MES functionality that feeds process data to other MES functionalities. Process analysis, (re-)design and modeling, and data modeling are fundamental. The collection of process data from the shop floor is influenced by the results of previously mentioned analysis and

[3] For more information, refer to http://www.matrikon.com.

[4] For more information, refer to http://www.softing.com.

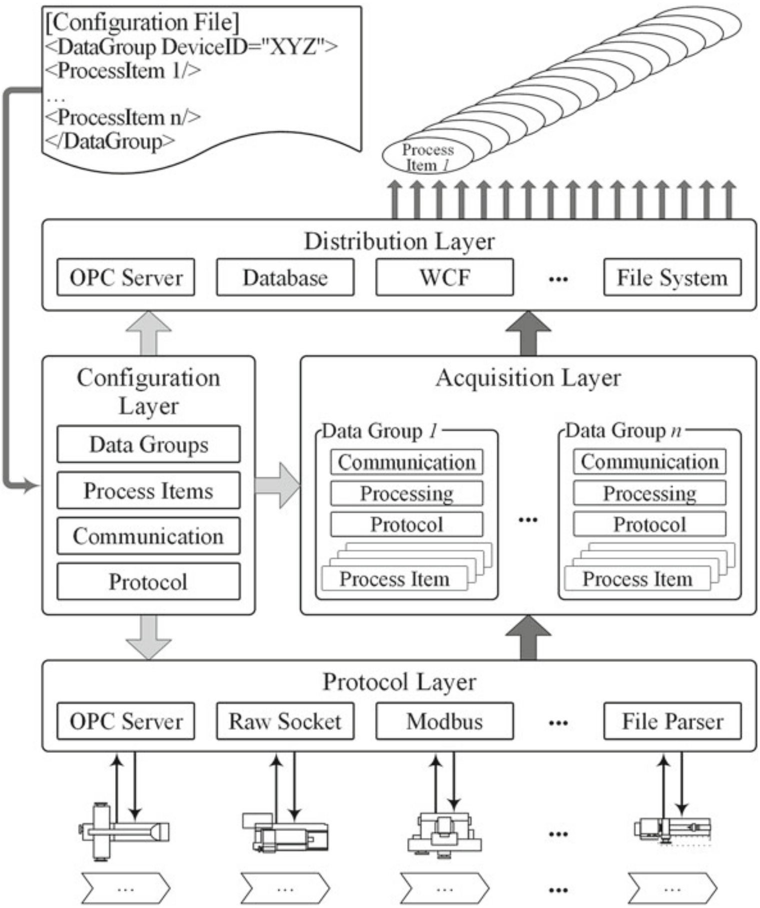

Fig. 4.5 Architecture of the data collection component

modeling. Furthermore, the collected process data impact the downstream processes of the reference architecture, like computing financial and operational metrics.

As part of reference architecture, modular data collection architecture has been designed to overcome the aforesaid drawbacks, as shown in Fig. 4.5. The architecture contains different layers: (i) the protocol layer at the bottom to initialize the communication protocols employed by the resources; (ii) the acquisition layer acquires selected process data delivered by the resources; (iii) the distribution layer communicates with external components and makes the process data available for these external components; and (iv) the configuration layer initializes the previously mentioned layers.

A PLC is identified as a small special purpose industrial computer [10, 64], which can be found in most of the new resources, and home automations, among others. Subsequently, data collection from the PLC is detailed out. A PLC is identified

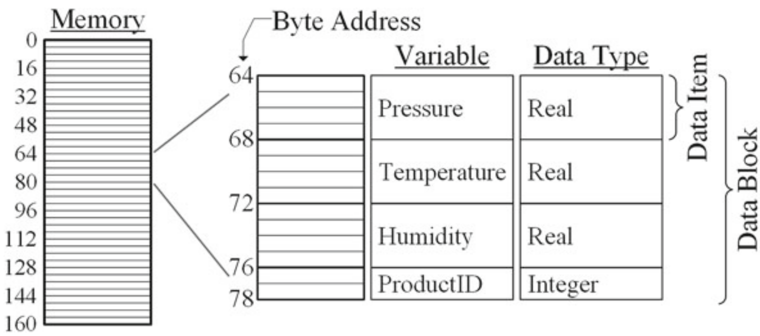

Fig. 4.6 Representation of a data item and data block in the PLC memory of a resource, adapted from [64]

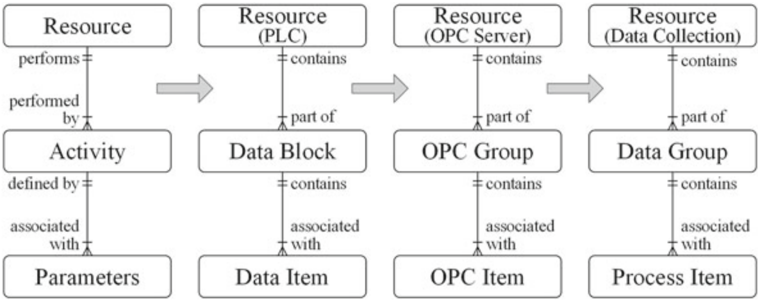

Fig. 4.7 Physical view of a resource and the corresponding logical view of data in the PLC, the OPC server and the data collection component

uniquely by an IP (Internet Protocol) address, which will be allocated to access it and its memory within the enterprise communication network. A PLC has input and output modules that are used to control the manufacturing process activities [64]. The PLC programs can be programmed outside using computers and copied into the PLC's internal memory that can be used to manipulate input and output modules, and thus the resource behavior [64].

A PLC supports elementary data types (e.g., integer, Boolean, real) and complex data types (e.g., string, array, structure) [64]. The process data of different data types can be randomly stored across the PLC's internal memory. However, in most of the cases, process activity information is stored together in a data block encompassing multiple data items, as illustrated in Fig. 4.6. The process data, i.e., consisting of data items, can be accessed directly or indirectly using memory addresses [64]. The access information can be obtained from the concerning resource vendor.

The data block and data items of PLC are first mapped onto the OPC group and OPC items of the OPC Server respectively, as depicted in Fig. 4.7. Furthermore, OPC group and OPC items of the OPC Server are mapped onto data groups and process items respectively in the data collection component. A data group represents

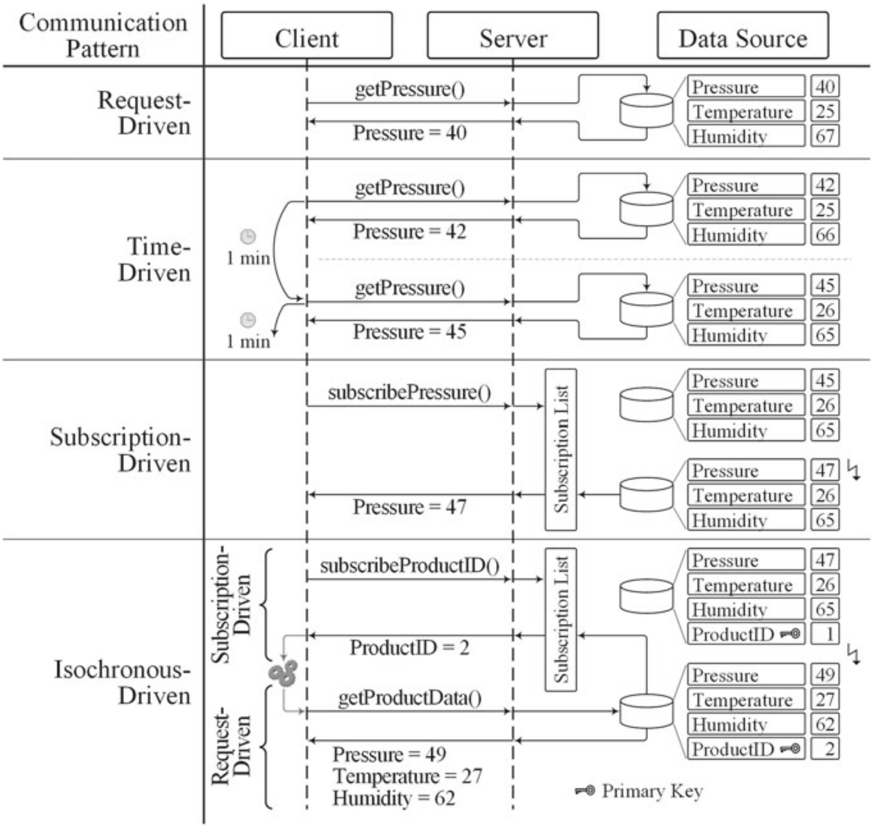

Fig. 4.8 Illustration of different communication patterns between client and server

a certain process activity (e.g., surface grinding) performed by a resource. Likewise, a process activity is identified by multiple process parameters (e.g., spindle speed, temperature) employed during its execution, termed as process items and clustered under a data group.

The OPC Server maintains a copy of internal memory of the PLC [111]. The OPC Server communicates with the PLC based on client-server architecture with the OPC Server as client and PLC as server. Subsequently, there are different communication patterns to access the process data from the PLC. Henceforth, process data and process items are used interchangeably. The use of a certain communication pattern depends upon numerous combinations of criteria—process activity, network bandwidth, and resource vendor, among others. Computer science has identified different communication patterns between client-server, as illustrated in Fig. 4.8. These patterns are listed below:

1. Request-Driven: In client-server architecture, a client initiates a request for data from a server and waits for a reply from the server [21, 166]. The server processes

the request and dispatches a reply to the client [21], which will be processed further by the client. The reply can constitute a simple data set or complex data structure.

2. Time-Driven: Also known as polling, a client initiates a request for data at a specified time [21] or at a pre-defined duration. However, the main drawback of time-driven communication is that the data is requested even when the data has not been modified. Nonetheless, in some situations it is necessary to have time-driven communication to monitor and control the manufacturing processes.
3. Subscription-Driven: In the case of a stable process, it is sufficient to know when there is a change in process data. A client subscribes to a server for data and the server maintains a subscription list [166]. On modification of the data, the server notifies the new data to all the subscribed clients [166]. Subsequently, subscription-driven communication can be used to automatically publish the data on its update.
4. Isochronous-Driven: Today's resources are complex in that they require several inputs to execute the manufacturing processes. In addition, enormous amount of process data are generated during the execution of the manufacturing processes, which are stored in the internal memory of PLCs as data blocks. In these situations, it is not optimal to acquire individual process data employing the aforesaid communication patterns. Subsequently, isochronous-driven communication can be employed using two steps. Firstly, subscription-driven communication is used only for subscribing to a data that is considered as a primary key. Secondly, request-driven communication is employed to request necessary data block whenever the client receives a modified primary key.

The process items delivered should have certain sets of attributes—meaningful name, value, unit, memory location, timestamp and quality of acquired data. Likewise, data groups should have certain attributes. Furthermore, the PLC should be uniquely identifiable in the enterprise network by providing the name, identification number and IP address. The aforementioned information can be defined in an XML based configuration file.

The configuration file, in addition, contains the communication pattern to be employed to access the process items, protocol details necessary to interact with resources, and any pre-processing to be carried out on the data of process items. For instance, resource communication using a shared file mechanism needs to define the location of the file and details about phrasing. Likewise, filtering and cleaning of process items with bad quality can be carried out before they are distributed by the data collection component.

The configuration file containing aforementioned information is forwarded to the configuration layer (see Fig. 4.5). The configuration layer is mainly concerned with initializing the other layers of data collection. The protocol layer lists all the different types of communication protocols that can be used to acquire process items from different resources in a manufacturing enterprise. The underlying systems and techniques of the protocols are initiated and launched by the protocol layer. Furthermore, new protocols can be added because of the modular design of the data collection architecture. The aforesaid information and protocol are mapped by the acquisition layer, which is in charge of acquiring only the data described in the configuration file.

Acquiring process items is not an end in itself. The acquired process items can be made available to different systems via interfaces and the communication is handled by the distribution layer. This layer is also initiated by the configuration layer. The implemented data collection can act itself as an OPC server and client simultaneously. Likewise, Windows Communication Foundation (WCF) interfaces based on .NET Framework can also be made available. In either case, the interfaces can be extended to include new ones.

4.5 Data Aggregation and Enterprise Integration

The previously mentioned XML based configuration file is used by the data aggregation component of reference architecture to subscribe to the process data from the distribution layer of the data collection component via the WCF interface. The configuration file, nonetheless, contains additional information related to resources, data groups and process items, which support the functionalities of the data aggregation component.

The data aggregation is central component of the reference architecture, as shown in Fig. 4.9. It is in charge of suitably processing delivered process items with collaboration from different functionalities, which are briefly described below:

1. Data—Integration, Storage and Analysis: The real-time process items along with the concerned data groups are used to retrieve necessary transactional data from enterprise applications and are integrated. The integrated process data is stored in the relational database for offline analysis.
2. Tracking: IEC 62264 stresses the importance of tracking of enterprise entities. The subset of process data from integrated process data is employed for tracking. This subset of process data contains critical control parameters from the perspective of different enterprise entities and manufacturing processes.
3. Event Processing: The resource controls are programmed to handle many of the pre-defined events related to resources in hard real-time, but provide little or no insight from the perspective of manufacturing processes. Subsequently, tracking information can be considered as simple events, which can be used to realize real-time monitoring and control of manufacturing processes by employing the state-of-the-art CEP engine.
4. Operational Metrics: The operational metrics can be computed using dedicated methods from stored process data at a predefined frequency (i.e., minute, hour, shift and day). Likewise, the tracking information can be employed to derive operational metrics in real-time by using CEP engine.
5. Financial Metrics: Along with the necessary financial context, real-time financial metrics can be computed with the tracking information by exploiting the techniques of managerial accounting and event processing.

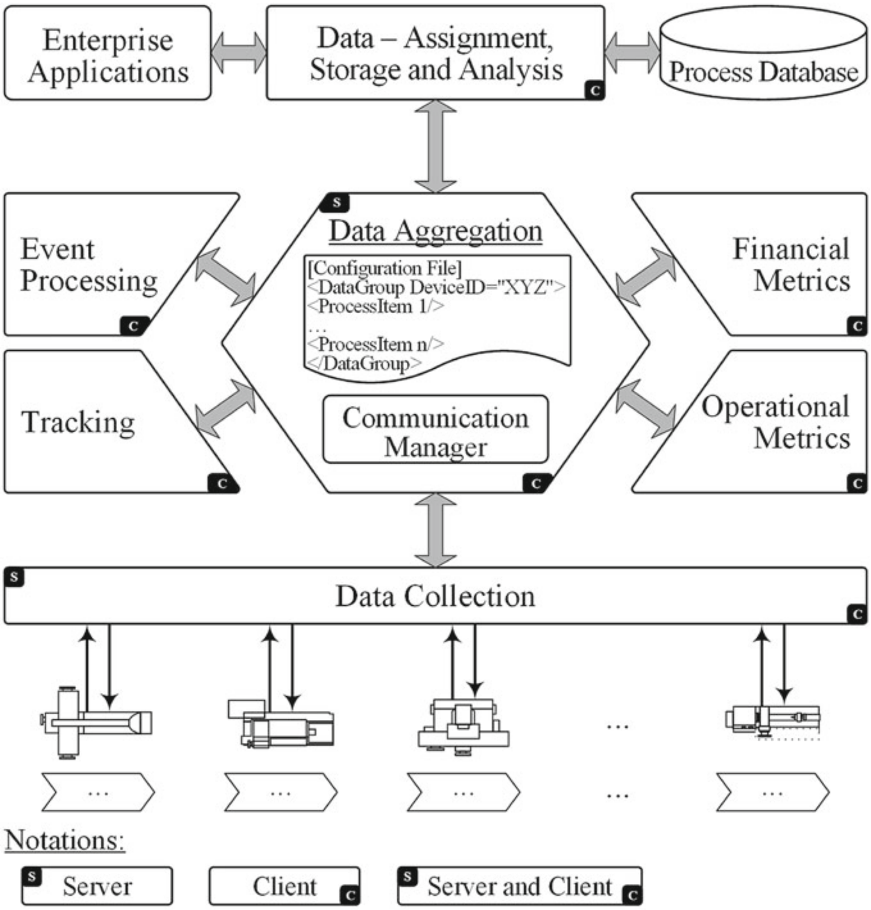

Fig. 4.9 Simplified view of the data aggregation component of the reference architecture and the interaction among its components

The collaborative interactions among the functionalities are based on client-server architecture. These interactions are handled by the communication manager of the data collection component, which provides request-driven and subscription-driven communication patterns. Furthermore, the communication manager handles numerous process visualization clients. These clients provide Graphical User Interfaces (GUI) to monitor and control manufacturing processes by enterprise members.

4.5.1 Data: Integration, Storage and Analysis

The integration of real-time process data with the corresponding transactional data can be employed in numerous ways. In the following paragraphs, the issues surrounding data integration and storage are presented and later the methodology to overcome the issues is elaborated. Finally, a short description is presented on data analysis.

4.5.1.1 Data Integration and Storage

Resources are arranged in different configuration layouts on the shop floor, like process/functional, product/flow line, fixed position and cellular layouts [63]. Furthermore, the resources within a configuration layout can be linked together [208]. Subsequently, the resources in a configuration layout are treated as islands of automation and the corresponding generated process data can be considered as an island of data [206]. Likewise, an island of data exists across different enterprise levels [27, 206].

Data historian, an OPC Server component, assists in partially addressing the collection of process data from resources and storage of process data into a relational database [143]. Data historian stores the process data as time-series data, i.e., data is sorted according to the timestamp of process data, and the individual process items are stored in different rows. Furthermore, data historian supports long-term storage and fast retrieval of process data [6].

Data historians have analytic processing capabilities [6]. For instance, they identify, if any, the deviation in temperature for a given time period. Subsequently, data historians alone might be sufficient in high volume production and low production mix schedules. Data historians, nevertheless, have issues surrounding the storage of process items, especially in low volume production and high mix production schedules. For instance, programming and computation capabilities involved are enormous to realize traceability functionality and to navigate among enterprise entities. This is mainly concerned with the number of process items retrieved and subsequent processing of retrieved rows.

The aforementioned issue of data historian can be addressed by storing multiple process items listed in a data group along with the necessary transactional data in process database. The enterprise entities and associated data groups should be uniquely identifiable, which would constitute a primary key. It is not sufficient to store the real-time process data alone and merely link it with the transactional data in the enterprise applications. The transactional data can be revised to match the existing situations of a manufacturing enterprise. In order to avoid this situation, the transactional data need to be retrieved from enterprise applications immediately after the acquisition of real-time process data and stored in process database, and further couple it with the corresponding real-time process data. The stored data can be termed as integrated process data. The stored integrated process data can be used later to perform offline analysis.

The XML based configuration file contains additional information about process items such as readable name, table and column names for mapping onto a process database, and unit, among others. In addition, it also identifies if a certain process item is a primary key or not. Overall, the information provided in the XML

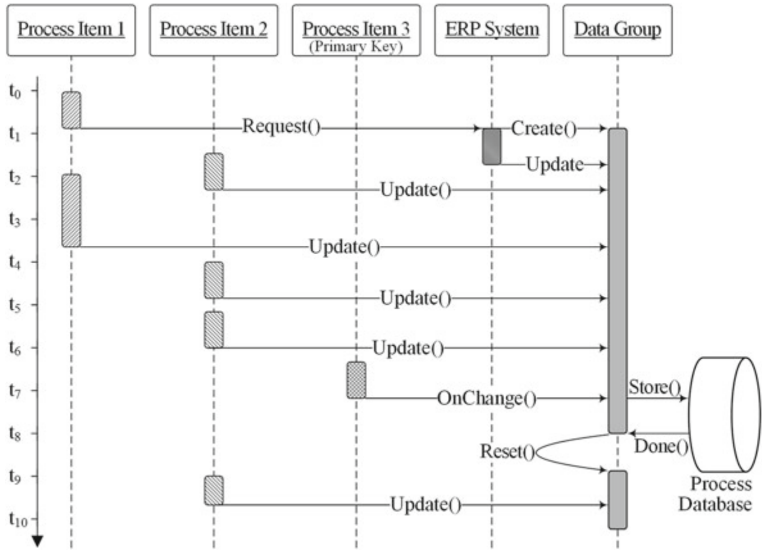

Fig. 4.10 Sequential diagram depicting arrival of process items, retrieval of transactional data from the ERP System, integration of process and transactional data, the arrival of trigger condition and storage of integrated data in the process database

based configuration file is indispensable during run-time of the data aggregation component and to manage its functionalities.

The data groups are initiated in the data aggregation component based on the configuration file. As depicted in Fig. 4.10, process items arrive at different times and frequency, and update the corresponding data group. In addition, transactional data are retrieved from enterprise applications corresponding to a data group and update the data group. Based on a trigger condition, which has been pre-defined in the configuration file, the data group along with the transactional data is processed for storing it to a process database as a single row. Once the data group is stored, it is reset and waits for arrival of new process items. Simultaneously, the data group is forwarded to other functionalities of the data aggregation component for further processing.

The trigger conditions indicate when the integrated process data is stable to store in a process database. This depends on manifold reasons, like operation performed, and resource and resource vendors, and so forth. In any case, the resource vendor should be in a position to inform when the process data are stable for further processing. There exist different trigger conditions as listed below:

1. `onChange` trigger condition is valid when a certain pre-defined process item's value is modified in comparison with the previous value. Subsequently, the data group is stored in relation to the process item, which can be treated as the primary key. As illustrated in Fig. 4.10, the complete data group is stored into a process database when the value of Process Item 3 is changed.

2. `always` trigger condition is used when the data group has to be continuously committed to a process database on arrival of associated process items. This is usually the case for short time duration during execution of an operation, which can be used to plot graphs against time to check any deviations for process compliance.
3. `onCondition` trigger condition is an extension of the `onChange` trigger condition with an additional condition, usually true or false, that a certain pre-defined process item has changed to a preset value. For instance, a process item is modified to true and the pre-defined condition is defined as true then the data group will be stored to a process database.

The list can be expanded to include new trigger conditions. In addition of storing the integrated process data, the data can be used in different ways to enhance monitoring and the control of manufacturing processes.

4.5.1.2 Data Analysis

Performance reports, like daily, weekly, monthly, quarterly, half-yearly or yearly, can be generated for members of higher enterprise levels that can be used for analyzing different scenarios, and planning and decision making. Likewise, KDD techniques can be employed on the stored data to derive new knowledge as rules. Furthermore, the identified rules can be modeled using EPL statements, which can be used to monitor and control manufacturing processes. However, product tracing and genealogy have received considerable attention, as stressed by MESA MES model [133, 137], IEC 62264 [121], and VDI 5600 Part 1 [148].

4.5.2 Tracing and Traceability, and Tracking

Manufacturing enterprises need to adhere to various stringent legislations and legal regulations. For instance, Regulation (EC) No 178/2002 of the European Parliament places requirements for tracing immediate suppliers and recipients of products [178]. Likewise, Original Equipment Manufacturers (OEMs) lay down severe requirements on its tier suppliers for tracing products for multiple reasons - quality audit, minimizing recall cost by identifying the defective products and corresponding customers, and so forth.

In short, tracking and tracing functionalities are indispensable in supporting previously mentioned challenges, and enhance transparency, quality, efficiency and inventory management [96].

4.5.2.1 Tracing and Traceability

Research has been carried out extensively in the area of tracking and tracing, especially in the area of inventory along the supply chain, and generally referred to as Track and Trace. Furthermore, various standards and regulatory bodies stress

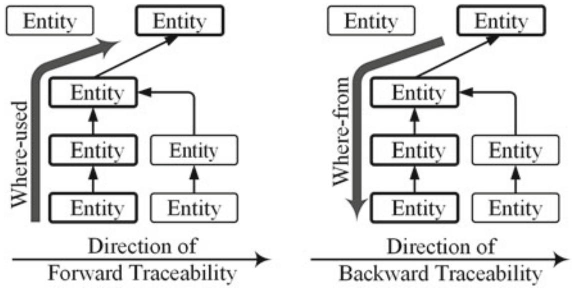

Fig. 4.11 Simplified overview of forward and backward traceability, adapted from [91]

the importance of tracking and tracing. Tracing and tracking, nonetheless, are used interchangeably, but have different meanings in relation to time.

Tracing is considered as an offline process, which uses the stored process data to pursue/follow enterprise entities through the supply chain [38]. IEC 62264-3 [123] identifies tracing as "activity that provides an organized record of resources and product use from any point, forward or backward, using tracking information." Likewise, tracing refers to "storing and retaining the manufacturing and distribution history of products and components" [38, 90]. Furthermore, tracing "focuses on changing relations with the production environment, including other components the given entity may enter a relation with" [91].

The tracing and traceability terms are used interchangeably. Traceability is defined as "the ability to preserve the identity of the product and its origins or more vividly as a 'possibility to trace the history and the usage of a product and to locate it by using documented identification'" [214]. Traceability can be employed in two different ways: forward and backward, as illustrated in Fig. 4.11. Forward traceability identifies where a particular enterprise entity has been used, i.e., material lot implosion, and poses questions about where-used relations [38]. Likewise, backward traceability identifies the enterprise entities consumed by a particular enterprise entity in consideration, i.e. material lot explosion, and inquiries related to where-from relations [38].

Traceability can be performed on different enterprise entities, like production orders, products, resources and raw materials [96]. These different entities are linked through different relationships to develop a reference traceability model [38], as illustrated in Fig. 4.3. BOM, BOR and production routings play an important role to establish different traceability relationships. Furthermore, the traceability model presents different ways to navigate between enterprise entities and their attributes [190]. Furthermore, traceability can be realized at different granularity/resolution [96, 190]. In general, a traceability resolution can be defined at two levels: the item level and the batch level [96, 190].

