

Evaluation of the Dynamic Impacts of Customer Centered  
Lead Time Reduction Improvements on  
Customer-Oriented and Financial Performance  
- A Hybrid Approach of System Dynamics and Queuing Network Analysis -

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**Arda ALP**

Accepted by the dissertation committee:

**Prof. Gerald Reiner**, University of Neuchâtel, thesis director

**Prof. Valéry Bezençon**, University of Neuchâtel, Switzerland

**Prof. Ümit S. Bititci**, Heriot Watt University, United Kingdom

**Prof. Andreas Größler**, Radboud University Nijmegen, The Netherlands

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UNIVERSITÉ DE NEUCHÂTEL  
FACULTÉ DES SCIENCES ÉCONOMIQUES

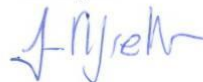
La Faculté des sciences économiques,  
sur le rapport des membres du jury

Prof. Gerald Reiner (directeur de thèse, Université de Neuchâtel)  
Prof. Valéry Bezençon (président du jury, Université de Neuchâtel)  
Prof. Ümit S. Bititci (Heriot Watt University, United Kingdom)  
Prof. Andreas Grössler (Radboud University Nijmegen, The Netherlands)

Autorise l'impression de la présente thèse.

Neuchâtel, le 27 mai 2014

Le doyen



Jean-Marie Grether



**To my family,**

*Mother and Father; one out of many,  
from the very beginning until the very end. Together forever.*



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# Summary

Motivated by the strategic importance of reduced lead times in today's competitive business environment, this doctoral dissertation analyzes the dynamic impacts of lead time reduction (LTR) improvements on customer satisfaction and related financial performance metrics. The core thesis is centered on development of an integrated dynamic performance measurement framework which covers operational, customer-oriented and financial performance dependencies over time. The framework is demonstrated through two empirical industrial cases.

Effective reduction of lead time is possible through understanding the relationship between lead time and lead time related factors, and the implications of these relations on system performance. Reducing lead time can have direct and indirect effects, improving overall company performance in short-term and long-term. Due to certain system interactions, not only does operational performance improve, but so do customer satisfaction and financial measures which are affected in terms of, e.g., reduced inventories and inventory carrying costs; improved service quality, diminished cancelled orders and reduced penalty costs; increased sales, improved market shares and profitability.

In particular, this research targets to identify which situational factors play a critical role between lead time reduction strategies and related effect on performance, and to understand how reduction of lead time impacts long-term performance compared to short-term effects.

In this direction, an integrated performance measurement framework has been developed by considering mathematical principles of lead time reduction and covering dynamic dependencies between financial and non-financial performance dimensions. The framework is comprehensive yet simple enough to consider trade-off characteristics among both time-based and non-time-

based metrics. The application of the framework was based on hybrid use of two methods: *Queuing Theory Based Modeling (QTM)* and *System Dynamics Modeling (SD)*.

Illustration of the lead time reduction framework is provided through two interrelated studies based on industrial applications done collaboratively with two international manufacturing companies. In this regard, two studies summarize these stages:

- The first study focuses on integrated analysis of some lead time reduction strategies on system performance (locating bottleneck capacity buffers, eliminating sources of waiting, setup time and reducing variability). In particular, we focus on the dynamic dependencies between bottleneck buffer configuration and station loading policies in order to analyze how those dependencies affect operational performance improvement: Throughput increase and reduction of lead time while considering various levels of demand variability. In particular, our analysis provides evidence for performance improvement without needing to invest to increase the bottleneck resource. Application of a particular station loading strategy and usage of multiple buffers (moving from a single common buffer to multi-buffers) yields better performance when variability increases.
- The second study focuses on analyzing the dynamic impacts of lead time reduction approaches on customer satisfaction and financial performance based on an industrial case created in joint collaboration with a European-based international company operating under make-to-stock manufacturing strategy. Based on the system's characteristics some lead time reduction strategies are selected (i.e. optimization of batch size, reallocation of system resources by pooling labor and improving the setup time) and the industrial production process is successfully improved without significant cost and time investments. Subsequently, related effects on customer-based performance and corresponding financials such as capacity investment (i.e. buying a new machine) are analyzed. Key cost figures, such as processing, inventory, labor costs and others were determined by evaluating the underlying cost accounting system. Later, motivated by the industrial application, the framework was further analyzed using sensitivity analysis. The insights gathered through industrial applications are used to present a sensitivity analysis based on short and long-term demand and lead time interaction. The sensitivity analysis is used for two main purposes: (i) to analyze the long-term performance impacts of lead time reduction under the extreme conditions of market demand; (ii) to question the conditions to maintain the long-term sustainability of lead time reduction. The sensitivity

analysis provided additional insight into the dynamic behavior of the demand and lead time interaction.

**Keywords:** Lead time reduction, integrated – dynamic performance measurement, system dynamics, rapid modeling



*“As a strategic weapon, time is the equivalent of money,  
productivity, quality even innovation”*

**GEORGE STALK, JR.**



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# Chapter 1

## Introduction

### 1.1 Background of the problem

Today's business world is driven by the needs of consumers (Firat *et al.*, 1995, pp. 46-49). Companies require low costs, shorter lead times and high customer service levels in order to be competitive (Gaither, 1994). Reduced lead times can provide quick response advantages while improving service levels and increasing customer satisfaction levels (Slack, 1998; Suri, 1998). Thus many companies have been putting significant efforts into reducing their lead times (Suri, 2010 and 1998; Askenazy *et al.*, 2006; Stalk and Hout, 1990; Tersine and Hummingbird, 1995).

Until the early 1980s, low cost and high quality were believed to be the fundamental sources of competitive advantage (Kim and Tang, 1997). Following World War II, economically devastated industries used low wages and scale-based strategies as an advantage to penetrate new markets. Higher workforce productivity and lower labor costs provided companies with competitive power against their competitors (Stalk, 1998, p. 42).

During the 1970s, companies started shifting their strategies from low wages to variety-based strategies, and flexible manufacturing became a competitive advantage (Dangayach and Desmukh, 2001). Flexible factories achieved flexibility and reduced costs, and surpassed traditional factories in terms of offered product variety. In this regard, Toyota Production System was a pioneer. Toyota was able to radically cut their response time to one day, achieved a much better customer response level compared to western competitors, and drastically lowered costs (Monden, 1983; Ohno, 1988). Toyota's success was inspirational for many companies.

Starting in 1980s, the popularity of strategies such as just-in-time, lean manufacturing, and kaizen increased. Toyota's emphasis on the just-in-time concept inspired Honda and Yamaha; they successfully competed against Suzuki and Kawasaki by executing processes faster and responding to customers rapidly. Mitsubishi initiated a time-based strategy by rapidly introducing innovative features for their air-conditioners and left western competitors ten years behind (Stalk, 1998, pp. 43-48). Such successes initiated an intensive focus on these strategies.

In the early 1990s, increased product and producer diversity in the market triggered a customer demand for shorter lead times which can be easily fulfilled from any competitor. Customers became willing to pay a price premium for shorter response times (Blackburn, 1991). Companies were forced to provide new products and better services at rapid rates (Stalk, 1988). Engineers and managers of many Japanese and western companies started to abandon cost-based and quality-based strategies and capitalize on speed-based strategies (Holmström, 1995; Schmenner, 2001).