Item usually represents a single product unit, which will be tagged with a unique identification; the resultant traceability is known as item level traceability. The item level traceability assists in the precise identification of products that deviate from the required product specifications. This will considerably minimize the product recall cost and moreover, assist in improving manufacturing processes. An enterprise, nonetheless, should provide item level traceability only when the production lot size is small, and products need to strictly adhere to the regulations and standards [91]. Further, cost and technical challenges, especially in terms of effort and processing capabilities, should also be considered to realize item level traceability [95]. For instance, the PLC program needs to be modified to support complicated data collection from resources.

In contrast, a unique ID will be tagged to identical products, i.e., production lot [190] and the unique ID will represent physical storage area that will contain the identical products. The number of identical products, i.e., lot size, varies considerably from few products to thousands of products. This unique ID can be employed while performing forward and backward traceability and the corresponding traceability is known as batch level traceability. Likewise, the batch level traceability is used in batch processing industry (e.g., chemical industry), where multiple products are manufactured from bigger input raw materials or (sub-)products. The batch level traceability can be classified into case and pallet, especially in food processing industries.

The technical challenges and costs to realize batch level traceability are fewer in comparison with item level traceability [91]. In most of the situations, the process data will be time-series data, which can be aggregated over the number of products, similar to data historian. Furthermore, the batch level traceability can be employed to check for compliance with the required regulations and standards, product specifications, and improving the manufacturing processes, among others. However, the major drawback of the batch level traceability is the loss that will incur in terms of cost and customer dissatisfaction during product recall.

4.5.3 Tracking

Forward and backward traceability are essential for monitoring and control of manufacturing processes. The outcome of traceability can be used to enhance the execution of future manufacturing processes. Subsequently, the previously mentioned concept of tracing and traceability can be exploited to realize real-time tracking of enterprise entities.

In contrast to offline tracing, tracking can be considered as a real-time activity that can be defined as an "act of observing, in most cases, the spatial motion of an entity" [91]. It is also identified as "gathering and management of information related to the current location of products or delivery items" [90]. Likewise, tracking is considered as trailing enterprise entities "through the supply chain and registering any data considered of any historic or monitoring relevance" [38]. Finally, IEC 62265-3 regards tracking as an "activity of recording attributes of resources and products through all steps of instantiation, use, change and disposition."

The concepts of Multi-Agent Systems (MAS) and Holonic Manufacturing Systems (HMS) have been elaborated to realize flexibility and agility, which are necessary to address the dynamic changes happening around a manufacturing enterprise [104]. These systems are characterized by autonomy, responsiveness, modularity and openness [163]. A complex control system can be split into decentralized control un its, which is the fundamental idea that MAS and HMS exploit [221]. The control units are termed as agents and holons in the case of MAS and HMS respectively [104]. Each control unit is autonomous and attempts to realize its own objectives [104] by resolving any issues via communication, collaboration and cooperation with other control units [163].

Prototypical implementations of MAS and HMS are found in research laboratories, but not widely accepted by practitioners [104]. Subsequently, the presented research considers tracking as a subset of previously elaborated concepts of agents and holons, but without any intelligence or autonomy. The intelligence and autonomy is realized using the centralized state-of-the-art CEP engine.

Tracking can be performed on various enterprise entities that should be uniquely identifiable and linked via different relationships (see Fig. 4.3) to realize item-level and batch-level traceability. Furthermore, the tracking information is managed in the main memory of a computer. Consequently, it is necessary to address the processing issues—performance, and memory footprint. In this case, the enterprise entities can be logically classified into resident entities and transient entities [198].

Resident entities are active in a system over a longer duration of time and are described with fewer attributes [198]. These attributes are more or less static and only a few of the attributes are dynamically updated. For instance, resources, and production orders can be considered as resident entities where it is sufficient to update only the number of corresponding products manufactured. In contrast, transient entities are created, updated and destroyed frequently [198]. Transient entities are described extensively with numerous attributes [198]. These attributes are dynamically modified. For example, a product can be considered as a transient entity, which is updated as and when it is processed on resources.

The job-driven and resource-driven models are described in discrete event simulation in addition to resident and transient entities respectively [198] [48]. In the job-driven model, jobs are part of an active system, which contains a separate record in the active system and a corresponding memory footprint [48]. This job record is created at the start of a manufacturing process and thereafter, the record is updated while moving through different manufacturing process steps. Finally, the job is destroyed when it departs from an active system. In contrast, resource as in a resource-driven model is part of the active system processing passive jobs. Therefore, a resource record contains fewer details (e.g., number of jobs processed) compared to a job record.

The previously mentioned models have benefits and shortcomings. In the case of a resource-driven model, execution of the system is fast and uses smaller memory footprint, which does not change over a period of time [48] resulting in a system operating at maximum performance [190]. Likewise, a job-driven model assists in tracking jobs with higher clarity but at the expenses of execution speed and an exhaustive memory footprint. Nevertheless, job-driven and resource-driven models or residents and transient entities have to be simultaneously employed to enhance monitoring and control of enterprise entities.

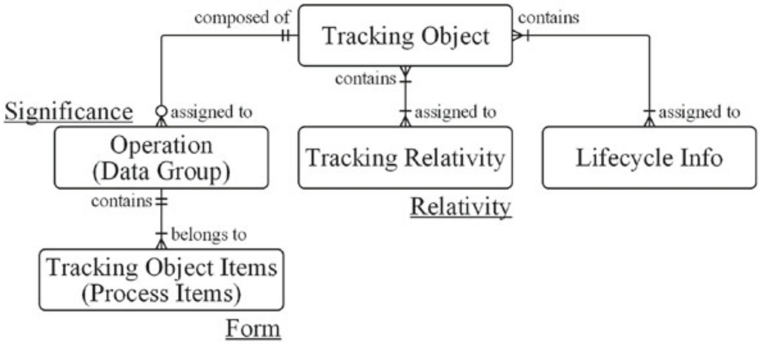

Fig. 4.12 Different elements of a tracking object and their relationships

As mentioned in Sect. 3.5, an event is defined as "an object that is a record of an activity in a system" [106]. Furthermore, an event object is represented by three aspects: form, significance, and relativity [106]. Subsequently, the tracking object should encompass the event aspects. Henceforth, tracking information is referred to as tracking object from computer science perspective, which is almost similar to an event object. The event significance, event form and event relativity can be mapped onto operation, tracking object item (also known as attributes) and tracking relativity respectively, as depicted in Fig. 4.12. In addition, information related to its lifecycle should be provided, which depends upon the entity type.

It is crucial to analyze the resources, manufacturing processes, and supporting activities to identify critical control-related process parameters. Subsequently, these parameters need to be mapped onto the tracking object items. These items are initially assigned to an operation, i.e., data group, and the operation is finally assigned to a tracking object. As illustrated in Fig. 4.3, enterprise entities can be related to other enterprise entities. For instance, the product entity has a relationship with the associated raw material and production order. Subsequently, tracking relativity captures the necessary relationships as references between enterprise entities. The previously mentioned concepts are illustrated in Fig. 4.13.

A tracking object will undergo different phases of the lifecycle—creation, modification and destruction. A tracking object is created by allocating memory and modified when the corresponding data groups are created, updated or deleted. Nonetheless, tracking objects are available in main memory and it is critical to define termination conditions, especially for transient entities and job-driven model.

The destruction of tracking objects results in removing the memory references and releasing the corresponding memory. As a consequence, performance is enhanced in terms of memory footprint and processing speed. The termination conditions can be specified in numerous ways. To begin with, maximum expected lifespan of tracking objects can be defined. A (short-term) production plan contains details about quantity, BOM, production routing, and BOR, among others [205]. The conclusion of the final processing step in production routing of a product can be considered as a termination

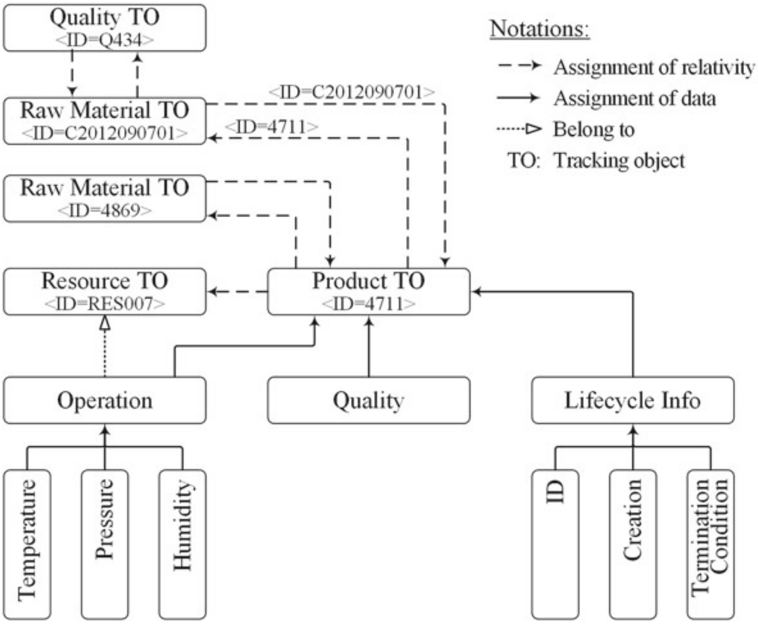

Fig. 4.13 An example of a tracking object and its associated tracking object items, tracking relativity and lifecycle information

condition. Likewise, workflow associated with a production order and managed in a workflow management system can also be considered for termination condition.

The previously mentioned information, like tracking objects items and termination conditions, needs to be defined in a separate XML based configuration file, similar to the configuration file defined for use with data collection and data aggregation components. Timestamps are crucial for processing by downstream components of the reference architecture. Subsequently, creation and modification timestamps of a tracking object and tracking object items are also recorded.

Tracking objects are composed of transactional data, subsets of real-time process data, operation details and references to various tracking objects. Research has identified different ways to navigate between tracking objects, operation and tracking object items [190, 214]. These objects can be used to create online reports from different perspectives and can be presented to enterprise members. With the up-to-date information, enterprise members can proactively perform corrective actions.

4.5.4 Event Processing

A manufacturing resource, especially a resource with PLC, provides mechanisms to support hard real-time monitoring and control of its operations. Nonetheless, this

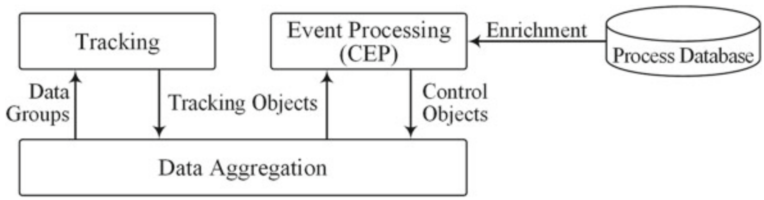

Fig. 4.14 Information flow among data aggregation, tracking, and event processing components to realize real-time monitoring and control of manufacturing processes

type of mechanism provides a narrow perspective of monitoring and control of manufacturing operations/activities. Subsequently, it is necessary to have a wider perspective of monitoring and control of manufacturing processes. Here wider perspective means invoking numerous proactive and reactive actions to minimize deviations from planned objectives associated with enterprise entities, like resources, production orders, production routings, production schedules, and products. For instance, increasing priority of a production order as it has not adhered to its delivery deadline might result in rescheduling of production orders. Subsequently, event processing and associated CEP can be employed to have a wider perspective of manufacturing processes, thus realizing soft real-time monitoring and control.

As stated earlier, several inputs are required to define manufacturing processes and the enormous number of process items is generated by resources. These process items can be considered as simple events. The data collection component delivers these process items and the delivery is characterized by frequency and volume. The frequency at which the process items are delivered and volume of process items delivered makes the processing of process items/events complicated, i.e., enormous effort is required to create a bigger picture of manufacturing processes.

To overcome the aforementioned issue, the concept of tracking object is employed. In short, tracking object is composed of a subset of transaction data and process items, which are derived from multiple data groups (see Fig. 4.12). Subsequently, tracking objects are treated as simple events in the presented research, rather than process items as simple events with the aim to address the process item delivery issues. These tracking objects are managed by a data aggregation component, which forwards them to an event processing sub-component as illustrated in Fig. 4.14.

In comparison to MAS or HMS, tracking objects do not have any in-built intelligence, but are abundant with necessary process data and transactional data. The intelligence shall be realized by employing centralized CEP via EPAs and EPNs. In the presented research context, CEP is considered as a black box and concerned with embedding predefined situations, i.e., for situation awareness, into EPAs and EPNs. Furthermore, the complex interaction among manufacturing processes can be simulated by linking EPAs to form EPNs.

The importance of creating events with higher abstractions has been stressed in CEP, rather than what to do when a predefined situation is detected. Nonetheless, CEP provides a rudimentary method that will be called whenever a predefined situation is identified. For example, NEsper provides `Listener` method [44]. Subsequently, this method needs to be enhanced so that it can be capable of dispatching control objects. The content of a control object, like a message and event triggering rule or actions, needs to be defined simultaneously while creating its EPA. Additionally, the control objects should dynamically encompass the triggering events.

The data aggregation component deduces suitable actions based on the content of a control object. The actions can include triggering events with higher abstraction, and visualization of predefined messages along with the selected integrated process data to concerned enterprise members. Likewise, the action can involve making suitable changes in the control program of a PLC via the data collection component. Nonetheless, displaying a message is more prominent and the concerned enterprise members have to react to bring back the manufacturing processes to a stable condition.

4.6 Real-Time Operational Metrics

Enterprise members, like operators, supervisors, engineers and managers, are interested in operational metrics. Subsequently, it is indispensable to compute the operational metrics in real-time to enhance monitoring and control of manufacturing processes. VDMA 66412-1 [150] and the corresponding English version ISO 22400-2 [125] list about thirty-four operational metrics, especially from the perspective of discrete industry and automated machines. Nonetheless, these metrics need to be analyzed and adapted by individual manufacturing enterprises.

Process analysis and modeling is crucial in order to identify operational metrics, relationships and dependencies between operational metrics, and data required to compute them. Nevertheless, the presented research does not highlight any specific operational metrics and elaborate procedures to select operational metrics. Rather, the research concentrates on different approaches to compute/quantify operational metrics in real-time.

The necessary equations related to operational metrics are hard coded into (MES) software resulting in implemented system being rigid and inflexible. Subsequently, the software code has to be compiled whenever any changes in equations and new operational metrics have to be included. To overcome the issue of inflexibility of defining operational metrics in software code, the operational metrics can be computed by employing the syntax of SQL of relational databases and CQL of event processing. In the former case, the operational metrics can be defined using the syntax of SQL, as depicted in Fig. 4.15. The SQL based operational metrics mostly use process data from the process database and transactional data from enterprise applications. Furthermore, the SQL based approach can be exploited to compute complex operational metrics.

Nevertheless, the SQL based operational metrics have to be computed periodically to simulate near real-time computation of operational metrics. Furthermore, the database queries can be time consuming influenced by the complexity of the operational metrics and its corresponding data requests. Consequently, the usage of

```
<KPI ID="1" KPIName="ProductManufacturedInLastHour"
        resourceType="CNC" resourceName="CNCName">
  <Type>Database_Request</Type>
  <Description>
        Determines the Products Manufactured in Last One Hour
  </Description>
  <SQLStatement>
    SELECT COUNT(1) AS PRODUCTSMANUFACTUREDINLASTHOUR
        FROM PRODUCTS WHERE CREATED > SYSDATE - (60/1440)
  </SQLStatement>
  <UpdateRate>60000</UpdateRate>
  <SubscriberEvent>onTick</SubscriberEvent>
</KPI>
```

Fig. 4.15 Structured Query Language (SQL) based definition of operational metrics

```
<KPI ID="2" KPIName="ProductManufacturedInLastHour"
        resourceType="CNC" resourceName="CNCName">
  <Type>Continuous_Analysis</Type>
  <Description>
        Determines the Products Manufactured in Last One Hour
  </Description>
  <CQLStatement>
    SELECT COUNT(*) AS PRODUCTCOUNT FROM NEWPRODUCT.WIN:TIME(60 MIN)
  </CQLStatement>
  <UpdateRate>0</UpdateRate>
  <SubscriberEvent>onUpdate</SubscriberEvent>
</KPI>
```

Fig. 4.16 Continuous Query Language (CQL) based definition of operational metrics

SQL based operational metrics should be invoked with a higher update rate or less frequent.

In contrast, the syntax of CQL can be employed to measure operational metrics in real-time on the incoming tracking objects, and enriched with historical process data and transactional data. Subsequently, a dedicated CEP engine capable of interpreting CQL statements needs to be employed to compute the operational metrics. An example of CQL based operational metrics definition is illustrated in Fig. 4.16. The syntax of CQL is similar to the syntax of database query, but the data is available in the main memory [44]. Subsequently, the computations of operational metrics will be fast. Nonetheless, the CQL based computation of operational metrics can be employed to determine straightforward operational metrics in real-time, especially problematic to create and manage the EPL statements necessary for computing complex operational metrics.

The operational metrics need to be adaptable. Accordingly, the aforementioned SQL based and CQL based operational metrics definitions can be stored in an XML based definition file, which provides a mechanism to realize the required adaptability. These definitions are initiated and loaded into the operational metrics component of data aggregation and used along with the aforesaid data to compute the operational metrics, as depicted in Fig. 4.17. An editor needs to be made available to manage,

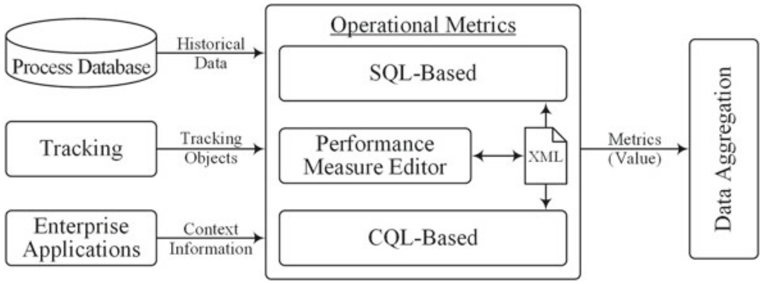

Fig. 4.17 Schematic illustration of operational metrics components of the reference architecture

i.e., create, modify and delete, the operational metrics definitions, and when changes occur, the definitions should be reloaded into the operational metrics component.

The conflicting requirements of enterprise members necessitate the use of both SQL based and CQL based operational metrics definitions, i.e., SQL based and CQL based computation complement each other. Also, the definitions of CQL based and SQL based operational metrics definitions are similar except for their type and update rate (see Figs. 4.15 and 4.16).

After computation, the operational metrics will be forwarded to the data aggregation component. Subsequently, the computed operational metrics will be used in numerous ways. Firstly, the operational metrics are forwarded to all subscribed process visualization clients for displaying those using visual elements, like charts and gauges. The process visualization clients also consider the roles and responsibilities of the enterprise members. Secondly, the operational metrics are analyzed by the event processing component. This component is in charge of aligning the enterprise processes according to the planned objectives. Finally, the performance measures will be stored in the process database for creating reports.

Operational metrics are crucial to monitor and control manufacturing processes by enterprise members, like operators, supervisors, engineers and managers. Furthermore, the aforementioned approaches can be used to compute operational metrics in (near) real-time. Nevertheless, operational metrics should be complimented with financial metrics, especially in real-time, for certain enterprise members like managers. Furthermore, these operational and financial metrics should be linked and aligned with the enterprise objectives.

4.7 Real-Time Financial Metrics

Financial metrics are crucial for enterprise members, including managers, CEOs and CFOs, for carrying out performance analysis, and subsequent planning and decision making. From the context of financial metrics, performance analysis, and planning and decision making are used instead of monitoring and control. Furthermore, there

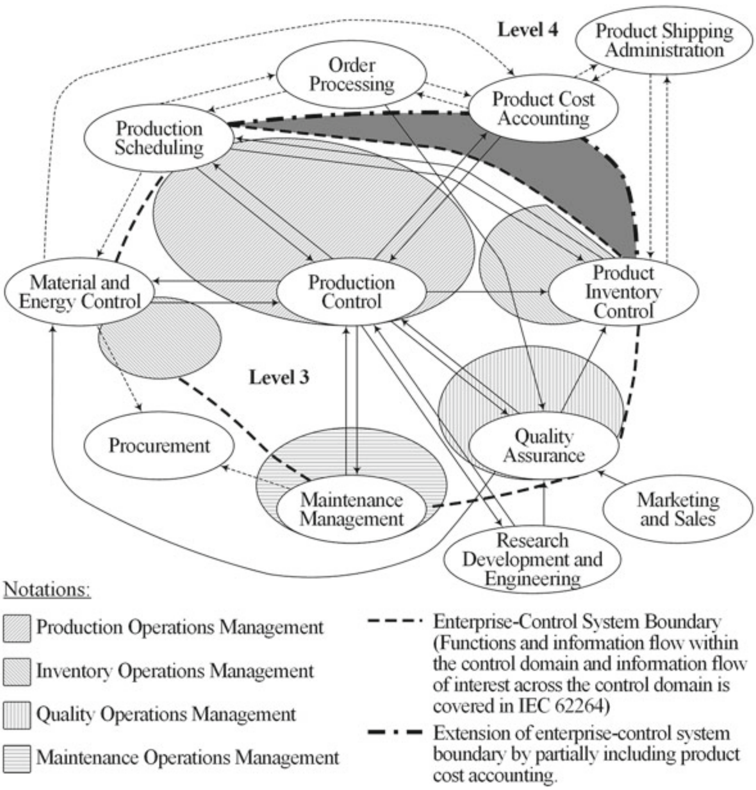

Fig. 4.18 Manufacturing operations management model as shown in IEC 62264-3 [123]. The enterprise-control system boundary has been extended in the presented research by partially including product cost accounting in the manufacturing control level

exist numerous techniques and systems to compute the financial metrics. For instance, Return on Quality (RoQ[5]) and ROA, and so forth are a few of the financial metrics.

IEC 62264-1 [121] presented a functional control model, which identifies the functionalities of manufacturing control or Level 3 and enterprise control or Level 4 (see Fig. 3.3). In addition, the detailed flow of information between the functionalities of manufacturing control and selected flow of information between manufacturing control level and enterprise control level are also presented in IEC 62264-1 [121] and IEC 62264-3 [123], as shown in Fig. 4.18. Nevertheless, the current subchapter will focus on the information flow of production performance and production cost objectives between production control and product cost accounting.

According to IEC 62264-1 [121], the production performance information flow from production control to product cost accounting is related to the actual consumption of raw materials, labor hours, energy and resources (i.e., AS-IS values). Further-

[5] ROQ is the ratio of increase in profit to cost of quality improvement programs [216].

more, the information can be identified with products, co-products and scrap. In this regards, IEC 62264-2 [122] provides necessary interface to successfully implement the information flow. The product cost accounting is involved with the computation of total product costs, reporting on production costs and setting future cost objectives (i.e., TO-BE values).

The product cost accounting functionality is part of Level 4 and supported by ERP System, may be in coordination with other enterprise applications, like SCM System. These systems are capable of computing extensive product costs across the entire supply chain, value chain, value network, or business network [175]. The outcome of product cost accounting is further aggregated to derive numerous financial metrics. Overall, the financial metrics are highly aggregated, i.e., operational details, product and production complexity, and production disturbances, among others are suppressed or not highlighted.

These financial metrics are calculated offline according to the enterprise's reporting cycle. The computed metrics are delivered late, and the performance evaluation, planning and decision making processes are temporally delayed. At the end, decisions taken will not match the current manufacturing situations. This scenario gets highly complicated when a manufacturing enterprise adheres to low volume production and high mix production schedules [84].

Thus, it is necessary to have a narrow perspective of product cost accounting at the manufacturing control level to accurately compute, especially in real-time, costs surrounding manufacturing in contrast to the broader perspective of ERP systems towards product cost accounting. Subsequently, the enterprise-control system boundary has to be extended to partially include product cost accounting, as illustrated by the long dash dot line and shaded area in Fig. 4.18. The costs surrounding manufacturing considered in the presented research are manufacturing cost, cost leakage and cost inefficiency. These costs can be assigned and tracked/traced to products, production orders and resources. Moreover, these costs can be used to calculate suitable financial metrics at higher level.

4.7.1 Resource: Costs, Capacity, and Assignment Levels

According to IEC 62264-1 [121], a resource is identified as an "enterprise entity that provides some or all of the capabilities required by the execution of an enterprise activity and/or business process," which is dependent on its availability. A resource can be represented by a collection of enterprise members, (automated) machines, and raw materials, and so forth. Furthermore, a resource can be characterized by its capabilities and capacity (see IEC 62264-1 [121]). The capability of a resource can be defined as "ability to perform actions, including attributes on qualifications and measures of the ability as capacity," which is more a functional and qualitative concept (see IEC 62264-1 [121]).

In contrast, capacity is identified as a "measure of the ability to take action, a subset of a capability," which is a quantitative concept expressed in relation to time (see IEC 62264-1 [121]). Likewise, the capacity of a resource is the “maximum output or producing ability of a resource, a person, a process, a factory, a product, or a service” [35] [82]. The capacity can be defined as available number of machine hours, available number of labor hours, and number of customer orders that can be handled, among others. Furthermore, the practical/rated capacity of a resource can be classified into committed, available and unattainable capacity, which can also indicate resource availability (see IEC 62264-3 [123]).

In addition to the aforementioned characteristics, a resource has certain monetary value. This monetary value will be, mostly, assigned or allocated to products and their production orders as costs that will be based on the use of resource capabilities and capacity to execute the production orders. Likewise, the costs should also be assigned to the management, such as managers, during non-utilization of resources, like non-use, especially helpful during make or buy decision [93]. Hence, it is crucial to determine resource rate accurately, which is highly influenced by the supplied practical capacity of a resource [84] and the resource cost of supplying capacity [83]. Finally, resource rate can be expressed as a ratio of resource cost to supply the practical capacity to the supplied practical capacity of a resource [83].

4.7.2 Resource Cost

In a manufacturing enterprise, it is absolutely necessary to determine the resource cost accurately, which influences the subsequent analysis and decision making. Resource, especially machine, cost should be composed of project cost, the physical machine cost and planned maintenance cost during its useful life [113]. In many cases, the resource costs are simply lifted from the accounting ledger. Nonetheless, there are different ways to calculate the resource costs.

A resource can be either owned or rented, which results in calculating the resource cost differently. Subsequently, an enterprise use depreciation recorded by their accountants in their accounting ledger when the resource is owned by the enterprise [83]. Nonetheless, the enterprise attempts to improve the accuracy of the resource cost [83]. In this regard, an enterprise can use replacement cost depreciation [83, 110] or cost of capital methods [83] to determine the resource costs. Finally, organizations, like International Accounting Standards Board (IASB[6]) lay down guidelines for calculating the resource costs, especially from a financial accounting perspective.

Likewise, a resource can be represented by employee/operator/labor, energy and raw-material. Because of the impact of globalization, the cost and availability of raw-materials and energy vary. This will have an undesirable impact on performance analysis, and planning and decision making because of the difficulty in comparing the past performances. Subsequently, the use of standard cost is proposed instead of actual cost over a period of time [84].

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[6] For more information, refer to http://www.ifrs.org.

In any case, the aforementioned cost details can be accessed from a process database and/or ERP System. These cost details need to be stored according to the accounting techniques that will be employed. For instance, RCA requires fixed and proportional costs associated with a resource for computing costs. Likewise, ABC needs only variable cost for calculating different costs. In addition, the cost associated with the raw-materials, and finished and semi-finished products need to be computed, may be on-the-fly, and stored in the process database and/or ERP System.

4.7.3 Resource Capacity and Assignment Levels

A resource rate is calculated from the accounting ledger, which is historical in nature, i.e., computed at the end of the enterprise reporting cycle [84]. In addition, the capacity utilization, especially excess capacity, is not considered while calculating the resource rate, which might lead to inaccurate cost assignments [84]. Furthermore, the previously mentioned situations, especially excess capacity, might lead to a cost death spiral in an enterprise by increasing the resource rate whenever excess capacity is encountered [84].

The supplied capacity, i.e., practical capacity, of a resource denotes that capacity can be used to fulfill production orders without "creating unusual delays, forcing overtime work, or requiring additional resources to be supplied" [84]. Initially, managers can estimate the practical capacity of resources as a percentage of rated capacity of a resource [82, 84]. For instance, machines are available around 80–85 % of weekly working hours and the remaining time is used for maintenance and handling scheduling fluctuations [82].

Nevertheless, it is absolutely necessary to classify the resource utilization into productive, non-productive and idle/excess to enhance performance analysis, and decision making [25, 35]. Likewise, the costs need to be assigned to different cost hierarchy levels [25, 84]. Additionally, the cost assignment preference (see Fig. 3.11) should be combined with the cost hierarchy levels, which support enhanced performance analysis, and planning and decision making. In short, it is crucial to make the costs associated with excess capacity and non-productive capacity visible to management [25, 84].

There exist different cost hierarchy levels—unit, batch and business sustaining [25, 84]. The costs associated with performing an activity on every individual unit of product is termed as unit-level costs [84]. The direct costs associated with raw material, energy, labor and resource that can be traced to products are treated as unit-level costs. In contrast, there are activities that need to be performed at the batch-level [25, 84]. For example, resource setup and processing a production order are performed independent of number of product units in the production order [84]. These costs need to be assigned to batch-level costs. Both the unit-level and batch-level costs can be related to products, production orders, and customers, and so forth [25]. In addition, these costs adhere to cause-and-effect relationships [25].

Apart from the aforementioned activities, there are activities that are performed on a wide range of enterprise entities that encompass multiple products, and customers, among others [25]. For instance, employee training, brand building exercises, and maintenance are activities that cannot be associated with a particular product or customer. The costs associated with these activities need to be assigned to the business sustaining costs [25], which do not adhere to cause-and-effect relationships as there is no relationship between business sustaining costs and products [25, 84]. The business sustaining costs can be further classified into product sustaining, brand sustaining, and channel sustaining, among others [84].

4.7.4 Effort and Accuracy

The issues surrounding the effort to collect the data necessary for accounting and the accuracy of accounting outputs have been stressed [25, 84]. It is noted that the effort increases drastically to improve the accuracy of accounting outputs after a certain level [25]. Subsequently, it is necessary to have a trade-off between effort to collect data and accuracy of accounting outputs, which can be supported with the selection of suitable types of activity drivers [84].

Transaction drivers are used to assign costs independent of an activity, like setup [84]. These drivers are easy to manage but can result in reduced accuracy of accounting output [84]. Transaction drivers assume that an activity (e.g., processing a production order) requires the same number of inputs [84]. Next, duration drivers consider the amount of time taken to execute an activity [84]. For instance, production orders can be charged according to the time consumed to perform the setups. Subsequently, the duration drivers are more accurate than transactional drivers, but are expensive to realize [84].

Finally, intensity drivers consider the complexity of the activity to be performed, which involves assigning extra cost [84]. The accounting output resulting from utilization of intensity drivers results in the most accurate, but on the other side they are the most expensive to implement [84]. The aforementioned drivers can be employed to realize the cost assignment based on causal relationships.

4.7.5 Manufacturing Cost, Cost Leakage and Cost Inefficiency

The cost of a product has been classified, as depicted in Fig. 4.19. About 70 % of the cost of a new product is decided/committed during the engineering stage, i.e., product development and process planning [23]; the engineering stage accounts for 15 % of the total product cost [65]. Furthermore, the manufacturing cost contributes to about 40 % of the selling price of a product, which is composed of direct and indirect costs.

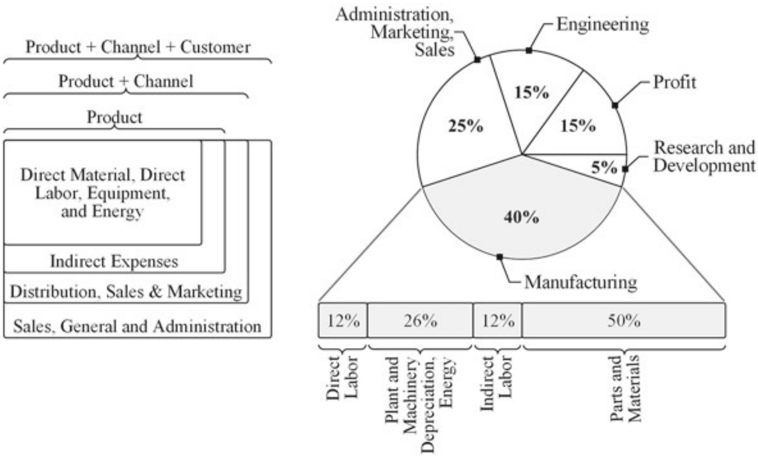

Fig. 4.19 Classification and distribution of product cost, adapted from [26, 62]

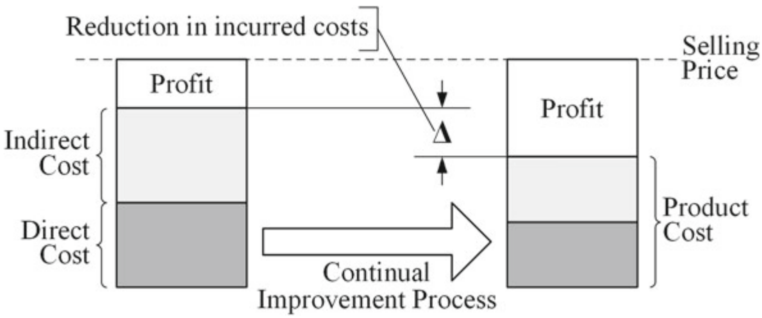

Fig. 4.20 Schematic illustration of product cost and profit - before and after initiation of process improvement programs, adapted from [217]

A manufacturing enterprise might employ a cost advantage strategy or differentiation advantage strategy to sustain its competitive advantage [55, 184]. In either strategy, it is essential to reduce the costs incurred during manufacturing, and increase the profit, as illustrated in Fig. 4.20. Subsequently, enterprise members should be constantly looking for opportunities to identify wastes [109]. This is highly critical for suppliers and SMEs, who have minimal influence on the product design and supply products according to the quoted price. Furthermore, a manufacturing enterprise has a higher possibility to efficiently managing its internal environment in comparison to its external environment [109]. Consequently, the presented research is concerned with the manufacturing processes and the corresponding costs surrounding manufacturing.

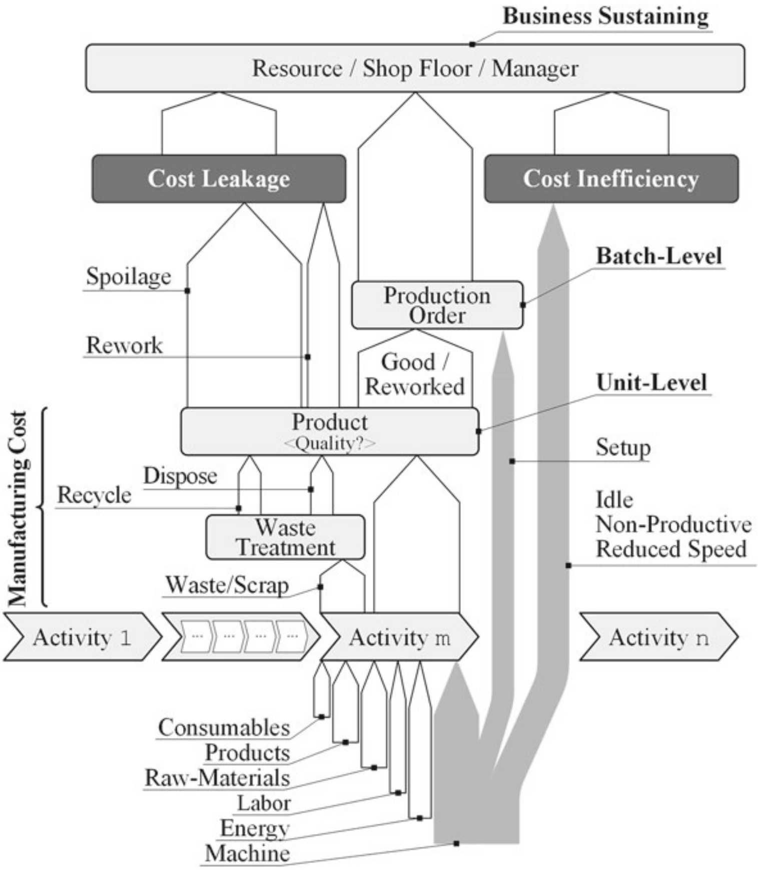

Fig. 4.21 Simplified view of various cost assignments and their flow for an activity using Sankey diagram notations, adapted from [87]

4.7.5.1 Manufacturing Cost

The manufacturing cost contributes considerably to the overall product cost and influence the profit. Furthermore, the manufacturing cost would have been estimated based on planned/budgeted values, which is particularly true in the case of suppliers where the cost would be reflected in the quotation sent to its customers, i.e., the price negotiated with its customer. Subsequently, the enterprise needs to manufacture products with the aim to keep the manufacturing cost below the stated value in the quotation.

Nevertheless, managers are not in a position to determine the manufacturing cost accurately and especially, in real-time. Moreover, the identification of profitable and not-profitable customer/product is hard. Overall, a manufacturing enterprise has opportunities to reduce the manufacturing costs by enhancing the manufacturing processes, only if these values are made available to the managers and concerned enterprise members along with the operational metrics within an appropriate time-frame, preferably in real-time. In addition, the accurate cost information can provide feedback to sales department and other upstream processes to calculate future quotes accurately or renegotiate the existing contracts.

A manufacturing activity consumes different types of inputs—labor, machine, energy, (sub-)products, raw material and consumables (see Figs. 2.2 and 4.21). According to IEC 62264-1 [121], consumables are identified as "resources that are not normally included in bills of material or are not individually accounted for in specific production requests." The transaction driver approach can be employed to derive the manufacturing cost after execution of an activity, which will rely on planned/budgeted values. On the contrary, the activity inputs, like raw materials, can be directly traced to products based on the actual consumption. Additionally, some of the activity inputs, such as labor and energy, can be assigned to the product based on the causal relationships after the actual consumption. Thus, this will satisfy the concept of intensity driver. Overall, it is necessary to maximize the exploitation of cost tracing and cost assignments to enhance the accuracy of the cost objects, especially products and production orders. In addition, the manufacturing cost can also consist of indirect costs (e.g., rent, training), which can be allocated based on a predefined rule. However, the indirect costs are not considered in the presented research.

The consumption of the inputs can be measured accurately because of the incorporation of suitable sensors and other technologies. These inputs are made available in the machine's PLC or provided through special terminals. Furthermore, these values are acquired by the data collection component and included as part of product tracking objects. Likewise, the necessary information related to labor (like roles, responsibility, and cost) can be obtained from the payroll software or from ERP System. Furthermore, the standard costs of consuming the inputs need to be accessed from the suitable process database, ERP Systems, and/or predefined locations. Subsequently, it is possible to compute the direct costs by processing product tracking objects in CEP engine. The EPL statements need to suitably incorporate the logic of cost tracing and cost assignments.

Figure 4.21 illustrates the computation of manufacturing cost at a manufacturing process activity. However, in reality, a product is manufactured by routing the product through different manufacturing process activities as defined in its production routing. The product tracking object is created after execution of the first process activity and subsequently updated after execution of different associated process activities. The manufacturing cost incurred at each process activity needs to be calculated and accumulated to derive the overall manufacturing cost associated with a product. Consequently, the EPAs associated with each manufacturing process activity need to be linked to EPNs representing the production routing of the concerned product, i.e., realize horizontal causality of event processing.

On a similar line, the outcome of a manufacturing activity can also constitute scrap, which can be identified as "residual material that results from manufacturing a product" [69]. This scrap needs to be further processed for various reasons. For instance, usable materials can be retrieved from the scrap that can be consumed later during manufacturing, i.e., recycling. Likewise, government laws and regulations, in some instances, impose stringent guidelines for disposing of scrap.

Subsequently, processing of scrap/waste and the associated costs should be suitably assigned to products. Nonetheless, this is a tricky issue as it depends upon the underlying recycling/disposal processes employed by the manufacturing enterprise. In addition, there will be issues associated with quantifying the scrap. In many instances, the scrap is accumulated over a period and later processed/sold, which is reflected in the accounting ledger [69]. Subsequently, predefined rules need to be employed to determine the costs to be allocated to products based upon a combination of inputs, activity and planned scrap.

The aforementioned processing of tracking objects will result in the computation of manufacturing cost of products at the unit level. These costs need to be aggregated to its production order tracking object at the batch level. Thus EPAs and EPNs should be linked to realize vertical causality of event processing. In addition, there are certain activities, like setup, that cannot be assigned to individual products but rather to a production order, as depicted in Fig. 4.21. In reality, the time consumed and corresponding cost of setup are assigned to non-productive or operating loss [25]. Because of advances in manufacturing design and technology, the setup activities can be performed quickly or offline during the manufacturing against a production order, i.e., simultaneously during the manufacturing.

The concept of Single-Minute Exchange of Die (SMED) from Toyota's production system was developed to reduce waste and realize rapid changeover to next production order [231]. Similarly, multiple setups related to different production orders can be performed beforehand on automated machines without stopping the execution of the current production order. In any case, the resource executing a setup activity can signal start and stop, and the corresponding timestamp can be included as part of machine or production order tracking objects. Furthermore, suitable EPAs need to be created to replicate the logic of transaction driver, duration driver, or intensity driver to assign setup costs to production orders.

4.7.5.2 Cost Leakage and Cost Inefficiency

Quality is identified as the "degree to which an inherent characteristic fulfills requirements" [80, 127], which has influence on revenue generated and costs incurred [77]. Manufacturing enterprises strive to achieve higher quality, but these enterprises face numerous obstacles to realize higher quality. Thus, there are costs associated with achieving (higher) quality and loss/lack of quality. The loss/lack of quality and the corresponding costs are not properly computed, recorded and tracked. This will hinder performance analysis, and planning and decision making.

The manufacturing resources are not efficiently used [52], which can be mainly attributed in realizing the higher quality of products or lack of resource reliability. For instance, higher quality is realized by employing extra cycle time in addition to planned cycle time [52]. Additionally, the unscheduled maintenance can contribute to the inefficient utilization of resources [52].

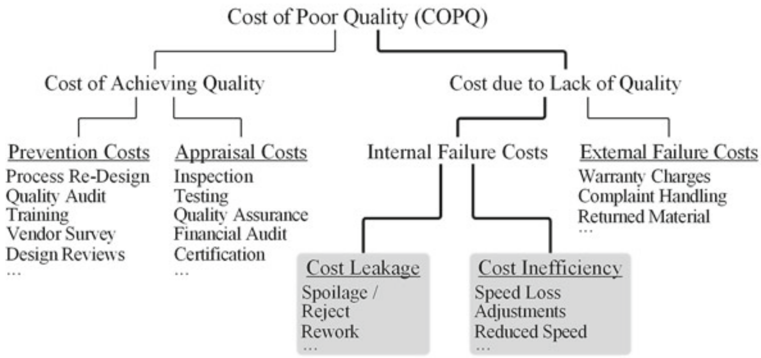

Fig. 4.22 Classification of Cost of Poor Quality (COPQ) according to Prevention-Appraisal-Failure (PAF) model, adapted from [79, 194]. The internal failure costs are further classified into cost leakage and cost inefficiency in the presented research

The concepts and procedures have been elaborated to address the aforementioned issues. The corresponding cost is labeled as Cost of Poor Quality (COPQ) [79]. COPQ is identified as "the costs that would disappear in the organization if all failures were removed from a product, service, or process" [79], which are usually expressed as a percentage of manufacturing cost, sales, total costs and so forth [194]. The term COPQ is also referred to as cost of quality [28] or poor-quality cost [66].

There exist different COPQ models [194, 216]. The most notably model is the Prevention-Appraisal-Failure (PAF) model categorizing quality costs as prevention, appraisal, and internal and external failure costs [194, 216], as illustrated in Fig. 4.22. Likewise, the process cost model, especially, focuses on processes and classifies the quality costs either as a cost of conformity or a cost of nonconformity [4]. Furthermore, there are Crosby's model, the opportunity or intangible cost model, and the ABC model [216]. In any case, extensive literature is available to assign different activities associated with quality costs to the previously mentioned categories [66, 81].

The prevention and appraisal costs can be figured out from the enterprise's accounting ledger [66]. The external failure costs are difficult to estimate as they might also include loss of future sales and customers. Likewise, the computation of internal failure costs is also not straightforward. In reality it is extremely difficult to determine accurately the COPQ and accounting systems do support the computation of COPQ [28, 81, 232]. Similarly, the process data and financial information is scattered across different departments and levels of an enterprise. The intensity of drawbacks associated with computation of COPQ is amplified when the manufacturing enterprise employs low volume production and high mix production schedules. Subsequently, most of the costs are purely estimates [81], which are subjective based on the enterprise members' role, responsibility and experience.

The presented research attempts to compute internal failure costs in real-time. The cost associated with the loss of quality and inefficient use of resources can be labeled as cost leakage and cost inefficiency respectively. These costs can be further categorized under internal failure costs, as illustrated in Fig. 4.22.

4.7.6 Cost Leakage

Products are, sometimes, manufactured with a lack of quality, which will result in rework and spoilage. The spoilage and rework costs are difficult to compute accurately, and further assigning and tracing these costs to products and production orders cannot be realized. The difficulty increases tremendously if the manufacturing enterprise employs low volume production and high mix production schedules.

Rework is defined as “action on a nonconforming product to make it conform to the requirements” (see ISO 9000 [127]). Likewise, rework is identified as “units of production that do not meet the specifications required by customers but which are subsequently repaired and sold as good finished units” [69], i.e., rework will result in adhering to requirements of a product including functional requirements of a product. On contrary, repair is defined as “action on a nonconforming product to make it acceptable for the intended use" (see ISO 9000 [127]). Thus, repair may not fully satisfy the product requirements, but might satisfy functional requirements of a product. Moreover, the repaired product, if possible, can be sold at reduced price. Subsequently, repair is considered as spoilage as it is difficult to compute the repair cost and predict the value added to the enterprise in the current research.

Rework can be seen in different ways and subsequently, influence the allocation of rework costs. Rework costs are assigned to a production order when the rework is induced because of certain requirements of a production order [69]. The rework costs are allocated to production orders as manufacturing overhead when the rework cannot be traced to specific products [69]. Finally, the rework costs are noted in the accounting ledger as losses when the rework is abnormal [69], i.e., costs cannot be traced.

Spoilage is recognized as “units of production-whether fully or partially completed-that do not meet the specifications required by the customer for good units and that are discarded or sold at reduced price" [69]. Furthermore, spoilage is classified as normal or abnormal [69]. The spoilage arising even if the production process is efficiently executed is termed as normal spoilage [69]. This issue can be addressed during production planning by increasing suitably, preferably according to a given predefined rule, the number of products to be manufactured for a given production order. Likewise, spoilage occurs because of process execution errors, and resource breakdowns, among others, which is termed as abnormal spoilage [69]. Abnormal spoilage can be avoidable and controllable by training operators, scheduling maintenance, and so forth [69].

Nonetheless, these aforementioned spoilage are treated differently from a financial accounting perspective. For instance, the cost associated with the normal spoilage is evenly distributed to good products [69]. Likewise, the costs associated with the abnormal spoilage are recorded into the accounting ledger under losses [69].

This will definitely impose constraints to identify profitable and loss making products/customers.

A production routing identifies different manufacturing process activities needed to be executed sequentially to realize a product [62]. Hence, quality issues can be identified after execution of a process activity, which again depends if the quality inspection is performed or not. In this regard, fall-off ratio, an operational metrics, has been identified to address the reduction in quantity after each process activity (see ISO 22400-2 [125], VDMA 66412-1 [150], VDMA 66412-3 [152]), but are difficult to interpret by the accountants. The non-confirming products are not processed at the later process steps and subsequently, the non-confirming products have a different completion status along production routing. Nevertheless, the aforementioned spoilage costs do not differentiate between the quality issues occurring at the first, intermediate or last process step. In addition, detailed feedback to the upstream departments, such as design and sales, is missing.

The loss of quality, represented by spoilage and rework, has been associated with the non-productive of resources [25] [84] and operating losses [52]. Non-productive encompasses inefficient utilization of a resource capacity whereas the operating loss encompasses time spent for setups, adjustments, producing spoilage and performing rework [52]. The operational metrics for computing non-productive or operational losses, like OEE and fall-off ratio, are mostly represented as indices that hide the complexity, product details, and production order details, among others. Furthermore, these values are aggregated over a time period and can represent multiple products and production orders. Nonetheless, these metrics can be transformed into costs and derive financial metrics [213]. These financial metrics, may be valid for high volume production and low production mix schedules, are vague and cannot be fully employed for performance analysis and decision making.

Spoilage, in most cases, are identified with waste with some value. For instance, spoilage can be sold at a low-price price as seconds [69]. Likewise, spoilage can be transformed into its initial raw material [69]. However, spoilage are accumulated over a period of time that cannot be tracked to any specific production orders and in some instances to products. Hence, the cost recovered from disposal and cost saved from recycling appears incorrectly in the accounting ledger. Overall, the performance analysis and decision making is hindered because of the previously mentioned reasons associated with the handling of spoilage and rework, and the associated costs.

According to Merriam-Webster dictionary, a leak is defined as “to enter or escape through an opening usually by a fault or mistake” [131]. The scrap and rework do not add any value to a manufacturing enterprise; rather the costs associated with the time and efforts invested to produce poor quality products are leaked. Hence, it is necessary to manage spoilage and rework costs in a different way. Subsequently, the cost associated with the scrap and rework can be included under cost leakage. The cost leakage needs to be computed in real-time and tracked from the perspective of different enterprise entities, especially production orders and resources, to initiate suitable process improvement programs.

Quality inspections are necessary to identify good products, rework products, and spoilage. These inspections are guided by the product specifications and manufacturing processes. In addition, quality policies of a manufacturing enterprise influence the quality inspections performed. In some instances, quality inspection is performed after execution of every process activity, and in other instances, quality inspection is carried out after execution of a few process activities. Likewise, quality inspections can be performed on a few randomly selected products employing Statistical Process Control (SPC) or they can be performed on all products. In the presented research, quality inspection is performed for all products at different stages of manufacturing processes.

Figure 4.23 illustrates the process of assignment of spoilage and rework costs to cost leakage. In the case of spoilage, the accumulated manufacturing cost needs to be assigned to cost leakage that will be further aggregated to the business sustaining level. The spoilage can occur at different stages in manufacturing processes. Subsequently, only the manufacturing cost of the current process activity and previous successfully executed, if any, process activities need to be assigned to the cost leakage.

Likewise, quality inspections can reveal flaws in products that can be rectified by reworking with additional process activities. Nevertheless, calculating the rework costs is a complicated issue that depends upon the process activities employed for rectifying the underlying flaws in the products and the management policies toward rework. Subsequently, rework costs can be accurately calculated after rectifying the flaws, which might hinder performance analysis and decision making. Subsequently, the different types of possible flaws must be properly identified and classified in general and specific to different products. Moreover, each flaw must be defined with attributes (e.g., severity) that assist in performing offline analysis and instantiating process improvement programs. In addition, financial related information, such as resource details, time required and cost that would be incurred to rectify a flaw, has to be defined in a process database.