The result was that manufacturers shifted their interest to increasing efficiency and gaining response advantages by reducing lead times. Gradually, time-based improvements became even more critical than cost- and quality-based ones (Krupka, 1992; Ghalayini and Noble, 1996). Time-based improvements drove cost improvements in terms of reduced inventory and penalty costs and quality improvements in terms of diminished manufacturing defects and reduced customer complaints. Meanwhile, as responsiveness to customer orders improved, customer service levels and customer satisfaction increased which are connected to cost and revenue (Bockerstette and Shell, 1993). In this regard, higher productivity, increased effectiveness and efficiency are possible through effective management of lead time and related factors (De Treville *et al.*, 2004, p. 618).

In today's business environment, organizations that are responding to customers' needs within shorter time frames are increasing their market shares, profits and enjoying competitive advantage (Ghalayini and Noble, 1996, p. 68; Woodruff, 1997). Toyota cut supply response time from 15 days to 1 and reduced delivery lead time of a custom built car from 30 to 60 days to within 5 days (Stalk, 1998; Simison, 1999). Matsushita cut washing machine production time from 360 hours to 2; Honda reduced motorcycle production time by 80% (Stalk, 1998). General Motors reduced lead time from 50 to 60 days to 10 days (Simchi-Levi *et al.*, 2003). Nissan cut the order-to-delivery lead time from 40 days to 7 days with a saving of \$3600 per vehicle (Ruderman, 2004).

Furthermore, firms started using short lead times as a marketing tool and advertising their response time. Pizza Hut and Dominos' promotion campaigns are based on the speed of delivery; Zara, Benetton and Sony are dominating market trends by introducing a variety of new products rapidly and frequently (Bruce, 1987; Dapiran, 1992); Hewlett-Packard and Dell offer quick response guarantees for custom-product demands (Feitzinger and Lee, 1997).

Several firms have been using speed-based strategies as their key competitive priority and marketing strength. In addition to operational improvement, lead time reduction provides financial advances and quick response capabilities to quickly adopt to changes in the market. Hence, the focus of this thesis is lead time reduction and impact of lead time reduction improvements on customer satisfaction and financial performance.

## **1.2 Statement of the problem**

Theoretical foundations of lead time reduction are well studied in the literature. There are several practical, inexpensive strategies proposed for reducing lead time (Suri, 1998 and 2010; Tersine and Hummingbird, 2005; De Treville and Ackere, 2006; De Treville *et al.*, 2004; Hopp *et al.*, 1990; Stalk and Hout, 1990; Reiner, 2009 and 2010).

These strategies mainly focus on improving effective use of system resources, minimizing time waste, delays and waiting times while reducing inventories, synchronizing the production, smoothing work flow and eliminating variability (Hopp and Spearman, 2006; Cattani and Schmidt, 2005; Hopp *et al.*, 1990). As a result, reducing lead time improves the overall performance '*in a multiplier fashion*' in the short- and long-term with direct and indirect effects (Ghalayini and Noble, 1996; Suri 1998 and 2010).

Operational performance is directly affected in terms of reduced work-in-process and finished goods inventories. As delivery time reduces, response time and service quality improves. As a result, customer satisfaction improves while the number of cancelled orders diminishes. In the long-term customer loyalties and market share improves (Reiner 2005; Reiner and Natter 2007). Financial measures are affected in terms of reduced inventory cost, improved delivery times and reduced penalty costs. Working capital, capital turnover and return on investment are also positively affected in the long-term (Ittner and Larcker, 1998).

Conversely, time inefficiencies can severely damage the system performance. As Stalk (1988, p. 48) highlighted, '*what distorts the system so badly is time*'; time can be easily wasted by poorly

managed operations, layout/workflow inefficiencies, misallocation of tasks (serialization of independent activities, non-synchronization of dependent activities) or reproduction of rejected parts due to low quality. Lengthy delays, non-value adding activities as well as variability distort the entire organizational performance in terms of process disruption, time waste and inefficiencies which are strategically linked with customers and satisfaction oriented value creation (Stalk, 1988, p. 48): *'Any activity that consumes more time than is necessary but does not add value to the production is a time inefficiency and should be an initial target for reduction or elimination of time waste'* (Tersine and Hummingbird, 1995, p. 10).