The product tracking object contains information about the executed process activities including the quality feedback. Thus, product tracking objects can be processed in the CEP engine to compute costs and the computed costs can be assigned to manufacturing costs or cost leakage based on the quality feedback. The necessary assignment logic has to be codified in EPAs and suitably create EPNs. In the case of rework costs, the EPAs need to access the process database that contains information about rework classification and corresponding expenses to rectify the flaws. Furthermore, the cost leakage is aggregated to the business sustaining level.

The cost leakage is primarily critical from a production order perspective and secondarily important from a resource perspective. Subsequently, reports of different types can be generated and presented to managers and supervisors, and so forth along with the operational metrics. Overall, the performance analysis and decision making can be enhanced.

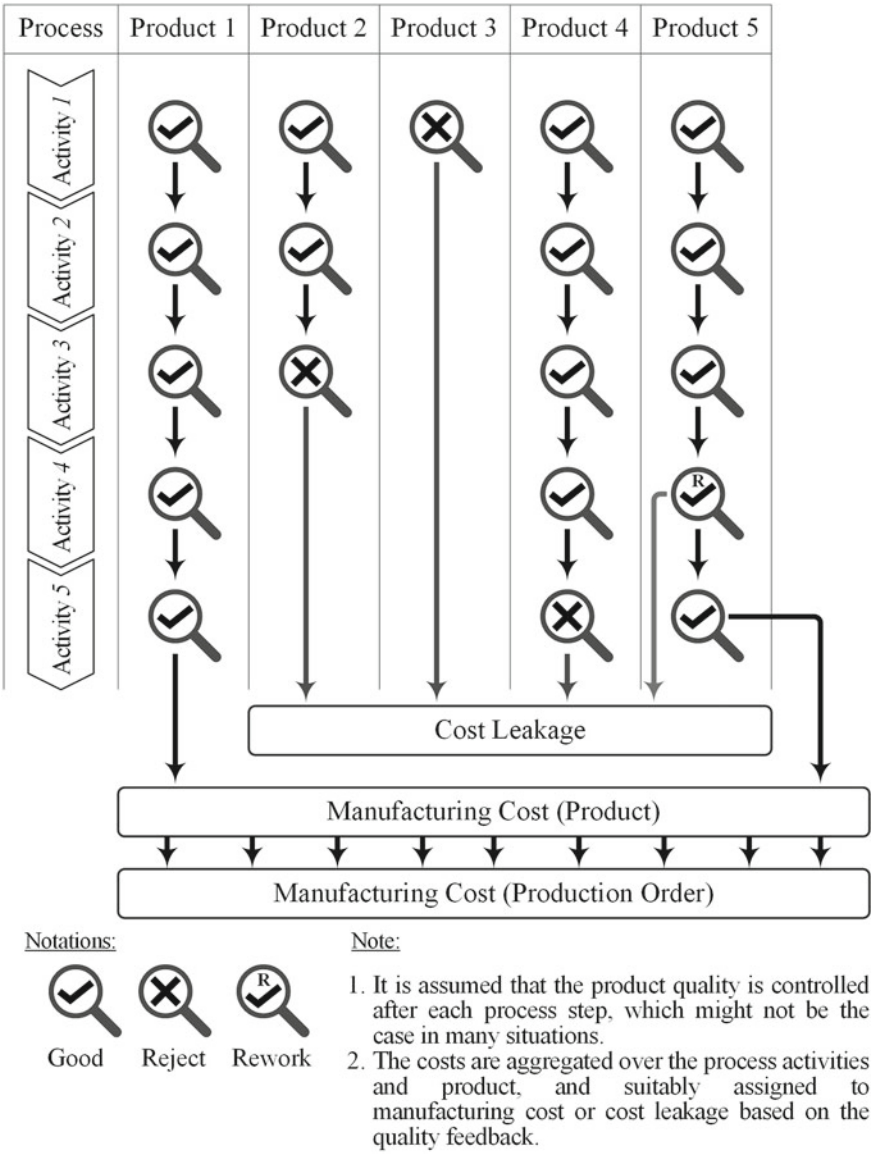

Fig. 4.23 An example demonstrating the assignment of spoilage and rework costs to cost leakage. The spoilage and rework are determined via quality inspections at different process activities

4.7.7 Cost Inefficiency

Cost leakage is highly indispensable from the perspective of production orders. Nevertheless, there are several costs that are incurred during execution of processes both internal and external to a manufacturing enterprise. These costs can be represented by the inefficient utilization of stated resource capacity, lousy material handling, deficient delivery of services [194], and loss of goodwill [31].

These costs have been termed as hidden costs, intangible costs and invisible costs, and so forth [28, 31, 52, 232], for the following reasons. The computation of these costs has received the least attention [52, 194]. The available accounting systems do not support the computation of these costs [28 ,232]. Furthermore, these costs do not appear adequately in the accounting ledger [232], as the values are estimated by quality managers and quality data collectors [194]. Also, there is no motivation to calculate this cost by the manufacturing enterprises [194].

Consequently, the monitoring and controlling of manufacturing processes as well as performance analysis and decision making is hampered [66], which will be based on operational metrics. Nonetheless, the presented research attempts to compute these costs with exclusive focus on manufacturing processes and corresponding inefficient use of resources. The internal inefficiencies encompass resource downtime, longer cycle time, small stops, adjustments, and reduced speed, among others [232]. The cost associated with internal inefficiency is labeled as cost inefficiency (see Fig. 4.22) in comparison to the hidden cost that covers the entire supply chain.

The availability of a resource can be classified into productive time, non-productive time and idle time [25], as illustrated in Fig. 4.24. Furthermore, the non-productive time should be converted into idle time through process improvement programs [25]. This extra idle time should be converted to productive time by scheduling new production orders [25]. Nevertheless, the collection of aforementioned time is done according to enterprise reporting cycles. This procedure might be sufficient for high volume production and low mix production schedules. Subsequently, it is necessary to have a timeline of resource availability, as illustrated in Fig. 4.25.

In comparison to the research on hidden cost, enormous amounts of research have been carried out surrounding OEE. Furthermore, OEE has been extensively adapted by manufacturing enterprises and is a standard module provided by many MES software vendors. The underlying fundamentals of OEE can be exploited to determine the cost inefficiency. OEE is composed of availability, performance and quality elements [15]. Additionally, the six big losses have been identified associated with these elements—breakdowns, setup and adjustments, small stops, reduced speed, startup rejects and manufacturing rejects, as illustrated in Fig. 4.26 [153]. These losses need to be identified and eliminated to improve productivity [153].

The first four big losses are related to time that increases non-productive time of a resource. The down time loss is composed of breakdown, and setup and adjustment losses [153]. Breakdown signifies the time spent on unscheduled maintenance, and rectifying tooling failure, among others [153]. Similarly, setup and adjustment indicates time lost because of changeover, material shortage, and operator shortage, and so forth.

The speed loss encompasses small stops and reduced speed [153]. Small stops comprise blocked sensors, cleaning [153], blockage of downstream processes, and starvation from upstream processes [15], and so forth. Likewise, reduced speed occurs

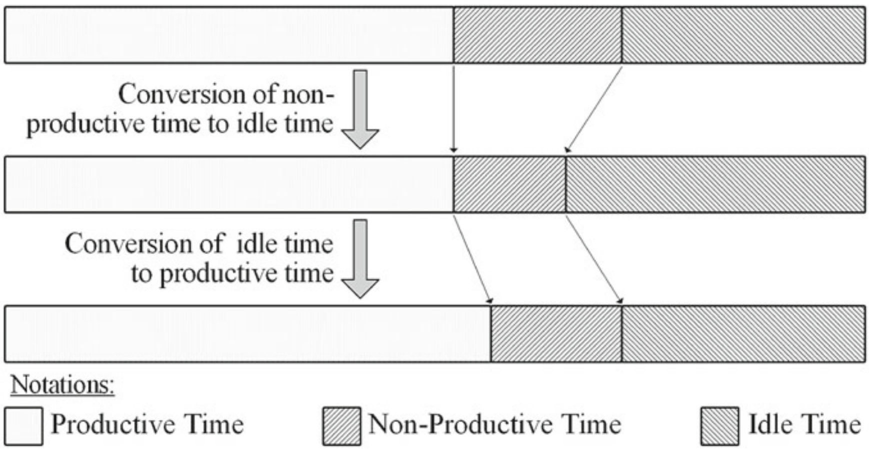

Fig. 4.24 Classification of resource availability, adapted from [25]. Furthermore, the transformation of non-productive time to idle time and idle time to productive time is also depicted [25]

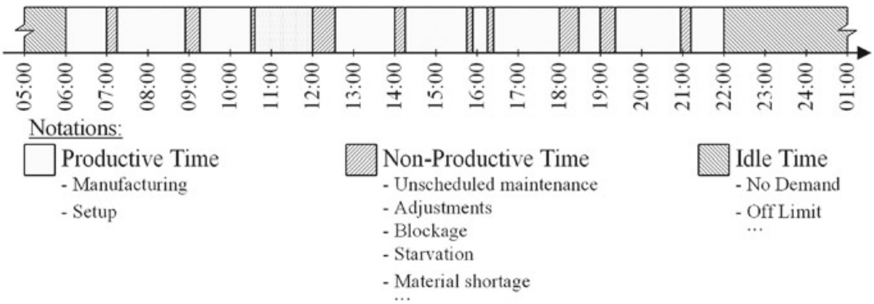

Fig. 4.25 Graphical representation of resource availability over a time period

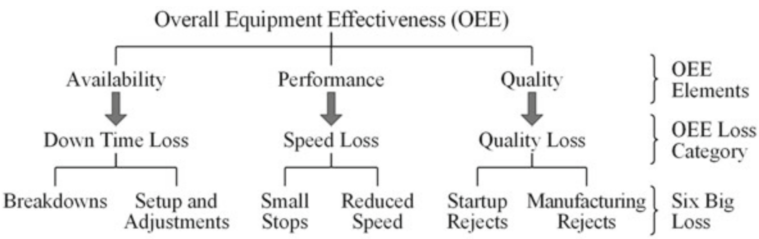

Fig. 4.26 Elements of Overall Equipment Effectiveness (OEE) and the six big losses, adapted from [153]

mainly because of combination of reasons, such as operator inefficiency, equipment wear [153], complex products, and specifications, among others.

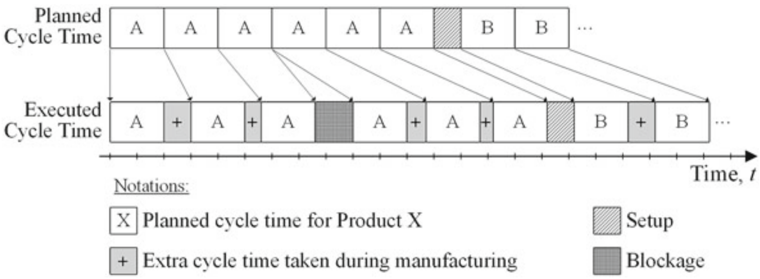

Fig. 4.27 Schematic illustration of differences between planned and executed cycle time

In the presented research, setups are considered as part of productive time for reasons stated previously whereas the remaining three losses are considered as non-productive, which can be taken into account for deriving the cost inefficiency. These down time losses indicate a major stoppage of a resource, which occurs for considerable time [153] and can be tracked manually and/or automatically. Subsequently, the down time loss situations should be made available by the operator by turning suitable knobs on the resource or by using the special terminal attached to the resource.

The small stops, in many cases, can be tracked efficiently, especially in the case of resources with PLC. Otherwise, the small stops will be aggregated across different products and production orders, which might hinder performance analysis and decision making due to lack of accuracy. The resource vendor should identify and classify the necessary small stop events, and make these events available in the PLC of a resource. In contrast, it is difficult to keep track of the reduced speed by operators. Subsequently, the actual cycle time can be compared with the planned cycle time to determine the extra cycle time taken to manufacture a product, as illustrated in Fig. 4.27. The actual cycle time can be determined using the timestamps of the manufactured product. In some scenarios, the actual cycle time might be lower than the planned cycle time. In this case, the actual cycle time can be used to compute only the manufacturing cost. This concept can be also applied to the adjustment losses. The planned cycle time and other information associated with a product can be queried from the corresponding production order.

The aforementioned data associated with non-productive can be acquired from the PLC of a resource or through a special terminal attached to a resource. The acquired data can be further used to create product and resource tracking objects. In addition, production order tracking objects are also created and made available. In any case, the tracking objects should have necessary timestamps. These tracking objects can be processed by a CEP engine by employing suitable EPAs and EPNs to determine the non-productive time and further computing cost inefficiency. The EPL statements of EPAs need to implement the logic of computing cost inefficiency and assigning the same to the business sustaining level.

As mentioned in Sect. 3.4.4.4, there exist different accounting techniques to compute and assign costs, most prominently ABC and RCA. ABC considers all costs incurred during manufacturing as variable costs [182]. Hence, it is an inaccurate technique to compute the cost inefficiency. On the contrary, RCA is a promising accounting technique that employs fixed and proportional cost to compute and assign different types of costs. Subsequently, RCA needs to be employed to compute cost inefficiency. The necessary total cost consisting of fixed and primary costs is assigned to products as a manufacturing cost based on causal relationships. The remaining non-productive time is converted to cost inefficiency by employing only fixed cost. The necessary financial information can be obtained from a predefined location—ERP System and/or process database.

The cost inefficiency is indispensable primarily from the perspective of resources. Nevertheless, the cost inefficiency can be also viewed from the perspective of production orders. Overall, different types of reports can be generated and presented to enterprise members along with the operational metrics. The cost inefficiency computed in real-time can be used proactively to initiate a suitable process improvement program. Likewise, the cost inefficiency can be employed to analyze capacity utilization and perform make-buy, i.e., outsourcing decisions (see [93]).

4.7.7.1 Performance Positioning: Linkage of Financial and Operational Metrics

PMS have stressed the importance of aligning enterprise objectives with performance metrics [49, 109]. Additionally, the employed operational and financial metrics should be balanced [49, 109]. Similarly, enterprise members can manage to systematically understand and react to only a few metrics at a given time [12]. Finally, the metrics must be computed and presented to enterprise members in real-time to enhance monitoring and control of manufacturing processes.

The aforementioned requirements induce constraints that are challenging to realize in manufacturing enterprises. Nevertheless, methodologies have been elaborated in previous sub-chapters to compute the operational and financial metrics using transactional data and real-time process data. However, these metrics are computed in isolation, and may be, presented side-by-side. Consequently, the presentation and interpretation of these metrics by enterprise members are not comprehensive.

To overcome the abovementioned issues, a methodology of performance positioning is presented. Performance positioning, analogous to global positioning system, attempts to link the financial and operational metrics on a predefined chart, as illustrated in Fig. 4.28. Furthermore, the financial metrics can be aligned with the enterprise objectives. The plotted chart will assist enterprise members in understanding their current situation and assists in initiating suitable process improvement programs, and decision making, and so forth. Quality (e.g., quality ratio [125]) and throughput are the operational metrics considered for the chart. Throughput can be defined as "volume of output generated by a resource in a specific period of time" [138]. The operational metrics is not only restricted to throughput and quality; rather the metrics should be suitably selected corresponding to overall productivity and quality. Likewise, the chart encompasses cost leakage and cost inefficiency as finan-

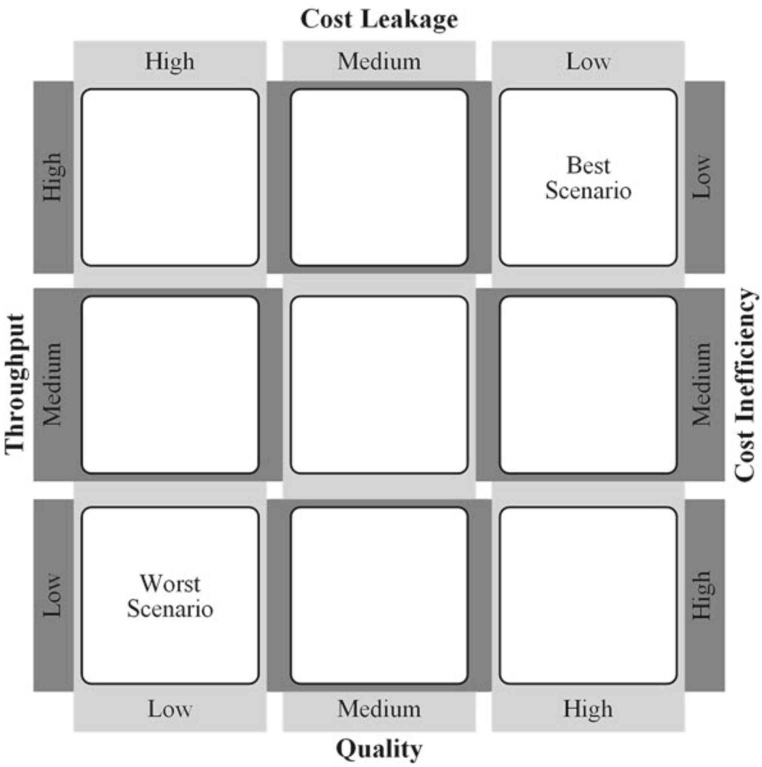

Fig. 4.28 Performance positioning chart generated by plotting throughput and cost inefficiency, and quality and cost leakage

cial metrics. Finally, performance positioning can be created for enterprise entities, such as resources and production orders, and for a given time range.

The values of the aforesaid metrics can be classified as high, medium and low by employing predefined rules based on comparison of the actual values (i.e., AS-IS values) with the planned production and cost objectives (i.e., TO-BE values) of a production order that are received by the production control module of Level 3 from the product cost accounting module of Level 4. It can be sufficient to plot the chart, either, by using quality and throughput, or cost leakage and cost inefficiency. Moreover, there exist inverse relationships between quality and cost leakage, and throughput and cost inefficiency. However, it is necessary to combine the plots to link the financial and operational metrics and cross check the accuracy of the computed metrics.

The classification of metrics' values lead into nine boxes, as depicted in Fig. 4.28. The lower left box in the chart indicates the worst scenario—low quality attained and corresponding higher cost leakage, and low throughput with matching higher cost inefficiency. This might be a situation, especially, with the manufacturing of low

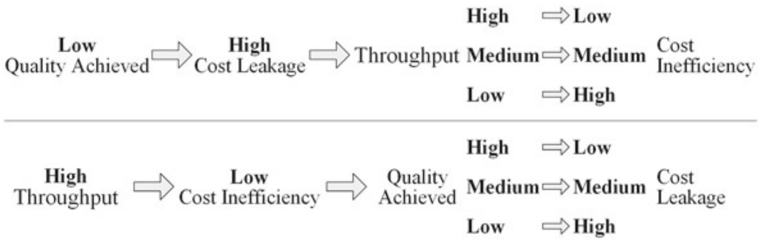

Fig. 4.29 Selected scenarios of generating performance positioning chart

volume and complex products during the initial stage of manufacturing. Likewise, the upper right box suggests the best scenario—high quality attained and corresponding lower cost leakage, and higher throughput with tallying low cost inefficiency. This might be a situation with medium/high volume and relatively simple products and stable manufacturing processes.

The quality and cost leakage, and throughput and cost inefficiency will be plotted in one of the boxes. Furthermore, interpreting the chart is vital to initiate suitable process improvement programs. The plotting can be done in different ways. For instance, Fig. 4.29 illustrates two scenarios to plot and interpret the performance positioning chart. These scenarios, especially, highlight the previously mentioned best and worst situations.

Performance positioning provides a comprehensive view of the shop floor by linking the operational and financial metrics in a single chart. Subsequently, managers and supervisors, among others can suitably commence process improvement programs to realize the performance of the best case as indicated on the upper right corner of the performance positioning chart. Nevertheless, the performance positioning has certain limitations. For instance, the chart assists in identifying the current manufacturing situation, but does not make any suggestion about improving the current situation. Likewise, the classification of ranges is highly subjective because it is influenced by quality policies of a manufacturing enterprise.

4.8 Process Visualization Client

The process visualization client assists enterprise members in real-time monitoring of manufacturing processes. In addition, it supports various offline tasks to carry out performance analysis. For these tasks, the client needs to consider the enterprise member's roles and privileges.

The process visualization client is based on server-client architecture with data aggregation component as server, as illustrated in Figs. 4.1 and 4.9. Furthermore, the clients, in comparison to the server, are thin clients with the aim to visualize process data employing numerous graphical elements (e.g., charts, gauges), reports, and tables. In addition, the client handles user interactions. The functionalities of the clients are listed below:

1. Visualize real-time process data along with the necessary transactional data, i.e., production order details;
2. Selection and display of different operational metrics and financial metrics;
3. Highlight events and alarms derived from the event processing component of the data aggregation component;
4. Interfaces for offline analysis of historical process data, such as traceability;
5. Administrative tools for configuring different components of the reference architecture.

Overall, the process visualization client provides different functionality to realize real-time monitoring of manufacturing processes.

4.9 Summary

PMS have identified different dimensions/characteristics, such as strategy alignment, balance, and dynamic adaptability [49]. However, these dimensions are difficult to realize in manufacturing enterprises. Additionally, it is more challenging to achieve in manufacturing enterprises employing low volume production and high mix production schedules.

A reference architecture encompassing numerous components has been presented. The architecture encompasses the following components: (i) the data collection component for integrating physical resources located on shop floor; (ii) the data aggregation component for relating transactional data with real-time process data from different MES levels; (iii) the data aggregation component facilitates tracking of enterprise entities; (iv) real-time control of enterprise processes using the CEP component and subsequently dispatching control data to achieve strategic objectives of a manufacturing enterprise; and (v) the process visualization clients provide interfaces for displaying real-time process data, tracking information, and support forward and backward traceability of enterprise entities. In addition, steps are elaborated to enable the aforementioned architecture. The steps include analysis, modeling and (re-)design of manufacturing processes, creation of data model and DFDs, and knowledge identification.

The presented research elaborates methodologies to calculate operational and financial metrics in real-time, especially by exploiting the functionalities of event processing. The operational metrics can be computed by employing the syntax of SQL of a relational database and CQL of event processing. These metrics are computed, mostly, as part of MES.

In contrast, the financial metrics are computed by enterprise applications, such as ERP Systems, especially by product cost accounting module. Thus, it is proposed in the presented research to utilize some of these functionalities of product cost accounting of ERP Systems to MES and make the necessary metrics available to enterprise members on the shop floor in real-time. Thus, the quality of products and efficiency of resources are crucial for the success of a manufacturing enterprise. Subsequently, the concepts of cost leakage and cost inefficiency are elaborated. Furthermore, methodologies have been presented to compute these costs. In addition to utilizing these cost for real-time monitoring and control, the computed costs can be used for offline performance analysis and provide detailed feedback to the upstream processes, like design and sales.

Nevertheless, the computed metrics need to be linked to enable real-time monitoring and control of manufacturing processes. Subsequently, performance positioning chart has been devised to link the financial and operational metrics. The cost leakage and cost inefficiency are considered for the financial metrics whereas the operational metrics considered are quality and throughput. The values of the previously mentioned metrics are used to identify the position of the manufacturing situation. This information can be used to initiate process improvement programs.

Chapter 5
An Industrial Case Study, Implementation and Evaluation

Sand casting is one of the oldest manufacturing processes that use expandable molds to manufacture complex metal products [30]. The metal can constitute most of existing ferrous and non-ferrous alloys [30]. However, majority of the metal products are made from aluminum, and ductile and gray cast iron [7]. In Germany, there are around 600 foundries employing roughly 87,000 employees with molten metal capacity exceeding 4.8 million ton/year [7]. Consequently, Germany takes first and fourth position in Europe and World respectively in the manufacturing of metal products employing sand casting [7].

Sand casting assists in manufacturing products with complex shapes and sizes, but the use of expandable molds has impact on throughput and quality [30]. Hence, it is necessary to monitor and control the sand casting process. The previously elaborated reference architecture has been implemented and evaluated in an aluminum foundry in Drolshagen, Germany. Subsequently, the foundry and the sand casting process are introduced in Sects. 5.1 and 5.2 respectively. Section 5.3 elaborates the implementation of different components of the architecture. The evaluation of the reference architecture is carried out in Sect. 5.4 against measurable and non-measurable criteria. Finally, Sect. 5.5 presents as short summary.

5.1 Foundry Profile

Ohm & Häner Metallwerk GmbH & Co. KG[1] is a foundry located in Olpe-Friedrichsthal and Drolshagen, Germany. The foundry employs more than 400 employees, and supplies aluminum alloy castings ranging from 20 g to 2,000 kg to automotive OEMs, machine builders, and so forth. Furthermore, sand casting and permanent mold casting techniques are employed. Ohm & Häner supports its customer's

[1] For more information, refer to http://www.ohmundhaener.de.

S. Karadgi, *A Reference Architecture for Real-Time Performance Measurement*,
Progress in IS, DOI: 10.1007/978-3-319-07007-0_5,

management concepts, including kanban and JIT. Finally, Ohm & Häner is capable of adjusting its manufacturing environment to facilitate different lot sizes—one piece, medium series and large series.

The previously elaborated architecture has been implemented and validated for the foundry in Drolshagen, which was commissioned in October 2008. The foundry has a state-of-the-art production line supported with numerous automated machines. The castings composed of different aluminum alloys can range from 500 g to 60 kg with the mold box size 700 mm × 630 mm. Furthermore, the foundry has a maximum capacity to handle 10,000 ton/year of molten metal and employs around 22 employees per shift.

The day-to-day planning and manufacturing activities of the aforementioned foundries are supported with numerous software applications, such as MAGMA SOFT, CATIA V5, ProE and STARCAST. In the presented research context, the foundry use RGU OPTI V7[2] as an ERP System. RGU OPTI V7 is a specialized ERP System for foundries that extensively support casting processes. It encompasses numerous functionalities, including production planning, sales, purchasing and material management. In addition, the production orders and associated production plans and inspection plans are managed in the RGU OPTI V7. The underlying database of RGU OPTI V7 is an Oracle Database 10*g*.

5.2 Sand Casting Process

Casting can be identified as "a process in which molten metal flows by gravity or other force into a mold where it solidifies in the shape of mold cavity" [63]. Casting is one of the oldest manufacturing techniques employed to create metal products [63]. Furthermore, casting is employed to manufacture components with complex geometries, and very large/bulky components, and so forth [63].

Sand casting is one of the important casting processes [63], that employs expandable sand molds to manufacture complex metal products by pouring the majority of the available alloys [30]. Figure 5.1 illustrates the necessary features and terms employed to define a sand casting technique [30, 63]. Sand casting is employed at Drolshagen plant and is restricted to different aluminum alloys.

The sand casting process has been well researched and documented involving the following activities:

1. Patterns consist of an external shape of the product to be cast, and are made of wood, plastic and metal [63]. Patterns are made available prior to the commencement of manufacturing of products against a given production order.
2. (Sand) cores are necessary to achieve the internal shape of the product. The cores are manufactured using dies and sand mixture. The sand is prepared according to a recipe stated in the production order. If required, the cores are assembled to form a complex internal shape.

[2] For more information, refer to http://www.rgu.de.

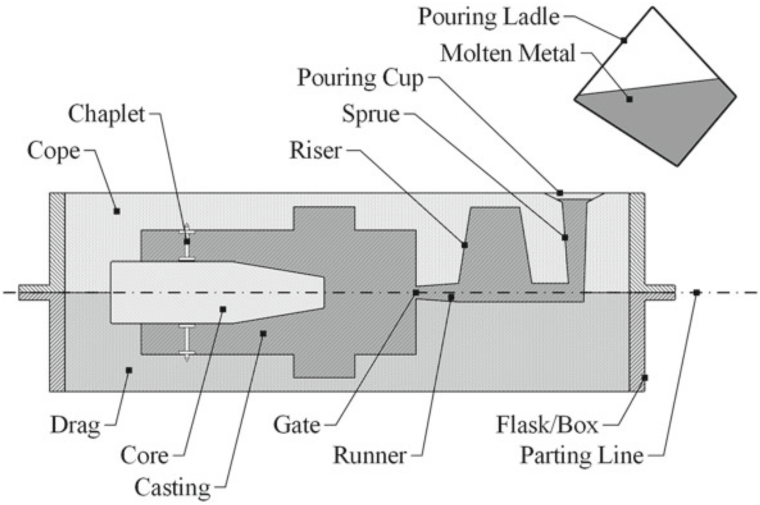

Fig. 5.1 Cross-sectional view of a sand casting along with its features and terms, adapted from [30, 63]

3. Drag and cope are molded by packing different types of sand around the pattern in molding machine [30]. These sands shall be prepared according to the recipes stated in the production order [63].
4. A gating system consisting of a pouring cup, sprue and gate are created in the cope [63]. A part of the gate and runner are part of the pattern. The cope might contain a riser that acts as a reservoir of molten metal to account for casting shrinkage [63].
5. Quality inspections, mostly visual, are carried out on cope and drag. Cores or core assembly and chills are set in the drag when both the drag and cope have confirmed to the required specifications, otherwise the drag and cope are disposed as waste. Chills assist in solidification of castings [63]. Now, the drag and cope are clamped and the clamped mold is now available for the molten metal to be poured [30].
6. The necessary metals are melted in a furnace to attain the required temperature, and treated, if necessary, to achieve the specifications stated in the production order [30]. Furthermore, different quality tests are performed.
7. The molten metal is shifted to a ladle and poured into the clamped mold, i.e., clamped cope and drag [30].
8. The casting and sand are separated in the knock out operation. Then, the casting is cooled for the specified amount of time in the cooling chamber [30], as mentioned in the production order.
9. Next, operations, such as core removal, surface cleaning, trimming, quality inspection and coding, are carried out [63].
10. Finally, operations, like surface grinding, heat treatment and machining, are performed based on the product specifications.

The elaborated sand casting process has been adapted at Drolshagen plant, as illustrated in Fig. 5.2. As mentioned earlier, the sand casting process is well documented. However, the underlying resources influence productivity as well as losses. The sand casting process is categorized into different areas and supported with automated machines. The production line is considered as the main or master process, which controls the productivity of the upstream and downstream processes. The main process is supported with sand mixing, core shooting and melting processes, which can be generally termed as supporting processes. In addition, there are pre-processing and post-processing/secondary activities, which are carried out at Olpe-Friedrichsthal plant. For instance, material purchasing, and pattern making, and so forth can be combined under pre-processing activities. Likewise, the product specification that might dictate metal treatment and grinding operations, among others are considered as post processing activities.

The casting defects (e.g., misruns, cold shuts) are well documented. Nevertheless, the probabilities of having casting defects are high. The casting quality is influenced by a combination of factors—pattern, molten metal temperature and sand, among others. In addition, the humidity of the air is critical for aluminum alloy casting. Subsequently, it is indispensable to monitor and control the aforementioned sand casting processes to increase productivity and decrease losses.

5.3 Implementation

The aforementioned foundry encompasses different characteristics of manufacturing. The foundry adheres to low volume production and high mix production schedules. The molds/castings are considered as discrete that are physical moved and sequentially operated by different automated machines located along the production line. Thus, the production line can be viewed as a flow line production that follows the First In, First Out (FIFO) principle. Finally, the molten metal and sand are prepared according to a pre-defined recipe and managed as part of batch processing, identical to processes in chemical industries. These characteristics present numerous challenges that impede the realization of real-time monitoring and control of sand casting processes in the foundry. Nonetheless, attempts are made to implement and evaluate the reference architecture in the foundry.

The reference architecture has been implemented using Microsoft Visual Studio IDE (Integrated Development Environment) and .NET framework 4.0. The process data is stored in an Oracle Database 10*g* and visualized as charts and gauges using Nevron[3] libraries. The different components of the reference architecture are based on client-server architecture and communicate through a WCF interface. Furthermore, many of the components are implemented as Windows Services. The following paragraphs elaborate on the implementation of the reference architecture.

[3] For more information, refer to http://www.nevron.com.

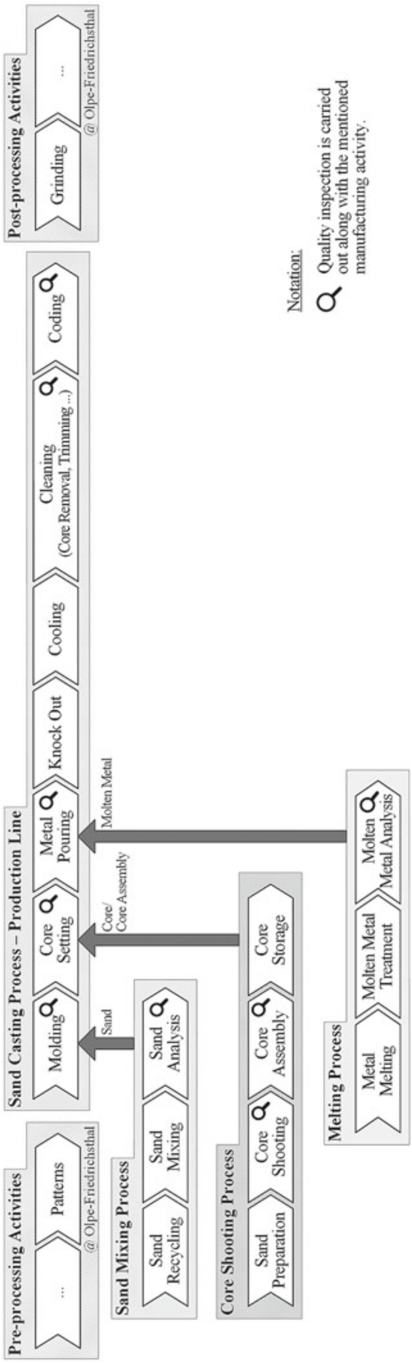

Fig. 5.2 Sand casting process employed at Ohm & Häner, Drolshagen. Some of the pre-processing and post-processing activities carried out Ohm & Häner, Olpe-Friedrichsthal are also shown

5.3.1 Process Analysis and Modeling

EI within and across different enterprise levels can be considered as a building block toward partially realizing monitoring and control of manufacturing processes. Furthermore, this building block can be exploited to support enterprise performance measurements. Subsequently, horizontal integration of different resources located on the shop floor and vertical integration of data across different enterprise levels are considered in the Drolshagen plant.

Process analysis and modeling of business and manufacturing processes is crucial for realizing the aforementioned integration. The processes employed in the Drolshagen plant are considered for analysis. Subsequently, structured interviews were carried out with the plant managers, plant supervisors, and quality engineers to comprehensively understand and model the business and manufacturing processes. The processes were modeled using ARIS[4] framework as EPCs.

The aforementioned modeling provides a coarse grained view of different processes employed in a manufacturing enterprise. Hence, it was necessary to analyze and model manufacturing resources and associated processes, especially with a focus on automated machine interfaces and information flow between resources. Likewise, information flow between RGU OPTI V7 and automated machines is considered for analysis and modeling.

Data models were created by referring to manuals of resources, interacting with resource vendors and structured interviews with the plan managers and plant supervisors. Figure 5.3 presents a coarse grained data model of the manufacturing processes employed in Drolshagen plant. Likewise, DFDs are created to capture the dynamic interaction among different manufacturing processes and the underlying automated machines and enterprise applications. The DFDs aid in relating different enterprise entities. Furthermore, process analysis assists in identifying the trigger conditions required to acquire process data and associate the data with the corresponding enterprise entities.

5.3.2 Data Collection

The previously mentioned processes are supported with highly automated resources, which need to be horizontally integrated. Subsequently, these resources are defined in an XML based configuration file. The data collection component has been implemented based on OPC DA Framework .NET and uses numerous Application Programming Interfaces (APIs) from Softing's OPC Classic Toolkit.[5] In addition, the implementation covers additional protocols, such as sockets and file servers. These implementations assist in accessing process data from different sources, which is based on the predefined communication pattern in the configuration file. For instance,

[4] For more information, refer to http://www.softwareag.com.

[5] For more information, refer to http://www.softing.com.

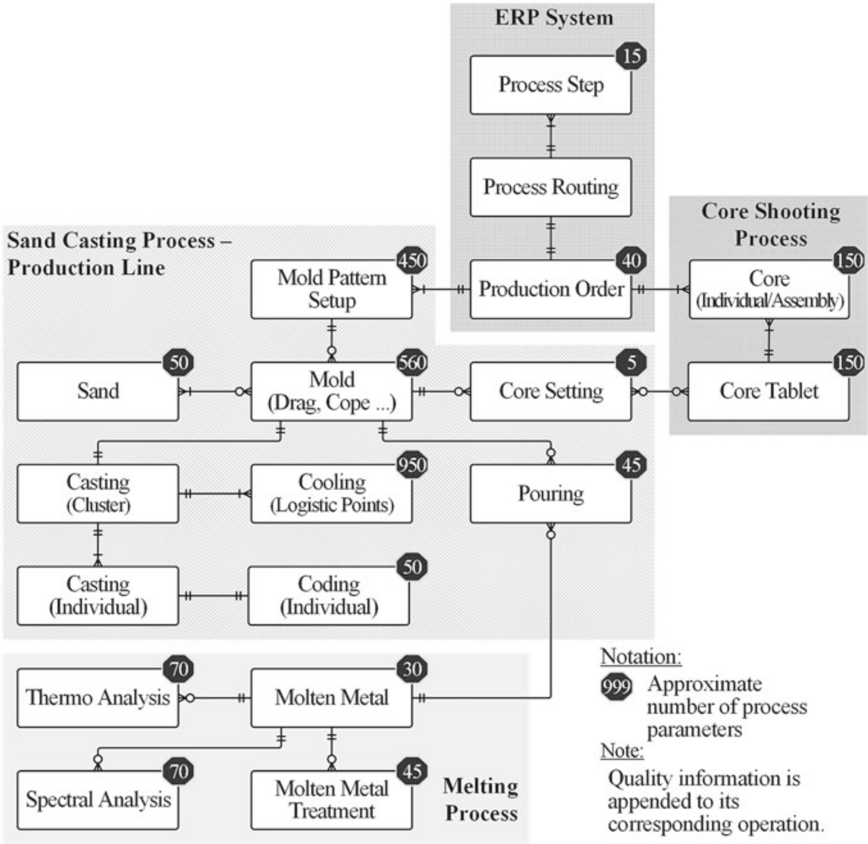

Fig. 5.3 Coarse grained data model of a sand casting process employed at Ohm & Häner, Drolshagen. Also, approximate number of process parameters collected is shown

a molding machine uses an isochronous communication pattern, in which the data group is requested when the mold number is incremented. Finally, the data collection component provides a WCF interface for subscribing to real-time process data.

5.3.3 Data Aggregation

The main functionality of the data aggregation component is to integrate the transactional data from RGU OPTI V7 with the real-time process data from automated machines. Furthermore, the molding machine is the master of the production line. On pattern changes, the production order details are assigned to the pattern. Subsequently, the production order ID is stored with the mold produced along with the other process parameters. Likewise, production order ID is also made available along with the core.

The data aggregation component subscribes to the data collection component and uses the XML based configuration file. Based on the communication pattern, the process data are delivered to the data aggregation component. Subsequently, the process data, i.e., AS-IS values, is combined with the corresponding transactional data, i.e., TO-BE values, from the RGU OPTI V7. This integrated data is stored in the Oracle Database 10*g*. Furthermore, the process data is published via WCF interface to all the subscribed process visualization clients. Additionally, the integrated data is used in numerous ways.

5.3.3.1 Tracking

The tracking component subscribes to the data aggregation component for the integrated data. Numerous enterprise entities are considered for tracking, as listed in Fig. 5.4. Furthermore, these entities are tracked at suitable traceability resolutions and processed either as transient or resident entity types. Furthermore, termination conditions are exclusively defined for tracking objects. For instance, mold tracking object are removed from the main memory after 180 min after creation. Likewise, production order tracking objects are made available in the memory for a day after creation, i.e., after the pattern change.

The tracking object items and relativities are also defined in the XML based configuration file. Furthermore, the necessary information for managing the tracking objects is defined in the configuration file. The tracking component is implemented as a Windows Service that subscribes via WCF interface to the data aggregation component for integrated data and returns back tracking objects. The tracking objects are used in numerous ways. The process visualization client provides an interface to visualize the tracking information associated with enterprise entities, as depicted in Fig. 5.5. In addition to presenting the critical process parameters as part of tracking information, the tracking information also contains creation and modification timestamps that are critical for manual control of manufacturing processes. This information is updated if any of the listed tracking objects are updated and terminated. In addition, the tracking objects are forwarded to the event processing and operational metrics component.

5.3.3.2 Real-Time Monitoring and Control

There are many situations on the shop floor that go undetected leading to reduced productivity and increased losses. For instance, pouring molten metal with the wrong specifications into a mold in comparison with the associated production order of the mold. Subsequently, real-time monitoring and control of manufacturing processes is absolutely necessary to avoid moving away from the set goals.

Enterprise Entities	Traceability Resolution	Processing Type	Remarks
Mold (Cope + Drag)	Unit	Transient	Molds are assigned virtual unique IDs, which are communicated to different downstream automated resources (e.g., coding on castings).
Sand (Mold)	Batch	Resident	
Sand (Core)	Batch	Resident	
Core (Tablet)	Batch	Transient	Cores are assigned virtual unique IDs, but the IDs are not physically marked on the cores. Further, the cores are placed on a tablet. Thus, unit traceability is lost.
Core Assembly (Tablet)	Batch	Resident	
Molten Metal	Batch	Resident	
Casting	Unit	Transient	A mold can consist of shape for a single product or cluster of products. In case of cluster, the products are identified with numbers. Thus, it is possible to uniquely identify a casting with the combination of virtual ID of a mold and cluster number.
Production Order	Batch	Resident	
Machine	Batch	Resident	

Fig. 5.4 Enterprise entities considered in foundry for realizing tracking and traceability, and the corresponding traceability resolution and processing type

Structured interviews have been carried out with the plant manager, plant supervisor and quality engineers to identify situations that are critical for executing the casting processes in an efficient manner. These situations are modeled as EPAs with the underlying EPL statements. Furthermore, the EPAs are connected to form EPNs that define complex situations. The EPAs and EPNs are loaded into the event processing component and are employed to process the incoming tracking objects. The event processing component uses NEsper for .NET as a CEP engine [44]. In comparison to CEP engines available for a Java platform, there exist very few CEP engines to support the .NET platform. According to the market overview of CEP engines conducted by [218], there exist three out of twenty one CEP engines that have interfaces to .NET platform of which two are commercial.

The control objects are dispatched to the data aggregation component for further processing upon detecting predefined situations, i.e., context awareness. The control objects are defined along the EPAs. These control objects have numerous attributes (e.g., priority) and these attributes are assigned values from the tracking objects that are used to detect the situations. The control objects, in most of the situations, are forwarded to process visualization clients by the data aggregation component for displaying warnings. In some situations, it is possible to modify the values in the PLC of the automated machine. For example, the pouring machine can be blocked

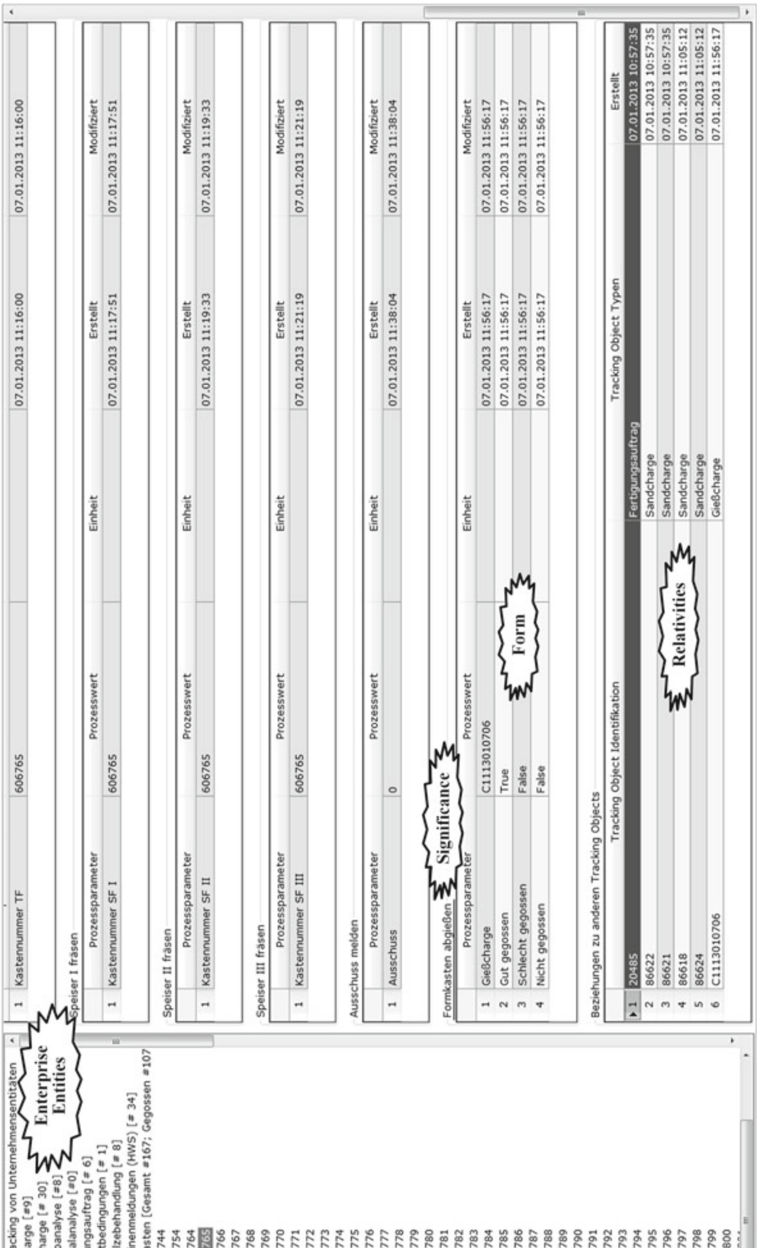

Fig. 5.5 Screenshot depicting tracking component in process visualization client (in German)

to avoid pouring molten metal into the mold when the molten metal specifications do not match the specification associated with the production order of the mold.

Figure 5.6 illustrates an EPL statement describing the pouring of molten metal with incorrect specification into molds, as described previously. In addition, Fig. 5.6 also presents a screenshot of warning messages displayed in the process visualization clients that are derived from the online control objects. The screenshot, especially, displays warning messages related to pouring of molten metal with incorrect specifications (see warning messages with Priority or Priorität 2 in Fig. 5.6). The detection of predefined situations and display of messages are done in real-time that supports to monitoring and control of manufacturing processes.

5.3.3.3 Traceability and Data Analysis

Traceability and data analysis are crucial for analyzing past performance and decision making, especially with the intent to initiate suitable process improvement programs. The implementation of the reference architecture provides different ways to navigate among enterprise entities, as shown in Fig. 5.7 with shaded area being the most frequently used navigation. This navigation supports forward and backward traceability. The traceability can be carried out using the interfaces provided in the process visualization client.

Nevertheless, traceability is not sufficient for effectively carrying out past performance analysis and decision making. Subsequently, numerous (historical) data analysis functionalities specific to foundries have been provided. For instance, product analysis functionality is used to analyze production orders for a given time range and assist in identifying golden and bad run, as mentioned in IEC 62264-3 [123]. Figure 5.8 presents an output of product analysis in the process visualization client, which displays planned cycle time, actual cycle time, and so forth. Likewise, product analysis can be complemented with the functionality to analyze the production schedules for a particular day, as depicted in Fig. 5.9. This will assist in identifying factors influencing the outcome of production schedules that result in a golden or bad run. For instance, identifying certain combinations of production orders that will lead to a golden run of a certain production order.

A report is dispatched via e-mail to the plant manager, plant supervisors and quality engineers every day at 05.00 a.m. The report contains different data analysis about the previous day that will be the basis for the daily discussion/meeting at 07.00 a.m. attended by the plant manager, plant supervisors and quality engineers. In addition, the team uses traceability functionality surrounding molten metal to perform root cause analysis to identify influencing factors that lead to good and bad performance. Additionally, the team exploits different data analysis functionalities to carry out root cause analysis. Overall, the outcome of the root cause analysis is used to initiate suitable process improvement programs.

```
select b.onlineTrackingItems('Legierung').data as legierung_fertigungsauftrag, c.onlineTrackingItems('Legierung').data as
legierung_giesscharge, a.trackingObjectKey as moldID, b.trackingObjectKey as orderID, c.trackingObjectKey as batchID from
PouredMold as a unidirectional, OrderWindow as b, MoltenMaterialBatchWindow as c where c.onlineTrackingItems('Legierung') !=
null and cast(a.onlineTrackingItems('Modellwechsel-ID').data, string) = b.trackingObjectKey and
cast(a.onlineTrackingItems('Gießcharge').data, string) = c.trackingObjectKey and cast(b.onlineTrackingItems('Legierung').data, string)
not like cast(c.onlineTrackingItems('Legierung').data, string) || '%' and a.onlineTrackingItems('Nicht gegossen') != null and
cast(a.onlineTrackingItems('Nicht gegossen').data, string) != 'True'
```

Zeitpunkt	Ereignisname	Ereigni...	Nachricht	Priorität
05.04.2013 01:20:20	Abguss ers...	Abguss...	Der Formkasten mit der ID '669136' wurde nicht nach 90 Minuten abgegossen.	5
05.04.2013 01:20:02	Falsche_Le...	Detekti...	Achtung! Formkasten wurde mit einer falschen Legierung (233 != 226) abgegossen. ...	2
05.04.2013 01:19:37	Abguss ers...	Abguss...	Der Formkasten mit der ID '669135' wurde nicht nach 90 Minuten abgegossen.	5
05.04.2013 01:19:37	Falsche_Le...	Detekti...	Achtung! Formkasten wurde mit einer falschen Legierung (233 != 226) abgegossen. ...	2
05.04.2013 01:19:00	Abguss ers...	Abguss...	Der Formkasten mit der ID '669134' wurde nicht nach 90 Minuten abgegossen.	5
05.04.2013 01:18:56	Falsche_Le...	Detekti...	Achtung! Formkasten wurde mit einer falschen Legierung (233 != 226) abgegossen. ...	2
05.04.2013 01:18:36	Falsche_Le...	Detekti...	Achtung! Formkasten wurde mit einer falschen Legierung (233 != 226) abgegossen. ...	2
05.04.2013 01:18:06	Falsche_Le...	Detekti...	Achtung! Formkasten wurde mit einer falschen Legierung (233 != 226) abgegossen. ...	2
05.04.2013 01:17:26	Falsche_Le...	Detekti...	Achtung! Formkasten wurde mit einer falschen Legierung (233 != 226) abgegossen. ...	2

Fig. 5.6 An example of EPL statement describing the situation of incorrect pouring of molten metal in comparison to the planned specification of molds and their production orders. In addition, suitable warning messages are also presented to process visualization clients as shown in the screenshot (in German)

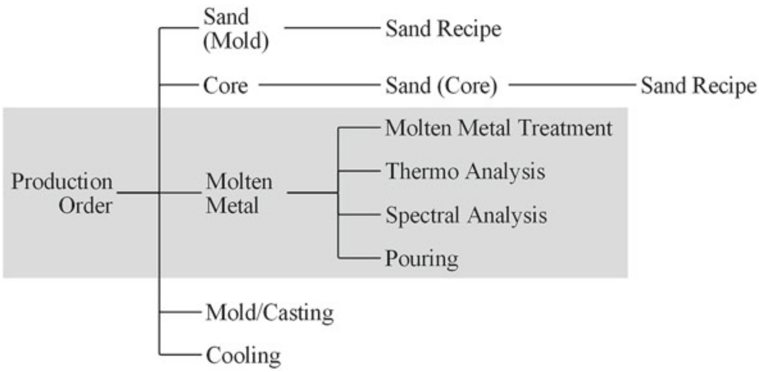

Fig. 5.7 Traceability navigation employed at Ohm & Häner. The shaded area is the most often used traceability navigation

5.3.4 Operational Metrics

The aforementioned data analysis should be strongly supported with operational metrics. The reference architecture introduced SQL based and CQL based methods to flexibly define and compute the operational metrics in real-time. In the implementation, the SQL based definitions of operational metrics have been used more frequently (see Fig. 5.10) in comparison to CQL based operational metric definitions. Nevertheless, the CQL based operational metrics definitions have been tested by defining suitable EPAs and processing mold tracking objects.