In fact, *'managing time is the mirror image of managing related factors such as quality, cost, profitability and productivity'* according to Tersine and Hummingbird (1995, p.10). Thus, effective reduction of lead time is possible through understanding the dynamics of non-financial and financial factors which are in close connection with lead time (Ghalayini and Noble 1996; Ghalayini *et al.*, 1997; Kaplan and Norton, 1997; Beamon, 1999; Neely, 1999; Li *et al.*, 2007).

Unfortunately Operations Management and Performance Measurement/Management literatures are limited in terms of studies focusing on performance interactions and trade-off characteristics while considering system dynamics over time (Santos *et al.*, 2002; Reiner *et al.*, 2007; Reiner *et al.*, 2009). Most state-of-the-art measurement systems do not focus on how overall performance will dynamically be influenced by lead time reduction in the short- and long-term.

The added value of lead time reduction is usually hindered by traditional performance measurement and cost allocation systems (Avanzi *et al.*, 2004; De Treville and Ackere, 2006). Such systems provide incomplete and biased information to managers leading to poor operations management decisions (Avanzi *et al.*, 2004 based on Ridgway, 1956). For instance, the impact of reduced lead times on manufacturing costs and further cost reductions are not considered (Suri, 1998); and related effects on quality, worker motivation, and learning are not covered (Hopp and Spearman, 1990). In fact, traditional systems fail to reflect complete dependencies of various dimensions of performance as their focus is far from providing insight on consumers' needs, expectations and real drivers of customer satisfaction. Therefore, related businesses decisions are insufficient to reach complete financial and market related success (Kaplan, 1990; Kaplan and Norton, 1997; Neely, 1999; Ittner and Larcker, 1996 and 1998; Gupta and Zeithaml, 2006).

Managers are failing to understand real drivers of performance by ignoring performance interactions and lead time related dynamics (Suri, 1998; Reppenning and Sterman, 2001; Maskell and Kennedy 2007) and business is still missing long-term effects of time-based improvement on

customer and financial performance as a part of their standard configuration. In fact, significant levels of productivity and profitability are achievable as long as time-based measures are integrated with financial performance and market requirements (Ittner and Larcker, 2003 and 1998; Banker *et al.*, 2000; Ghalayini and Noble, 1996; Krupka, 1992; Li *et al.*, 2007).

Today performance interactions and trade-off characteristics, and related system dynamics, are an undeniable part of improvement and evaluation processes (Bititci *et al.*, 1997, 2000, 2002 and 2006; Grünberg, 2004; Ghalayini *et al.*, 1997; Santos *et al.*, 2002; Neely *et al.*, 1995 and 2000; Neely, 1999). When companies invest more on understanding dynamics of time-based improvement strategies and multiple performance effects they may reinforce their decision making process and strengthen their competitive advantage compared to their rivals basing their strategies on less integrated, static performance measurement systems (Ittner and Larcker, 2003 and 1998; Banker *et al.*, 2000 and Bourne *et al.*, 2000). In today's business environment companies are becoming more proactive and dependent on dynamic information (Aedo *et al.*, 2010). Thus, integrated, dynamic, accurate, up-to-date performance information is more required in order to facilitate agility and responsiveness. In this regard, recent studies indicate the importance of dynamic, proactive and continuous use of performance information to deliver more value to customers and maintain the sustainability (Corona, 2009; Taticchi *et al.* 2010; Ostrom *et al.*, 2010; Nudurupati *et al.*, 2011; Bititci *et al.*, 2011a, 2011b and 2012).

### **1.3 Research purpose**

The purpose of this thesis is to better understand the dynamic impacts of lead time reduction approaches over time while considering the dynamic interactions among three dimensions of performance: Operational, customer-oriented and financial dimensions.