Additionally, time and quality analysis is performed, which leads to the computation of OEE, as shown in Fig. 5.11. As mentioned earlier, the molding machine is thought of as the master of the production line in the Drolshagen plant. In the case of time analysis, the cycle time to produce molds is classified into different time ranges. For instance, the molding machine cycle time is classified into 0–1, 1–2 and 2–5 min, which are considered as productive time. Likewise, cycle time greater than 5 min representing lunch break, blockage and so forth is considered as non-productive. These classifications of productive and non-productive time are necessary for deriving OEE. Similarly, the average cycle time and average planned cycle time is also presented. The quality analysis provides detailed information about molds produced, molds poured, and mold rejected, among others. Finally, the trend in OEE is also displayed in the process visualization client. Overall, the operational metrics present a real-time picture of the foundry.

The real-time operational metrics are made available to managers, supervisors, quality engineers and operators along the production line. Subsequently, suitable corrective actions can be initiated in a timely fashion. For instance, the operators on the molding machine have access to the operational metrics of the pouring line and vice versa. This can be used to minimize the blockage and starvation of the molding machine and the pouring line respectively by manually rescheduling the production orders.

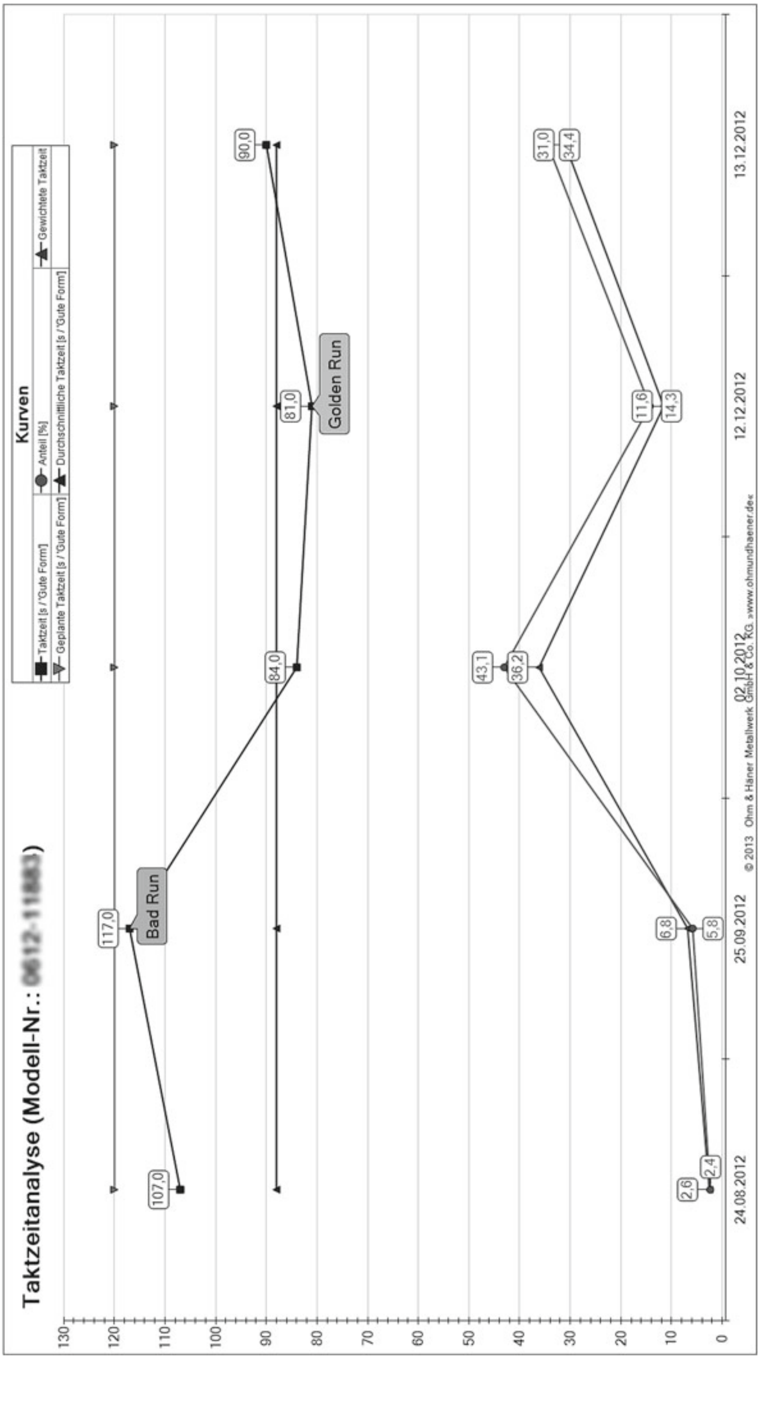

Fig. 5.8 Screenshot showing the output of product analysis functionality for a selected production order and time range in a process visualization client (in German)

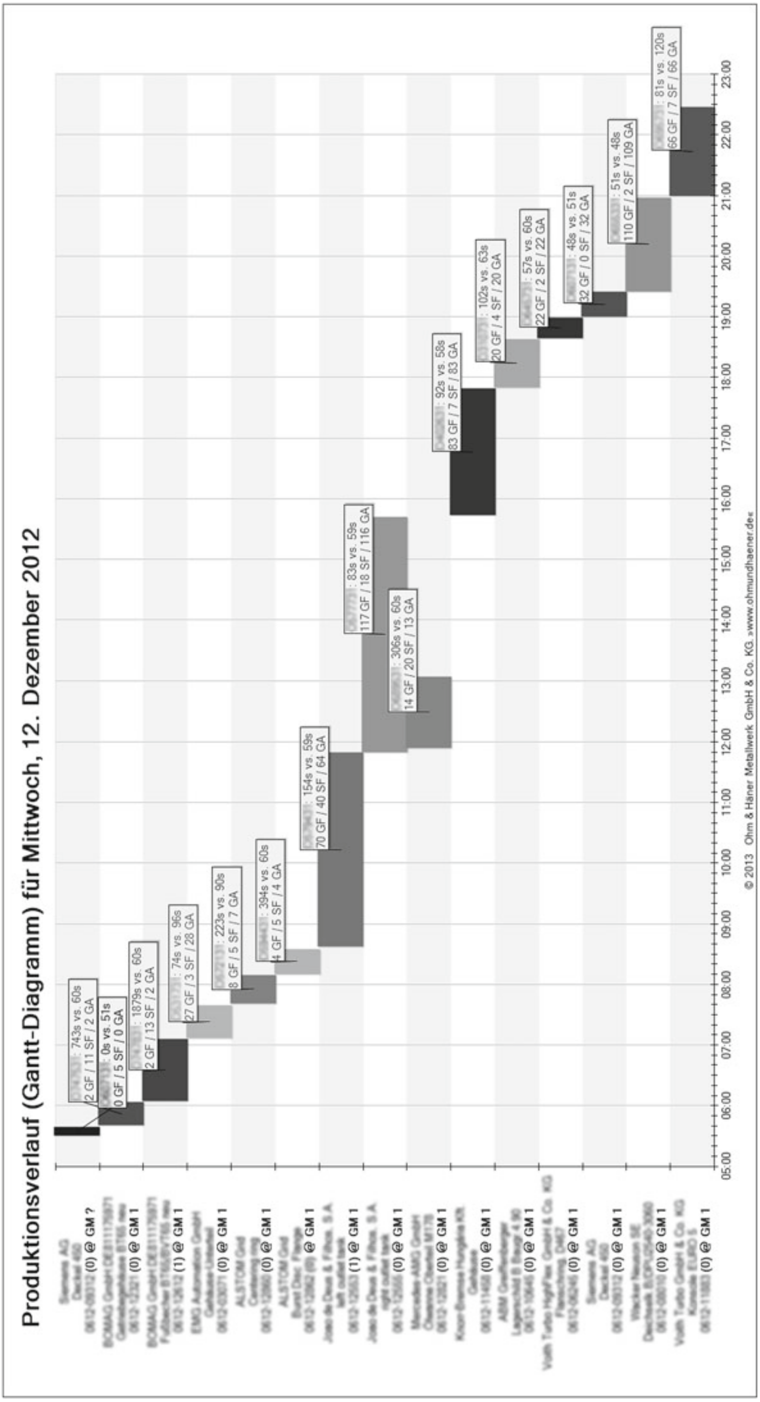

Fig. 5.9 Screenshot presenting the production schedule for a particular day in a process visualization client (in German)

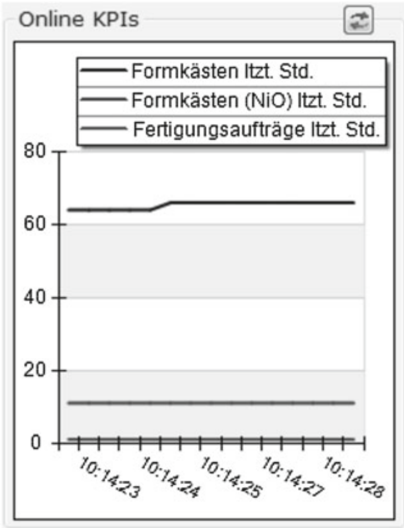

Fig. 5.10 Screenshot showing the output of operational metrics calculation in process visualization clients that are described using the SQL based definition of operational metrics (in German)

5.3.5 Financial Metrics

The previous implementation was carried out during a three-year bi-lateral project between Ohm & Häner and University of Siegen. In contrast, the research on financial metrics elaborated in Sect. 4.7 was carried out at University of Siegen, which was an extension of ideas and results of the bi-lateral project. Furthermore, a prototype was implemented to validate the elaborated concepts of financial metrics.

The prototype emphasis on quantification of financial metrics, especially manufacturing cost, cost leakage and cost inefficiency. These computed metrics can be presented to managers and concerned members in real-time for (manual) monitoring and control of manufacturing processes. These metrics can be processed in event processing component of the reference architecture to determine critical situations in real-time, which provides mechanism to realize speedy and early diagnostics functionalities.

The prototype has not been integrated into the previously implemented system at Drolshagen. Nevertheless, the financial metrics can be presented side-by-side with the operational metrics for offline analysis, which are helpful during root cause analysis. For instance, the product analysis reports shown in Fig. 5.8 can be enhanced by including the curves for manufacturing cost and cost leakage. Similarly, the OEE trend displayed in Fig. 5.11 can be made more meaningful by superimposing the cost inefficiency curve. The following paragraphs elaborate the prototype implementation.

The molding machine and its certain activities are considered, and suitably simulated to validate the concepts of financial metrics elaborated in Sect. 4.7. The molding machine is complex with two sub-automated machines that can be programmed to manufacture cope, and drag respectively. In addition, quality feedback about the cope

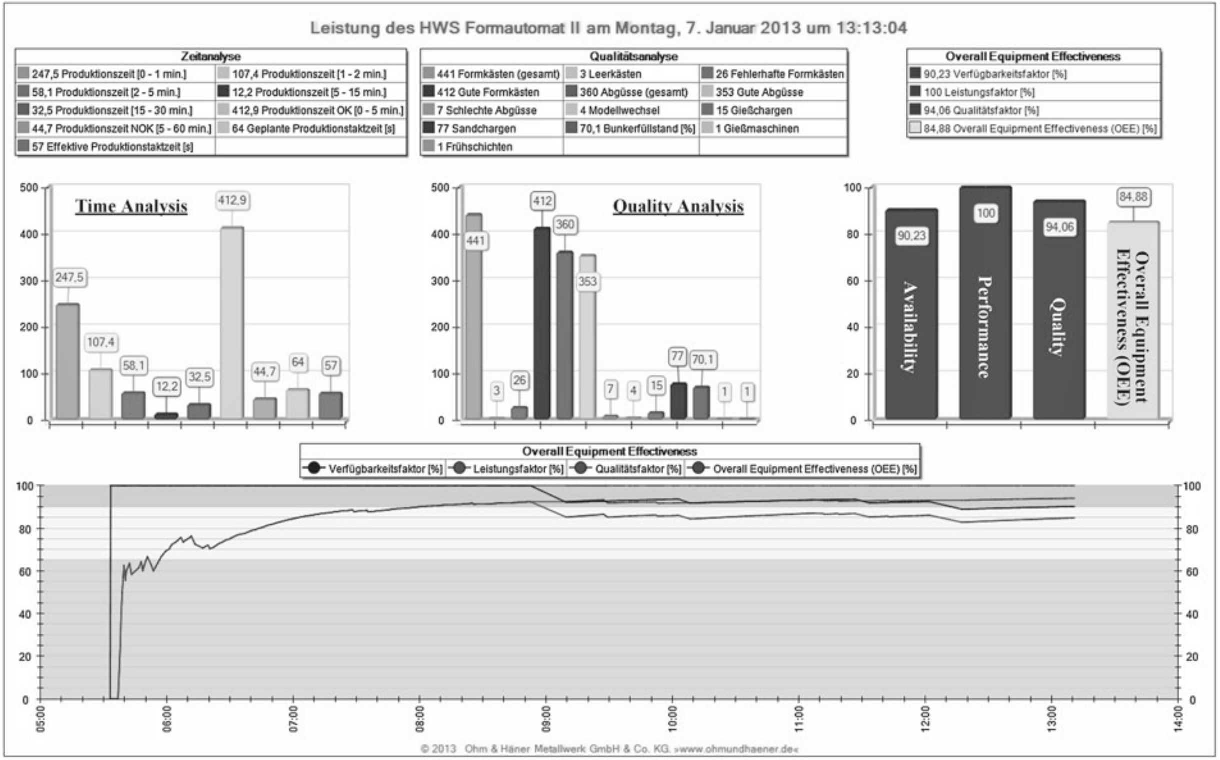

Fig. 5.11 Screenshot illustrating the time analysis, quality analysis, and OEE in a process visualization client. At the *bottom*, the *curves* indicate the evolution of OEE for the current day (in German)

and drag are provided before they are clamped. The previously mentioned scenario has been simulated, as illustrated in Fig. 5.12. Nevertheless, rejection of a cope will automatically lead to rejection of its corresponding drag, and vice versa. Additionally, the manufacturing of cope and drag requires numerous inputs—sand, energy, labor, and so forth. Nonetheless, only sand consumption with different types of sand (e.g., premium) is used to compute the costs.

Section 3.4.4.4 presented a few important accounting techniques. RCA technique is selected for the prototypical implementation in comparison to ABC for the following reasons: RCA overcomes the shortcomings of ABC (see [93]); RCA uses the logic of cost follows quantity, which is crucial for performance analysis (see [201]); and RCA splits the total cost into fixed and proportional costs, which are indispensable for determining cost leakage and cost inefficiency.

Figure 5.13 illustrates the computation of fixed and proportional costs for molding machine. The illustration is based on many assumptions and the values are fabricated, but in reality, these costs should be decided based on structured interviews with plant managers, accountants and other concerned members. Likewise, the costs are calculated for different types of sand, which are considered as secondary costs from the perspective of molding operation. These fabricated primary and secondary costs are stored in Microsoft® SQL Server® 2008 R2 database.

EPAs along with the underlying EPL statement are created. Furthermore, these EPAs are connected to create EPNs that will replicate the logic of different cost assignment preferences, especially cost tracing and cost assignment. Figure 5.14 illustrates an example of EPL statement that assigns different input costs to drag. EPNs and their underlying EPAs and EPL statements are loaded into the NEsper CEP engine. The mold tracking objects contain information about the consumption of raw materials and the causal relationship with the molding machine via the cycle time, as illustrated in Fig. 5.12. In addition, the production order tracking objects contain planned values and relativity to its concerned mold tracking objects.

The cycle time can be computed by considering the timestamps of the molding operation available in the mold tracking objects. However, the cycle time is considered as one of the input in the prototype. Subsequently, the mold tracking objects are processed to compute manufacturing costs in the NEsper CEP engine by employing the previously loaded EPNs and EPAs. Furthermore, the EPL statements access the fixed and proportional costs from the Microsoft® SQL Server® 2008 R2 database. Finally, the manufacturing costs are aggregated to the concerned production order defined by the production order tracking object, as illustrated in Fig. 5.15.

The mold tracking object also contains information about the quality feedback, which will be provided later along the production line due to the construction of the molding machine and production line. In the current case study, the quality of the mold, i.e., cope or drag, is assumed to have the required specifications. Thus, the manufacturing cost, initially, is computed and aggregated to the production order. Upon the receipt of quality feedback, if necessary, the manufacturing costs are reassigned to cost leakage. Furthermore, the cost leakage can be aggregated according to the production orders for creating suitable reports, as depicted in Fig. 5.15.

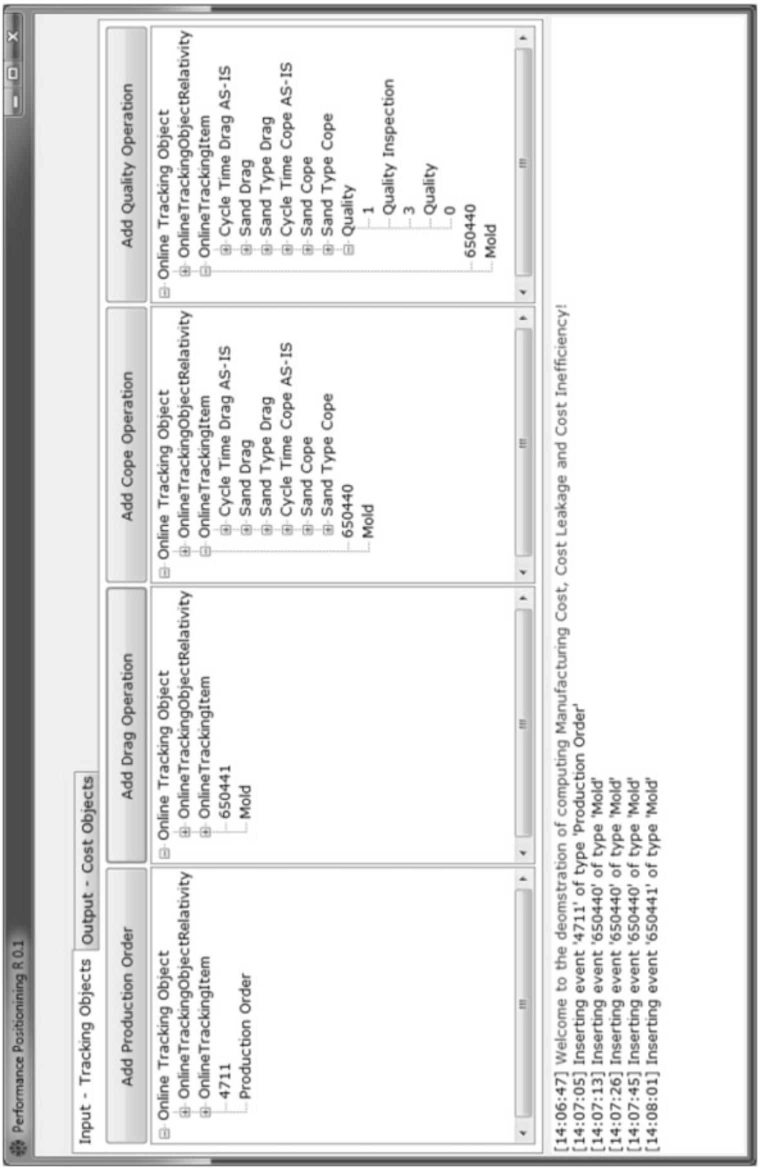

Fig. 5.12 Screenshot of the input interface in the prototype to compute manufacturing costs, cost leakage and cost inefficiency

Molding Machine	Resource Output: 8 Machine Hours		
Primary Expenses	Fixed (Eur)	Proportional (Eur)	Total (Eur)
Supervisor Salary	250.00	-	250.00
Labor	-	700.00	700.00
Depreciation	1500.00	-	1500.00
Energy	400.00	1400.00	1800.00
Secondary Expenses	Fixed (Eur)	Proportional (Eur)	Total (Eur)
Maintenance	130.00	300.00	430.00
Total	2280.00	2400.00	4680.00
Resource Output Unit Rate: Eur / Machine Hour	285.00	300.00	585.00

Fig. 5.13 Computation of fixed and proportional costs of molding machine by considering different inputs and expenses. Furthermore, the resource output is considered for only 8 h and the values are fabricated. In reality, the inputs, expenses, and resource output need to be arrived at by consulting the plant manager, accountants and other concerned members

```
INSERT INTO Price_Window_LowerBox(trackingObjectType, trackingObjectKey,
lowerBoxCost, quality) SELECT lowerBox.trackingObjectType,
lowerBox.trackingObjectKey,
Math.Round(PROPORTIONAL_COST*cast(lowerBox.onlineTrackingItems('Sand
Drag').data, double), 2), cast(onlineTrackingItems('Quality').data, int) from
OnlineTrackingObject(trackingObjectType='Mold' and onlineTrackingItems('Sand Type
Drag') is not null and onlineTrackingItems('Sand Drag') is not
null).std:unique(trackingObjectKey) as lowerBox, sql:SQLServer2008R2 ['select * from
performance_positioning'] as SANDCOST WHERE SANDCOST.ENTITY_NAME =
cast(lowerBox.onlineTrackingItems('Sand Type Drag').data, string)
```

Fig. 5.14 An example of an EPL statement depicting the assignment of different input costs to their corresponding lower mold or drag

Since a prototype has been developed considering only the molding machine, the cost leakage does not include rework costs. This is mainly for the following reasons. Firstly, the molds cannot be reworked and can be identified only as good or bad. Secondly, the castings are inspected during the trimming operation at the end of the production line, and are classified as good, bad, or rework. Furthermore, suitable flaw types are assigned to the castings, especially for bad and rework castings.

The current cycle time can be computed using two successive mold tracking objects or it can be part of the tracking object. In the prototype, the cycle time is part of the mold tracking object. Furthermore, the production order tracking objects contain the planned cycle time. Thus the extra cycle time taken to produce the mold can be considered as unproductive and used to calculate cost inefficiency. Subsequently, the EPL statements can access only the fixed cost to operate the molding machine as the remaining costs to manufacture the mold would have been already assigned to the production order or cost leakage. Similar to cost leakage, the cost inefficiency

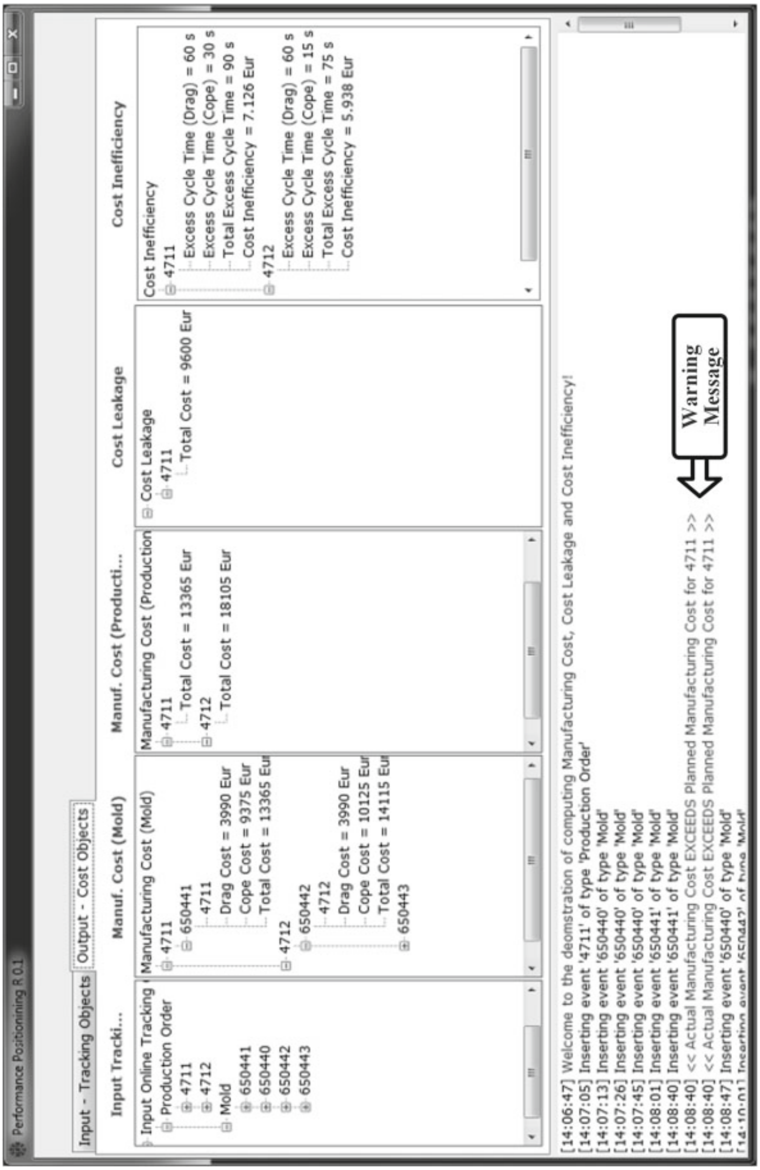

Fig. 5.15 Screenshot of the output interface in the prototype to compute manufacturing costs, cost leakage and cost inefficiency. In addition, messages are shown when a predefined situation has been detected that will assist in speedy and early diagnostics

```
select OKey, 'COST EXCEEDING LIMIT' from CEL_WarningWindow JOIN
OnlineTrackingObject( trackingObjectType='Order').std:unique(trackingObjectKey)
as limitTable WHERE CEL_WarningWindow.OKey=limitTable.trackingObjectKey
and  CEL_WarningWindow.result >
cast(limitTable.onlineTrackingItems('Sollkosten').data, double)
```

Fig. 5.16 An EPL statement to identify if the actual manufacturing cost of a production order has exceeded its planned manufacturing cost

can be categorized according to the production orders to create suitable reports for performance analysis and decision making, as depicted in Fig. 5.15.