In particular, this thesis focuses on finding answers for the following research questions:

- I.** What are the dynamic impacts of lead time reduction approaches on customer satisfaction and financial performance?
- II.** Which situational factors play a critical role between lead time reduction strategies and related effects on performance?
- III.** How does the reduction of lead time impact long-term performance compared to short-term effects?

To be able to answer these research questions, a System Dynamics-based performance evaluation framework is developed. This framework explores how the performance is dynamically affected by lead time reduction. In parallel, this will also help us to enrich our understanding on performance metrics interactions and related performance trade-offs. In the end, this provides a wider perspective to comprehend direct and indirect effects of lead time reduction, and short- and long-term performance influences in contrast to similar research results provided for a single period.

## **1.4 Thesis outline**

Chapter 2 provides the theoretical background and detailed analysis of both the lead time reduction literature and performance measurement/management literature. Being in line with research objectives, particularly the focus is on the features and characteristics of the integrated performance measurement frameworks which became popular over recent years.

Chapter 3 focuses on theoretical foundations of the integrated dynamic performance measurement framework. Framework development is explained in detail for operational, customer-oriented and financial performance dimensions. For each dimension, the theoretical motivation is provided through a discussion of the related academic literature.

Chapter 4 highlights the motivation behind the methodology selection, focusing on two modeling approaches: *Queuing Theory Based Modeling* and *System Dynamics Based Modeling*. The motivation behind the hybrid usage of these methods is explained by discussing how these methods complement each other while providing a wide range of critical scenarios and strong analyzing capabilities. The chapter is concluded with related methodological contributions.

Chapters 5 through 6 present the illustration of the lead time reduction framework through interrelated studies based on industrial applications.

In particular, Chapter 5 focuses on integrated analysis of some lead time reduction strategies (locating bottleneck capacity buffers, eliminating sources of waiting, reducing variability) on system performance. In particular we analyze how bottleneck buffer configurations and station loading policies and related dependencies affect operational performance improvement.

Chapter 6 focuses on analyzing the dynamic impacts of lead time reduction approaches on customer-oriented and financial performance based on an industrial case. In particular, effects of

optimization of batch size, reallocation of system resources by pooling labor and improving the setup time on customer satisfaction and corresponding financials are analyzed. An additional sensitivity analysis is conducted in order to analyze dynamic impacts of lead time reduction on long-term performance compared to short-term effects.

Chapter 7 concludes by providing insights gathered through the industrial applications, and presenting related managerial implications and further research opportunities.



## Chapter 2

# Theoretical Background

### 2.1 Lead time reduction literature

In the 20<sup>th</sup> century, companies began to focus more on customers (Gaither, 1994). Recently, there is a growing managerial interest in customer satisfaction (Rust, *et al.*, 2010). Organizations are much more focused on reducing their lead times, by responding to customers on time, improving service quality and thereby satisfying a greater number of customers (Anderson *et al.*, 1997; Fornell, 1992; Gaither, 1994; Bielen and Demoulin, 2007) as high customer satisfaction ratings are linked to a company's future success and profits (Anderson and Sullivan, 1993 and 1997). Today, effective lead time management is viewed as a competitive advantage (Tersine and Hummingbird, 1995; De Treville *et al.*, 2004). Reducing lead time provides companies an advantage of producing and delivering products and providing services on time, in an efficient and cost-effective way compared to competitors (Stalk, 1988; Stalk *et al.*, 1992; Stalk and Hout, 1990; Askenazy *et al.*, 2006).

In the late 1970s and early 1980s, researchers started becoming interested in lead time reduction as a result of the rising popularity of JIT production (De Treville *et al.*, 2004; Avanzi *et al.*, 2004). During this period the western industry began to realize that the Japanese manufacturing methods far exceeded those of the European and American industries. The Japanese were able to achieve better quality, improve productivity and provide higher responsiveness using fewer resources (Womack and Jones, 1996 and 2003). The success of Japanese manufacturing systems motivated western companies to improve their operational efficiency using JIT principles and

lean philosophy (Askin and Goldenberg, 2002; De Treville and Antonakis, 1995). Researchers began focusing on exploring the elements of success by comparing the differences between Japanese and western manufacturing systems.