The previously mentioned computed costs can be aggregated to compute higher financial metrics, and can also be stored in the process database for offline analysis. For instance, the product analysis reports can be made more revealing by including curves for manufacturing cost and cost leakage. Similarly, the OEE trend can be made more expressive by superimposing the cost inefficiency curve. Additionally, the computed costs can provide feedback to the upstream processes (e.g., sales and design) that can used to enhance the process execution in future.

Apart from the offline analysis, the computed costs and the financial metrics can be used for real-time monitoring and control of manufacturing processes, i.e., provide mechanisms to realize speedy and early diagnostic functionalities. This is especially required if the manufacturing enterprise supporting JIT or kanban management concepts, and the products have to be delivered to its customers on a regular basis. The manufacturing performance, traditionally, would be communicated to ERP System, which would then compute the manufacturing and other related costs. These costs would be communicated to the plant managers and others based on enterprise reporting cycle. Based on these costs, process improvement programs might be initiated. However, these costs are delivered late and substantial changes would have happened on the shop floor that would contradict with the current manufacturing situations.

The aforementioned situations can be avoided if the computed costs can be utilized to detect predefined situations as they happen by employing event processing. This will lead to analyzing the situation and implementing corrective actions within a reasonable amount of time. For instance, the production order can encompass planned manufacturing cost (see Fig. 5.12). A situation can be defined that will identify if the actual manufacturing cost has exceeded the planned manufacturing cost by employing an EPA and its underlying EPL statement, as illustrated in Fig. 5.16. The EPA can be loaded into the NEsper CEP engine, and analyze the actual manufacturing cost of production orders as an when it gets updated against the planned manufacturing cost. If the situation is detected, suitable warning message can be displayed, as shown in Fig. 5.15. Additionally, e-mails and SMS can be sent to concerned enterprise members, i.e., plant manager and supervisors. Overall, different situations can be defined considering manufacturing cost, cost leakage and cost inefficiency.

The prototype validates the concept of financial metrics, especially the computation of manufacturing cost, cost leakage and cost inefficiency, elaborated in Sect. 4.7. Additionally, the prototype demonstrates the identification of predefined situations that will assist in speedy and early diagnostic that are crucial for real-time monitoring and control of manufacturing processes. However, the prototype does not demonstrate the integration with the operational metrics and various data analysis functionalities of the implemented system in Drolshagen.

5.3.6 Performance Positioning

The performance positioning chart requires both operational and financial metrics. However, the operational metrics have been computed using the actual shop floor data, and have been extensively employed in the Drolshagen plant. In contrast, the financial metrics, especially cost leakage and cost inefficiency, have been computed using fabricated values, with the aim to demonstrate that the previously elaborated concepts can be put into practice. Hence, it is not possible to create the performance position chart.

5.4 Evaluation

The aforementioned implementation, excluding financial metrics and performance positioning, has been evaluated against measurable and non-measurable criteria. The measurable evaluation criteria in a manufacturing enterprise are related to cycle time, setup time, planning time, and so forth [159]. Likewise, transparency, flexibility, and adaptability, among others are a few of the non-measurable evaluation criteria. Nevertheless, it is difficult to evaluate the previously elaborated implementation.

The Drolshagen plant was commissioned in October 2008 with a single shift. The second shift was introduced in February 2011. Similarly, the implementation of the reference architecture started in September 2009 and was completed in March 2012. The analysis was considered for March 2011 and January 2012, where the manufacturing was carried out in two shifts. Hence, the collected process data was analyzed from the perspective of cycle time and throughput, which are considered as measurable evaluation criteria. It was observed that the average cycle time was reduced by 17.6 % in January 2012 in comparison to March 2011. In addition, the throughput increased by 17.1 % and the corresponding production time reduced by 3.3 %. The collected process data was incomplete to support setup time, planning time, and so forth as measurable evaluation criteria.

Likewise, the implemented architecture was evaluated for non-measurable evaluation criteria, especially transparency. The traceability functionality along with the visualization of real-time process data, historical process data and numerous reports renders a comprehensive view of the Drolshagen plant. This view can be accessed by plant manager, plant supervisors, quality engineers and operators with some restriction based on employee roles and designation. Thus, transparency of manufacturing processes is enhanced.

The aforementioned improvements are not only due to the implementation of the reference architecture; rather they are to numerous other reasons, such as enhancement in processes employed after analysis of historical process data. Overall, the implemented reference architecture supports different steps of the Plan-Do-Check-Act (PDCA) cycle. PDCA cycle or Shewhart cycle or Deming wheel is an important management tool to perform root cause analysis and to initiate process improvement programs [78]. Likewise, the implemented reference architecture assists different management strategies and tools especially lean production, like Total Quality Management (TQM), and Define-Measure-Analyze-Improve-Control (DMAIC) of Six Sigma (6σ).

The evaluation has been exclusively performed for the implementation carried out at Drolshagen, i.e., the evaluation does not cover the financial metrics. The evaluation of financial metrics can be carried out when the financial metrics component has been implemented and integrated with the operational metrics in Drolshagen.

5.5 Summary

Ohm & Häner Metallwerk GmbH & Co. KG is an aluminum foundry operating in Germany. Ohm & Häner commissioned an aluminum foundry in Drolshagen in October 2008 and has a sand casting production line supported with state-of-the-art automated machines. The Drolshagen plant employs 22 employees per shift and has capacity to handle 10,000 tons of molten metal per year. Furthermore, the production line is flexible enough to handle different lot sizes—one piece, medium series and large series.

The reference architecture encompassing different components has been implemented and evaluated in the aforementioned Drolshagen plant. In addition, process analysis and modeling have been carried out to assist the implementation of the architecture. The implementation is being extensively used by the plant manager, plant supervisors, quality engineers and operators to carryout monitoring and control of manufacturing processes.

Finally, the reference architecture has been evaluated against measurable and non-measurable evaluation criteria. For instance, the cycle time has been reduced considerably. Likewise, the transparency has increased mainly because of the comprehensive view of the shop floor. Nonetheless, these improvements have resulted from combination of factors, (e.g., real-time monitoring and control of manufacturing processes, data analysis to determine anomalies in the processes) and subsequently, will help to initiate process improvement programs.

Chapter 6
Conclusions and Future Work

Manufacturing enterprises are facing increasing pressure from the internal and external environments to realize and sustain their competitive advantage. Subsequently, monitoring and control of manufacturing processes is crucial. In this regard, performance measurement within and across different enterprise levels is indispensable. Thus, operational metrics are critical for the employees on the shop floor where as the financial metrics are indispensable for top management.

PMS stresses the importance of the previously mentioned metrics being aligned and balanced, among others. Nevertheless, enormous amounts of research have been carried out related to these metrics, but in isolation. The operational metrics are computed in real-time whereas the financial metrics are computed according to enterprise's financial reporting cycles, i.e., offline. Furthermore, these metrics are not linked in real-time, which hampers monitoring and control of manufacturing processes. The horizontal integration of different resources on the shop floor and temporal/semantic vertical integration of different applications across different enterprise levels can be considered as a building block to partially overcome the aforementioned issues.

In the presented research, a reference architecture based on MES concepts encompassing different components has been envisaged to realize these integrations and additionally support numerous functionalities to realize monitoring and control of manufacturing processes. This architecture relies extensively on analysis and modeling of manufacturing processes, which need to be performed from time to time to keep the physical processes and previously modelled processes, if any, in synchronization.

The resources on the shop floor implement numerous standard and proprietary communication protocols. The data collection component contains these protocols in a modular technique that enables communication and collect process data in real-time. The real-time process data is forwarded to the data aggregation component, which facilitates the realization of the horizontal integration of resources from the perspective of products and production orders. In addition, vertical integration of data across different enterprise levels is also realized by integrating the real-time process

S. Karadgi, *A Reference Architecture for Real-Time Performance Measurement*, Progress in IS, DOI: 10.1007/978-3-319-07007-0_6,

data on the fly with the corresponding transactional data from the ERP System. The integrated data provides complete context information to carryout different tasks that support the realization of real-time monitoring and control of manufacturing processes.

The integrated process data is stored in the process database that can be employed for realizing forward and backward traceability, and data analysis. In contrast, the integrated process data is also employed to create tracking objects in real-time. The tracking objects represent enterprise entities that can be actually monitored and controlled. Furthermore, the tracking objects incorporate only a subset of integrated process data that are critical for monitoring and control. The tracking objects are treated as events and processed in the CEP engine to detect predetermined situations. These situations are modeled as EPAs with underlying EPL statements and loaded into the CEP engine.

The stored process data can be employed to compute operational metrics using an SQL based definition of operational metrics. In this case, the defined metrics can be complex and the computation might be time consuming as multiple database queries might be required. In contrast, the CQL based definition of operational metrics provides a mechanism to compute the operational metrics in real-time by processing the tracking objects in the CEP engine. However, the metrics defined should be simple and straightforward. Likewise, the tracking objects can be processed in the CEP engine to compute the manufacturing cost of products and production orders, cost leakage and cost inefficiency. The EPL statements employed should reflect the logic of cost tracing and cost assignment. The previously mentioned costs can be basis for computing different financial metrics.

The aforementioned operational and financial metrics can be linked and visualized using a performance positioning chart. The chart considers throughput and cost inefficiency, and quality and cost leakage. Furthermore, the values can be classified into low, medium and high, which can be performed by comparing the computed values with the planned values made available with the production order by the ERP System.

The reference architecture has been implemented in an aluminum foundry as part of three-year bi-lateral project between Ohm & Häner and University of Siegen. The foundry employs automated machines along the production line, uses ERP System and adheres to low volume and high mix production schedules. The architecture has been used by the employees to monitor and control the casting processes, and to suitably initiate changes in the processes. The cycle time has reduced by 17.6 % and throughput has increased by 17.1 %. Likewise, the transparency of manufacturing has increased tremendously; this cannot be measured. These improvements are partially due to the availability of operational metrics in real-time and increased transparency. The computation of financial metrics was (prototypically) demonstrated using fabricated values as it was not envisioned during the 3-year project. Subsequently, the creation of a performance positioning chart is also hindered.

Performance positioning provides a concept to link and visualize the financial and operational metrics in real-time. Furthermore, performance positioning is introduced briefly. Research has to be further carried out to enhance the description, creation, and interpretation of performance positioning so that can be adapted by manufacturing enterprises. IEC 62264 lays down the guidelines for MES in discrete industry. Likewise, multi-part IEC 61512 standard defines procedures for MES in batch processing industry [185]. This is also highlighted by discrete and process tracks in MES Conference held along the sideline of Hannover Trade Fair [120]. The previously described concept and computation of operational and financial metrics and creation of performance positioning chart can be extended to batch processing industry.

Tracking objects contain control related information about numerous enterprise entities, which are stored in the main memory of a computer. Furthermore, the concept of tracking objects is partly based on the concepts of agents and holons of MAS and HMS respectively. Subsequently, the concept of tracking objects can be exploited to realize real-time scheduling or dynamic scheduling. The scheduling can involve a combination of a mathematical model and heuristic algorithms, and exploit past/historical schedules to determine new schedules.

The computation of a carbon footprint has gained considerable importance to determine the Greenhouse Gas (GHG) emissions produced by an activity, especially across the product's lifecycle [215]. Manufacturing enterprises can initiate suitable corrective measures to reduce GHG emissions, which can also be part of the CSR. The tracking objects can be used to determine the carbon footprint in real-time, especially from the perspective of manufacturing. Furthermore, attempts can be made to link the carbon footprint with the performance positioning.

References

[1] Abraham, A.: Rule-based expert systems. In: Sydenham, P.H., Thorn, R. (eds.) Handbook of Measuring System Design, pp. 909–919. Wiley, Chichester (2005)

[2] Aguilar-Savén, R.S.: Business process modelling: review and framework. Int. J. Prod. Econ. **90**(2), 129–149 (2004)

[3] Allen, J.F.: Towards a general theory of action and time. Artif. intell. **23**(2), 123–154 (1984)

[4] Antonaras, A., Memtsa, C., Iacovidou, M.: The challenge of measuring the cost of quality (2010)

[5] Arasu, A., Babu, S., Widom, J.: The cql continuous query language: semantic foundations and query execution. http://ilpubs.stanford.edu:8090/758/ (2003)

[6] AutomationWorld: Historians bring relief to data explosion. http://www.automationworld.com/ (2007)

[7] BDGuss: BDG bundesverband der deutschen gießerei-industrie. http://www.bdguss.de/ (n.d.)

[8] Bititci, U.S., Mendibil, K., Martinez, V., Albores, P.: Measuring and managing performance in extended enterprises. Int. J. Oper. Prod. Manag. **25**(4), 333–353 (2005)

[9] Bocij, P., Chaffey, D., Hickie, S., Greasley, A.: Business Information Systems: Technology, Development and Management for the e-Business, 3rd edn. Financial Times/Prentice Hall, New York (2005)

[10] Bollinger, J.G., Duffie, N.A.: Computer Control of Machines and Processes. Addison-Wesley, Reading (1988)

[11] Bose, R.: Understanding management data systems for enterprise performance management. Ind. Manag. Data Syst. **106**(1), 43–59 (2006)

[12] Bourne, M.: Handbook of Performance Measurement, 3rd edn. Sweet and Maxwell Ltd, London (2004)

[13] Bourne, M., Bourne, P.: Handbook of Corporate Performance Management. Wiley, Chichester (2011)

[14] Bourne, M., Neely, A., Mills, J., Platts, K.: Implementing performance measurement systems: a literature review. Int. J. Bus. Perform. Manag. **5**(1), 1–24 (2003)

[15] Braglia, M., Frosolini, M., Zammori, F.: Overall equipment effectiveness of a manufacturing line (oeeml): an integrated approach to assess systems performance. J. Manufact. Technol. Manag. **20**(1), 8–29 (2009)

[16] Busi, M., Bititci, U.S.: Collaborative performance management: present gaps and future research. Int. J. Prod. Perform. Manag. **55**(1), 7–25 (2006)

[17] Caplice, C., Sheffi, Y.: A review and evaluation of logistics performance measurement systems. Int. J. Logist. Manag. **6**(1), 61–74 (1995)

S. Karadgi, *A Reference Architecture for Real-Time Performance Measurement*, Progress in IS, DOI: 10.1007/978-3-319-07007-0,

[18] Castillo, E., Gutiérrez, J.M., Hadi, A.S.: Expert Systems and Probabilistic Network Models. Springer, New York (1997)

[19] Chaffey, D., Wood, S.: Business Information Management: Improving Performance Using Information Systems. Prentice Hall/Financial Times, Harlow (2005)

[20] Chakravarthy, S., Jiang, Q.: Stream Data Processing: A Quality of Service Perspective: Modeling, Scheduling, Load Shedding, and Complex Event Processing. Springer, Boston (2009)

[21] Chandy, K.M., Schulte, W.R.: Event Processing: Designing IT Systems for Agile Companies. McGraw Hill, New York (2010)

[22] Chen, D., Vernadat, F.: Standards on enterprise integration and engineering—state of the art. Int. J. Comput. Integr. Manuf. **17**(3), 235–253 (2004)

[23] Chryssolouris, G., Mavrikios, D., Papakostas, N., Mourtzis, D., Michalos, G., Georgoulias, K.: Digital manufacturing: history, perspectives, and outlook. Proc. Inst. Mech. Eng. Part B J. Eng. Manuf. **223**(5), 451–462 (2009)

[24] Cocca, P., Alberti, M.: A framework to assess performance measurement systems in SMEs. Int. J. Prod. Perform. Manag. **59**(2), 186–200 (2010)

[25] Cokins, G.: Activity-Based Cost Management: An Executive's Guide. Wiley, New York (2001)

[26] Cokins, G., White, L., van der Merwe, A.: A conceptual framework for managerial costing. http://www.altavia.com/publications.php (2011)

[27] ControlGlobal.com: Peter Martin whacks 'em between the eyes. http://www.controlglobal.com/articles/2007/212.html (2007)

[28] Crandall, R.E., Julien, O.: Measuring the cost of quality. Indus. Manag. Data Syst. (2010)

[29] Curtis, G., Cobham, D.P.: Business Information Systems: Analysis, Design, and Practice, 5th edn. Financial Times Prentice Hall, Harlow (2005)

[30] CustomPartNet: Sand casting. http://www.custompartnet.com/wu/SandCasting (n.d.)

[31] Dahlgaard, J.J., Kristensen, K., Kanji, G.K.: Quality costs and total quality management. Total Qual. Manag. **3**(3), 211–222 (1992)

[32] Dahlgaard-Park, S.M.: Reviewing the european excellence model from a management control view. TQM J. **20**(2), 98–119 (2008)

[33] Dal, B., Tugwell, P., Greatbanks, R.: Overall equipment effectiveness as a measure of operational improvement—a practical analysis. Int. J. Oper. Prod. Manag. **20**(12), 1488–1502 (2000)

[34] Davenport, T.H., Short, J.E.: The new industrial engineering: Information technology and business process redesign. Sloan Manag. Rev. **31**(4), 11–27 (1990)

[35] Dierks, P.A., Cokins, G.: The CAM-I glossary of activity-based management: version 3.0. J. Cost Manag. **15**(1), (2001)

[36] Dodhiawala, R., Sridharan, N.S., Raulefs, P., Pickering, C.: Real-time ai systems: A definition and an architecture. Proc. Int. Jt. Conf. Artif. Intell. **16**, 256–261 (1989)

[37] Doerman, S.M., Caldwell, R.K.: Lean techniques: Improving process efficiency. In: Juran J.M., Feo J.A.d. (eds.) Juran's Quality Handbook, pp. 327–354. McGraw Hill, New York (2010)

[38] van Dorp, C.A.: Reference-data modelling for tracking and tracing. Wageningen (2004)

[39] Draheim, D.: Business Process Technology: A Unified View on Business Processes, Workflows and Enterprise Applications, Online-Ausg, edn. Springer, Berlin (2010)

[40] EFQM: EFQM excellence model. http://www.efqm.org/

[41] ElMaraghy, H.A.: Flexible and reconfigurable manufacturing systems paradigms. Int. J. Flex. Manuf. Syst. **17**(4), 261–276 (2005)

[42] ElMaraghy, H.A.: Reconfigurable process plans for reconfigurable manufacturing. In: Proceedings of the 3rd International Conference on Digital Enterprise Technology (2006)

[43] ElMaraghy, H.A.: Changing and evolving products and systems—models and enablers. In: ElMaraghy, H.A. (ed.) Changeable and Reconfigurable Manufacturing Systems, pp. 25–45. Springer, London (2009)

[44] EsperTech: EsperTech: Event stream intelligence. http://www.espertech.com/ (2012)

[45] Etzion, O., Niblett, P.: Event processing in action. Manning, Greenwich and 74 w. long (2011)
[46] FASAB: Statement of Federal Financial Accounting Standards 4: Managerial Cost Accounting Standards and Concepts: Fasab Handbook, Version 11 (06/12). http://www.fasab.gov/resources/managerial-cost-accounting-resources/ (2012)
[47] Ferstl, O.K., Sinz, E.J.: Grundlagen der Wirtschaftsinformatik, 7th edn. R, München, Oldenbourg (2013)
[48] Fowler, J.W.: Grand challenges in modeling and simulation of complex manufacturing systems. SIMULATION **80**(9), 469–476 (2004)
[49] Garengo, P., Biazzo, S., Bititci, U.S.: Performance measurement systems in SMEs: a review for a research agenda. Int. J. Manag. Rev. **7**(1), 25–47 (2005)
[50] Gartner: Manufacturing 2.0: A fresh approach to integrating manufacturing operations with DDVN. http://www.gartner.com/ (2010)
[51] Giachetti, R.E.: A framework to review the information integration of the enterprise. Int. J. Prod. Res. **42**(6), 1147–1166 (2004)
[52] Giakatis, G., Enkawa, T., Washitani, K.: Hidden quality costs and the distinction between quality cost and quality loss. Total Qual. Manag. **12**(2), 179–190 (2001)
[53] Goepp, V., Kiefer, F., Avila, O.: Information system design and integrated enterprise modelling through a key-problem framework. Comput. Ind. **59**(7), 660–671 (2008)
[54] Gomes, C.F., Yasin, M.M., Lisboa, J.V.: Performance measurement practices in manufacturing firms revisited. Int. J. Oper. Prod. Manag. **31**(1), 5–30 (2011)
[55] Grant, R.M.: Contemporary Strategy Analysis: Text and Cases Edition, 7th edn. Wiley, Chichester (2010)
[56] Grauer, M.: Information technology. In: Warner, M. (ed.) Concise International Encyclopedia of Business and Management, pp. 296–305. International Thomson Business Press, London and Boston (1997)
[57] Grauer, M., Karadgi, S., Metz, D.: Enhancement of transparency and adaptability by online tracking of enterprise processes. In: Wirtschaftinformatik Proceedings, pp. 282–291 (2011)
[58] Grauer, M., Karadgi, S., Metz, D., Schäfer, M.: Real-time enterprise—schnelles handeln für produzierende unternehmen. Wirtschaftsinformatik Manag. **5**, 40–45 (2010)
[59] Grauer, M., Karadgi, S., Müller, U., Metz, D., Schäfer, W.: Proactive control of manufacturing processes using historical data. In: Setchi, R., Jordanov, I., Howlett, R., Jain, L. (eds.) Knowledge-Based and Intelligent Information and Engineering Systems. Lecture Notes in Computer Science, vol. 6277, pp. 399–408. Springer, Berlin (2010)
[60] Grauer, M., Metz, D., Karadgi, S.S., Schäfer, W., Reichwald, J.W.: Towards an it-framework for digital enterprise integration. In: Kacprzyk, J., Huang, G.Q., Mak, K.L., Maropoulos, P.G. (eds.) Advances in Intelligent and Soft Computing, pp. 1467–1482. Springer, Berlin (2010)
[61] Grauer, M., Seeger, B., Metz, D., Karadgi, S., Schneider, M.: About adopting event processing in manufacturing. In: Hutchison, D., Kanade, T., Kittler, J., Kleinberg, J.M., Mattern, F., Mitchell, J.C., Naor, M., Nierstrasz, O., Pandu Rangan, C., Steffen, B., Sudan, M., Terzopoulos, D., Tygar, D., Vardi, M.Y., Weikum, G., Cezon, M., Wolfsthal, Y. (eds.) Lecture Notes in Computer Science, pp. 180–187. Springer, Berlin (2011)
[62] Groover, M.P.: Automation, Production Systems and Computer-Integrated Manufacturing, 2nd edn. Prentice Hall, Upper Saddle River (2001)
[63] Groover, M.P.: Fundamentals of Modern Manufacturing, 3rd edn. Wiley, Hoboken (2007)
[64] Habermann, M., Weiss, T.: STEP®7—Crash Course, Extended edn. VDE Verlag GmbH, Berlin (2009)
[65] Halevi, G., Weill, R.: Principles of Process Planning: A Logical Approach, 1st edn. Chapman and Hall, London and and New York (1995)
[66] Harrington, H.J.: Cost of poor quality. Int. J. Strateg. Cost Manag. **2**(1), 17–27 (1999)
[67] Harvey, F., Kuhn, W., Pundt, H., Bishr, Y., Riedemann, C.: Semantic interoperability: a central issue for sharing geographic information. Ann. Reg. Sci. **33**(2), 213–232 (1999)

[68] Ho, L.T., Lin, G.C.I.: Critical success factor framework for the implementation of integrated-enterprise systems in the manufacturing environment. Int. J. Prod. Res. **42**(17), 3731–3742 (2004)

[69] Horngren, C.T., Datar, S.M., Foster, G., Rajan, M.V., Ittner, C.: Cost Accounting: A Managerial Emphasis, 13th edn. Pearson/Prentice Hall, Upper Saddle River (2009)

[70] Huang, S.H., Dismukes, J.P., Shi, J., Su, Q., Razzak, M.A., Bodhale, R., Robinson, D.E.: Manufacturing productivity improvement using effectiveness metrics and simulation analysis. Int. J. Prod. Res. **41**(3), 513–527 (2003)

[71] Hudson, M., Smart, A., Bourne, M.: Theory and practice in SME performance measurement systems. Int. J. Oper. Prod. Manag. **21**(8), 1096–1115 (2001)

[72] Hurbean, L.: The business of process integration. SSRN Elect. J. (2007)

[73] IFAC: Environmental Management Accounting: International Guidance Document. International Federation of Accountants, New York (2005)

[74] IFAC: Evaluating and Improving Costing in Organizations. International Federation of Accountants, New York (2009)

[75] IFAC: Evaluating the Costing Journey: A Costing Levels Continuum Maturity Model. International Federation of Accountants, New York (2009)

[76] Jammes, F., Smit, H.: Service-oriented architectures for devices—the SIRENA view. In: Schoop, R. (ed.) 3rd IEEE International Conference on Industrial Informatics, pp. 140–147 (2005)

[77] Juran, J.M.: Attaining superior results through quality. In: Juran J.M., Feo, J.A.D. (eds.) Juran's Quality Handbook, pp. 3–39. McGraw Hill, New York (2010)

[78] Juran, J.M.: Quality control: assuring repeatable and compliant processes. In: Juran J.M., Feo, J.A.D. (eds.) Juran's Quality Handbook, pp. 195–226. McGraw Hill, New York (2010)

[79] Juran, J.M.: The universal methods to manage quality. In: Juran J.M., Feo, J.A.D. (eds.) Juran's Quality Handbook, pp. 69–81. McGraw Hill, New York (2010)

[80] Juran, J.M., Feo, J.A.D. (eds.): Juran's Quality Handbook: The Complete Guide to Performance Excellence, 6th edn. McGraw Hill, New York (2010)

[81] Juran, J.M., Feo, J.A.D.: Quality improvement: Creating breakthroughs in performance. In: Juran J.M., Feo, J.A.D. (eds.) Juran's Quality Handbook, pp. 137–194. McGraw Hill, New York (2010)

[82] Kaplan, R.S., Anderson, S.R.: Time-driven activity-based costing. Harvard Bus. Rev. (2004)

[83] Kaplan, R.S., Anderson, S.R.: Time-Driven Activity-Based Costing: A Simpler and More Powerful Path to Higher Profits, [repr.] edn. Harvard Business School Press, Boston (2009)

[84] Kaplan, R.S., Cooper, R.: Cost and Effect: Using Integrated Cost Systems to Drive Profitability and Performance. Harvard Business School Press, Boston (1998)

[85] Kaplan, R.S., Norton, D.P.: The balanced scorecard—measures that drive performance. Harvard Bus. Rev. **70**(1), 71–79 (1992)

[86] Karadgi, S., Metz, D., Grauer, M.: Enhancing monitoring of enterprise processes by integrated online performance measurement. In: Proceedings of 21st International Conference on Production Research (ICPR 21) (2011)

[87] Karadgi, S., Metz, D., Grauer, M.: Real-time managerial accounting: A tool to monitor and control a manufacturing enterprise. In: Wang K., Strandhagen, J.O. Tu, D. (eds.) Proceedings of International Workshop of Advanced Manufacturing and Automation (IWAMA 2012), pp. 327–334 (2012)

[88] Karadgi, S., Metz, D., Grauer, M.: Towards real-time computation of cost of poor quality for discrete manufacturing processes. In: Proceeding of the 5th International Conference on Changeable, Agile, Reconfigurable and Virtual Production (CARV 2013) (2013)

[89] Karadgi, S., Metz, D., Grauer, M., Schafer, W.: An event driven software framework for enabling enterprise integration and control of enterprise processes. In: 10th International Conference on Intelligent Systems Design and Applications (ISDA) 2010, pp. 24–30 (2010)

[90] Kärkkäinen, M., Ala-Risku, T., Främling, K.: Efficient tracking for short-term multi-company networks. Int. J. Phys. Distrib. Logist. Manag. **34**(7), 545–564 (2004)

[91] Kemény, Z., Ilie-Zudor, E., Szathmári, M., Monostori, L.: TraSer: An open-source solution platform for cross-company transparency in tracking and tracing. In: Chung, M.J., Misra, P. (eds.) Proceedings of the 17th IFAC World Congress 2008, pp. 4493–4498. Elsevier (2008)

[92] Kendall, K.E., Kendall, J.E.: Syst. Anal. Des., 6th edn. Pearson/Prentice Hall, Upper Saddle River (2005)

[93] Keys, D.E., van der Merwe, A.: The case for RCA: excess and idle capacity. J. Cost Manag. **15**(4), 21–32 (2001)

[94] Keys, D.E., van der Merwe, A.: Gaining effective organizational control with RCA. Strateg. Finance 41–47 (2002)

[95] Khabbazi, M., Ismail, M.Y., Ismail, N., Mousavi, S., Mirsanei, H.: Lot-base traceability requirements and functionality evaluation for small- to medium-sized enterprises. Int. J. Prod. Res. **49**(3), 731–746 (2011)

[96] Khabbazi, M., Ismail, M.Y., Mousavi, S.: Modeling of traceability information system for material flow control data. Aust. J. Basic Appl. Sci. **4**(2), 208–216 (2010)

[97] Kjaer, A.P.: The integration of business and production processes. IEEE Control Syst. Mag. **23**(6), 50–58 (2003)

[98] Kletti, J.: Manufacturing Execution Systems—MES. Springer, Berlin (2007)

[99] Kopetz, H.: Real-Time Systems Series. Springer, Boston (2011)

[100] Kosanke, K., Vernadat, F.: Cimosa and geram: standardization in enterprise engineering. In: Morel, G., Vernadat, F. (eds.) Information Control in Manufacturing 1998, pp. 383–393. Published for the International Federation of Automatic Control by Pergamon, New York (1999)

[101] Kosanke, K., Vernadat, F., Zelm, M.: Cimosa: enterprise engineering and integration. Comput. Ind. **40**(2–3), 83–97 (1999)

[102] Laitinen, E.: A dynamic performance measurement system: evidence from small finnish technology companies. Scand. J. Manag. **18**(1), 65–99 (2002)

[103] Laudon, K.C., Laudon, J.P.: Essentials of Business Information Systems, 7th edn. Pearson Prentice Hall, Upper Saddle River (2007)

[104] Leitão, P.: Agent-based distributed manufacturing control: a state-of-the-art survey. Eng. Appl. Artif. Intell. **22**(7), 979–991 (2009)

[105] Levina, O., Stantchev, V.: Realizing event-driven SOA. In: 2009 Fourth International Conference on Internet and Web Applications and Services, pp. 37–42. IEEE (2009)

[106] Luckham, D.C.: The Power of Events: An Introduction to Complex Event Processing in Distributed Enterprise Systems, 5th edn. Addison-Wesley, Boston (2007)

[107] Luckham, D.C.: Event Processing for Business: Organizing the Real-Time Enterprise. Wiley, Hoboken (2012)

[108] Luckham David C. Schulte, W.R.: Event processing glossary: Version 2.0 (2011). http://www.complexevents.com/

[109] Lynch, R.L., Cross, K.F.: Measure Up! Yardsticks for Continuous Improvement, 2nd edn. Blackwell, Malden (1999)

[110] MacArthur, J.B.: Practical guidelines for replacement cost depreciation in RCA. J. Cost Manag. **22**(1), 29–35 (2008)

[111] Mahnke, W., Leitner, S.H., Damm, M.: OPC Unified Architecture. Springer, Berlin (2009)

[112] Malmi, T., Brown, D.A.: Management control systems as a package—opportunities, challenges and research directions. Manag. Acc. Res. **19**(4), 287–300 (2008)

[113] Martin, P.: Bottom-Line Automation, 2nd edn. ISA, Research Triangle Park (2006)

[114] Martin, P.G.: Dynamic performance measures: It in manufacturing. http://www.instrumentation.co.za (2012)

[115] Martin, P.G.: One out of many... pointing the whole organization in the same direction. http://reliabilityweb.com/index.php/articles/one_out_of_many...pointing_the_whole_organization_in_the_same_direction/ (n.d.)

[116] Mathur, A., Dangayach, G., Mittal, M., Sharma, M.K.: Performance measurement in automated manufacturing. Measur. Bus. Excellence **15**(1), 77–91 (2011)

[117] DIN EN 14051: Environmental management—material flow cost accounting—general framework (2011)
[118] Drools JBoss Community: JBoss drools. http://www.jboss.org/drools (n.d.)
[119] FORCAM GmbH: FORCAM—live cache: driving productivity. http://www.forcam.co.uk/ (2013)
[120] Hannover Messe: Hannover messe. http://www.hannovermesse.de/
[121] IEC 62264–1: Enterprise-control system integration—part 1: models and terminology (2004)
[122] IEC 62264–2: Enterprise-control system integration—part 2: model object attributes (2003)
[123] IEC 62264–3: Enterprise-control system integration—part 3: activity models of manufacturing operations management (2008)
[124] ISO 15704: Industrial automation systems—requirements for enterprise-reference architectures and methodologies (2000)
[125] ISO 22400–2: Automation systems and integration—key performance indicators for manufacturing operations management—part 2: definitions and descriptions (2014)
[126] ISO 26000: Guidance on social responsibility (2011)
[127] ISO 9000:2005: Quality management systems—fundamentals and vocabulary (2005)
[128] ISO19439: Enterprise integration—framework for enterprise modelling (2007)
[129] ISO/IEC 15504–1: Information technology—process assessment—part 1: Concepts and vocabulary (2004)
[130] ISO/IEC/IEEE 42010: Systems and software engineering—architecture description. http://www.iso-architecture.org/42010/
[131] Merriam Webster: Dictionary and thesaurus—merriam-webster online. http://www.merriam-webster.com (2013)
[132] MESA: Execution-driven manufacturing management for competitive advantage: white paper number 5 (1997)
[133] MESA: MES explained: a high level vision: white paper number 6 (1997)
[134] MESA: MES functionalities and MRP to MES data flow possibilities: white paper number 2 (1997)
[135] MESA: Controls definitions and MES to control data flow possibilities: white paper number 3 (2000)
[136] MESA: SOA in manufacturing guidebook (2010)
[137] MESA: MESA model evolution (2011)
[138] MESA: MESA collaborative manufacturing dictionary (2012)
[139] MESA: Performance improvement and metrics practices: white paper number 40 (2012)
[140] MESA Metrics: MESA metrics guidebook and framework (2011)
[141] MESA Metrics: Pursuit of performance excellence: business success through effective plant operations metrics (2012)
[142] OPC Foundation: OPC unified architecture specification part 1: overview and concepts. http://www.opcfoundation.org/ (2009)
[143] OPC Foundation: OPC—the interoperability standard for industrial automation and other related domains. http://www.opcfoundation.org (n.d.)
[144] PAS 1074: myOpenFactory: process and data standard for multi-enterprise management (2007)
[145] ProLeiT AG: The hybrid approach. http://www.proleit.com/fileadmin/basis/mes_solutions/MES_CS_hybrid_aproach_ProLeiT_EN.pdf (2007)
[146] Supply Chain Council: Supply chain operations reference (SCOR) model. http://supply-chain.org/ (2010)
[147] TIBCO Software Inc.: TIBCO businessevents. http://www.tibco.com/ (n.d.)
[148] VDI 5600 Part 1: Manufacturing execution systems (MES) (2007)
[149] VDI 5600 Part 3: Manufacturing execution systems (MES)—logic interfaces for machine and plant control (2011)
[150] VDMA 66412–1: Manufacturing execution systems (MES)—kennzahlen (2009)
[151] VDMA 66412–2: Manufacturing execution systems (MES)—kennzahlen (2010)

[152] VDMA 66412–3: Manufacturing execution systems (MES)—operational sequence description of data acquisition (2013)
[153] Vorne Industries: The fast guide to OEE. http://www.oee.com/ (2008)
[154] McKay, K.N., Wiers, V.C.S.: Planning, scheduling and dispatching tasks in production control. Cogn. Technol. Work **5**(2), 82–93 (2003)
[155] van der Merwe, A., Keys, D.E.: The case for RCA: understanding resource interrelationships. J. Cost Manag. **15**(5), 27–36 (2001)
[156] van der Merwe, A., Keys, D.E.: The case for resource consumption accounting. Strategic Finance 31–36 (2002)
[157] Metz, D.: The Concept of a Real-Time Enterprise in Manufacturing: Design and Implementation of a Framework based on EDA and CEP. Springer, Wiesbaden (2014)
[158] Metz, D., Karadgi, S., Grauer, M.: A process model for establishment of knowledge-based online control of enterprise processes in manufacturing. Int. J. Adv. Life Sci. **2**(3 & 4), 188–199 (2010)
[159] Meyer, H., Fuchs, F., Thiel, K.: Manufacturing Execution Systems: Optimal Design, Planning, and Deployment. McGraw-Hill, New York (2009)
[160] Michelson, B.: Event-Driven Architecture Overview. Patricia Seybold Group, Boston (2006)
[161] Molina, A., Chen, D., Panetto, H., Vernadat, F., Whitman, L.: Enterprise integration and networking: Issues, trends and vision. In: Bernus, P., Fox, M. (eds.) IFIP—The International Federation for Information Processing, pp. 303–313. Springer, New York (2005)
[162] Molina, A., Panetto, H., Chen, D., Whitman, L., Chapurlat, V., Vernadat, F.: Enterprise integration and networking: challenges and trends. Stud. Inform. Control **16**(4), 353–368 (2007)
[163] Monostori, L., Ilie-Zudor, E., Kemény, Z., Szathmári, M., Karnok, D.: Increased transparency within and beyond organizational borders by novel identifier-based services for enterprises of different size. CIRP Ann. Manuf. Technol. **58**(1), 417–420 (2009)
[164] Morel, G., Vernadat, F. (eds.): Information Control in Manufacturing 1998: Proceedings of 9th IFAC Symposium on Advances in Industrial Engineering (INCOM'98). Published for the International Federation of Automatic Control by Pergamon, New York (1999)
[165] Muchiri, P., Pintelon, L.: Performance measurement using overall equipment effectiveness (OEE): literature review and practical application discussion. Int. J. Prod. Res. **46**(13), 3517–3535 (2008)
[166] Mühl, G., Fiege, L., Pietzuch, P.: Distributed Event-Based Systems. Springer, Berlin (2006)
[167] Muthiah, K.M.N., Huang, S.H.: Overall throughput effectiveness (OTE) metric for factory-level performance monitoring and bottleneck detection. Int. J. Prod. Res. **45**(20), 4753–4769 (2007)
[168] Nachiappan, R., Anantharaman, N.: Evaluation of overall line effectiveness (OLE) in a continuous product line manufacturing system. J. Manuf. Technol. Manag. **17**(7), 987–1008 (2006)
[169] Neely, A., Adams, C., Crowe, P.: The performance prism in practice. Measur. Bus. Excell. **5**(2), 6–13 (2001)
[170] Neely, A., Gregory, M., Platts, K.: Performance measurement system design: a literature review and research agenda. Int. J. Oper. Prod. Manag. **25**(12), 1228–1263 (2005)
[171] Nenadál, J.: Process performance measurement in manufacturing organizations. Int. J. Prod. Perform. Manag. **57**(6), 460–467 (2008)
[172] Nicholas, J.M.: Lean Production for Competitive Advantage: A Comprehensive Guide to Lean Methodologies and Management Practices. Resource Management Series. Productivity Press, New York (2011)
[173] Nof, S.Y.: Automation: what it means to us around the world. In: Nof, S.Y. (ed.) Springer Handbook of Automation, pp. 13–52. Springer, Dordrecht (2009)
[174] Oechsner, R., Pfeffer, M., Pfitzner, L., Binder, H., Müller, E., Vonderstrass, T.: From overall equipment efficiency (OEE) to overall fab effectiveness (OFE). Mater. Sci. Semicond. Process. **5**(4–5), 333–339 (2002)

[175] Österle, H.: Enterprise in the information age. In: Österle, H., Fleisch, E., Alt, R. (eds.) Business Networking, pp. 17–54. Springer, Berlin (2000)
[176] Panetto, H.: Towards a classification framework for interoperability of enterprise applications. Int. J. Comput. Integr. Manuf. **20**(8), 727–740 (2007)
[177] Panetto, H., Molina, A.: Enterprise integration and interoperability in manufacturing systems: trends and issues. Comput. Ind. **59**(7), 641–646 (2008)
[178] Parliament, E.: The general principles and requirements of food law, establishing the european food safety authority and laying down procedures in matters of food safety. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32002R0178:EN:NOT (2002)
[179] Parliament, E.: Setting emission performance standards for new light commercial vehicles as part of the union's integrated approach to reduce co2 emissions from light-duty vehicles. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:145:0001:0018:en:PDF (2011)
[180] Parmenter, D.: Key Performance Indicators: Developing, Implementing, and Using Winning KPIs. Wiley, Hoboken (2010)
[181] Paschke, A., Kozlenkov, A.: Rule-based event processing and reaction rules. In: Hutchison, D., Kanade, T. Kittler, J., Kleinberg, J.M,, Mattern, F., Mitchell, J.C., Naor, M., Nierstrasz, O., Pandu Rangan, C., Steffen, B., Sudan, M., Terzopoulos, D., Tygar, D., Vardi, M.Y., Weikum, G., Governatori, G., Hall, J., Paschke, A. (eds.) Lecture Notes in Computer Science, pp. 53–66. Springer, Berlin (2009)
[182] Perkins, D., Stovall, O.S.: Resource consumption accounting— where does it fit? J. Appl. Bus. Res. **27**(5), 41–51 (2011)
[183] Pinedo, M.: Scheduling: Theory, Algorithms, and Systems, 2nd edn. Prentice Hall, Upper Saddle (2002)
[184] Porter, M.E.: Competitive Advantage. Free Press, New York (2004)
[185] Power, M., Wlodarczyk, P.: Process definition management: Using ISA-88 and BatchML as a basis for process definitions and recipe normalization. In: WBF Wuropean Conference (2008)
[186] Pun, K.F., White, A.S.: A performance measurement paradigm for integrating strategy formulation: a review of systems and frameworks. Int. J. Manag. Rev. **7**(1), 49–71 (2005)
[187] Qiu, R.: Mengchu Zhou: Mighty MESs. IEEE Robot. Autom. Mag. **11**(1), 19–40 (2004)
[188] Riahi-Belkaoui, A.: Handbook of Cost Accounting Theory and Techniques. Quorum Books, New York (1991)
[189] Robbins, R.: Overall equipment effectiveness. Control Eng. **55**(1), 64 (2008)
[190] Rönkkö, M.: A model for item centric material control in manufacturing. Ph.D. thesis, Helsinki University Of Technology, Helsinki (2006)
[191] Scheer, A.W.: Architecture of Integrated Information Systems: Foundations of Enterprise Modelling. Springer, Berlin (1992)
[192] Scheer, A.W.: ARIS—Business Process Frameworks, 3rd edn. Springer, Berlin (1999)
[193] Schiefer, J., Rozsnyai, S., Rauscher, C., Saurer, G.: Event-driven rules for sensing and responding to business situations. In: Proceedings of the 2007 Inaugural International Conference on Distributed Event-Based Systems (DEBS'07), pp. 198–205. ACM Press (2007)
[194] Schiffauerova, A., Thomson, V.: A review of research on cost of quality models and best practices. Int. J. Qual. Reliab. Manag. **23**(6), 647–669 (2006)
[195] Schmidt, M.: The sankey diagram in energy and material flow management. J. Ind. Ecol. **12**(1), 82–94 (2008)
[196] Schmidt, M.: The sankey diagram in energy and material flow management. J. Ind. Ecol. **12**(2), 173–185 (2008)
[197] Schonberger, R.J.: Overall equipment effectiveness: an unworthy metrics. Cost Manag. **23**(3), 46–48 (2009)
[198] Schruben, L.W., Roeder, T.M.: Fast simulations of large-scale highly congested systems. SIMULATION **79**(3), 115–125 (2003)
[199] Schütz, W.: Fundamental issues in testing distributed real-time systems. Real-Time Syst. **7**(2), 129–157 (1994)

[200] Scott, D., Pisa, R.: Can overall factory effectiveness prolong Moore's law? Solid State Technol. **41**(3), 513–527 (1998)
[201] Sedgley, D.J., Jackiw, C.F.: The 123 s of ABC in SAP: Using SAP R/3 to Support Activity-Based Costing. Wiley, New York (2001)
[202] Sharman, P.A.: Bring on german cost accounting. Strateg. Finance **85**(6), 30–38 (2003)
[203] Souza, L.M.S.D., Spiess, P., Guinard, D., Köhler, M., Karnouskos, S., Savio, D.: SOCRADES: A web service based shop floor integration infrastructure. In: Floerkemeier, C. (ed.) The Internet of Things, pp. 50–67. Springer, Berlin (2008)
[204] Spitzer, D.R.: Transforming Performance Measurement: Rethinking the Way We Measure and Drive Organizational Success. American Management Association, New York (2007)
[205] Stadtler, H.: Production planning and scheduling. In: Stadtler, H., Kilger, C. (eds.) Supply Chain Management and Advanced Planning, pp. 199–216. Springer, Berlin (2008)
[206] Stark, J.: Product Lifecycle Management: 21st Century Paradigm for Product Realisation. Springer, London (2011)
[207] Strauß, E., Zecher, C.: Management control systems: a review. J. Manag. Control **23**(4), 233–268 (2013)
[208] Sun, H.: Current and future patterns of using advanced manufacturing technologies. Technovation **20**(11), 631–641 (2000)
[209] Suwignjo, P., Bititci, U., Carrie, A.: Quantitative models for performance measurement system. Int. J. Prod. Econ. **64**(1–3), 231–241 (2000)
[210] System Insights, I.: System insights—vimana. http://www.systeminsights.com/ (n.d.)
[211] Taticchi, P., Tonelli, F., Cagnazzo, L.: Performance measurement and management: a literature review and a research agenda. Measur. Bus. Excell. **14**(1), 4–18 (2010)
[212] Taylor, H.A., Phillips, L., Martinez, F.: Event-Driven Architecture: How SOA Enables the Real-Time Enterprise. Addison-Wesley, Upper Saddle River (2009)
[213] Terwiesch, P., Ganz, C.: Trends in automation. In: Nof, S.Y. (ed.) Springer Handbook of Automation, pp. 127–143. Springer, Dordrecht (2009)
[214] Töyrylä, I.: Realising the potential of traceability: A case study research on usage and impacts of product traceability. Ph.D. thesis, Helsinki University Of Technology, Espoo and Finland (1999)
[215] Trust, C.: Guide to PAS 2050: How to Assess the Carbon Footprint of Goods and Services. BSI, London (2008)
[216] Vaxevanidis, N.M., Petropoulos, G.: A literature survey of cost of quality models. J. Eng. Ann. Fac. Eng. Hunedoara **6**(3), 274–283 (2008)
[217] Venohr, B.: Strategic management: Economics of strategy. http://www.berndvenohr.de (2007)
[218] Vidačković, K., Renner, T., Rex, S.: Market Overview Real-Time Monitoring Software: Review of Event Processing Tools. Fraunhofer-Verl, Stuttgart (2010)
[219] Vijayaraghavan, A.: MTConnect for realtime monitoring and analysis of manufacturing enterprises. http://www.systeminsights.com/ (2009)
[220] Wadhwa, S., Rao, K.S.: Flexibility and agility for enterprise synchronization: knowledge and innovation management towards flexagility. Stud. Inform. Control **12**(2), 111–128 (2003)
[221] Wagner, T.G.P.U.P.d.: Softwareagenten - einführung und überblick über eine alternative art der softwareentwicklung. Teil 1: Agentenorientierte Softwareentwicklung **45**, 48–57 (2003)
[222] Walzer, K., Rode, J., Wunsch, D., Groch, M.: Event-driven manufacturing: Unified management of primitive and complex events for manufacturing monitoring and control. In: Proceedings of 7th IEEE International Workshop on Factory Communication Systems, pp. 383–391. IEEE (2008)
[223] Walzer, K., Schill, A., Löser, A.: Temporal constraints for rule-based event processing. In: Varde, A., Pei, J. (eds.) Proceedings of the ACM first Ph.D. Workshop in CIKM (PIKM '07), pp. 93–100. ACM Press (2007)
[224] Wegmann, G.: Developments around the activity-based costing method: A state-of-the art literature review. SSRN Electron. J. (2007)

[225] White, L.: Resource consumption accounting: manager-focused management accounting. J. Corp. Acc. Finance **20**(4), 63–77 (2009)

[226] White, L.: Standard costs are not dirty words. Automation World 51 (2012)

[227] Wiendahl, H.P., ElMaraghy, H., Nyhuis, P., Zäh, M., Wiendahl, H.H., Duffie, N., Brieke, M.: Changeable manufacturing—classification, design and operation. CIRP Ann. Manuf. Technol. **56**(2), 783–809 (2007)

[228] Williams, T.J.: A Reference Model for Computer Integrated Manufacturing (CIM): A Description from the Viewpoint of Industrial Automation. Instrument Society of America, Research Triangle Park (1989)

[229] Williamson, R.M.: Using overall equipment effectiveness: The metric and the measures. https://www.swspitcrew.com (2006)

[230] Wollert, J.F.: Einführung. In: Gevatter, H.J., Grünhaupt, U. (eds.) VDI-Buch, pp. 475–484. Springer, Berlin (2006)

[231] Womack, J.P., Jones, D.T., Roos, D.: The Machine that Changed the World: The Story of Lean Production, 1st edn. HarperPerennial, New York (1991)

[232] Yang, C.C.: Improving the definition and quantification of quality costs. Total Qual. Manag. Bus. Excell. **19**(3), 175–191 (2008)

[233] Zhang, Y.H., Dai, Q.Y., Zhong, R.Y.: An extensible event-driven manufacturing management with complex event processing approach. Int. J. Control Autom. **2**(3), 1–12 (2009)