The Toyota Production System was seen as a major evolutionary step in terms of business efficiency and effectiveness (Liker, 2004). A production genius, Taiichi Ohno, located at Toyota, developed a manufacturing system, which was flexible, responsive and used less resources (Sohal and Egglestone, 1994), which far exceeded Western competitors (Ohno, 1988). Toyota's success in achieving higher productivity, sharply reduced lead times, levels of responsiveness and cost advantages (Monden, 1983) motivated researchers to synthesize the success factors behind the Toyota Production System (Liker and Jeffrey, 2004). Toyota's manufacturing philosophy and management principles initiated the foundations of lean production (see Krafcik, 1988 and Avanzi *et al.*, 2004 for further discussion regarding the link between the Toyota Production System and lean production).

The increasing popularity of lean thinking, lean production and the just-in-time concept led to a growing academic interest in the lead time reduction (De Treville *et al.*, 2004; Avanzi *et al.*, 2004). Today, in the field of operations management, theory concerning lead time reduction is well developed (as mentioned by De Treville *et al.*, 2006, p. 397). Various researchers have studied the theoretical foundations and practical implications of lead time reduction (Suri, 1998 and 2010; Tersine and Hummingbird, 2005; De Treville *et al.*, 2004; De Treville and Ackere, 2006; Hopp *et al.*, 1990; Stalk and Hout, 1990).

One of the pioneering articles of lead time literature titled, '*Industrial Dynamics: A Major Breakthrough For Decision Makers*', was published in 1958 in the *Harvard Business Review* by Jay W. Forrester (Stalk, 1988, p. 47). In his article, Forrester analyzed the impact of time delays and decision rates on organizational performance using systems thinking methodology and industrial dynamics models (Forrester, 1961). Basically, Forrester showed how a slight increase in demand can significantly deteriorate system performance, thus, causing fluctuations in production (boosting ups and cutting backs); and the system then required a long period to return to stability. According to Forrester, a long cycle time and lengthy response time in the planning loop inevitably creates an inaccurate view of the market, leading to weak decisions and ever-growing deteriorations in overall performance. The longer the time it takes for the system to realize and respond to demand fluctuations, the more distortions, waste and inefficiencies (Forrester, 1958; Stalk, 1988, pp. 47-48).

Three decades after Forrester's article, Sterman (1989b) noted that related performance disruption arises from misinterpreted feedback and neglected factor interaction; and Lee *et al.* (1997, p. 548) demonstrated that lead times are positively related to the distortion of demand fluctuations (De Treville *et al.*, 2004, p. 616).

Goldratt and Cox (1984) focused on operational factors that have an effect on lead time. The authors draw specific attention to how resource utilization and lot sizing decisions affect lead times (De Treville *et al.*, 2004). Karmarkar *et al.* (1985) and Karmarkar (1987) studied the systematic relationship between lot sizes and lead times. The authors demonstrated the impact of lot sizing decisions on manufacturing lead times and related in-progress inventories.

Hopp *et al.* (1990) studied the causes of long lead times and suggested key principles for reducing lead times. These principles are important to completely understand the relationship between processing times, waiting times, lead times, work-in-progress and finished goods inventories, as well as the effects of variations in lead time and process performance.

Steele and Shields (1993) studied the relationship between capacity, lead time, and inventories. The authors showed that, in addition to low cost advantages, capacity slacks also have a positive impact on various performance dimensions.

In another study, Karmarkar (1993) provided a detailed discussion as to how the production lead time affects the operational performance, which was provided by detailed literature in this area. The author especially highlighted the quantifiable negative effects of long lead times on safety stock inventories and the service level provided.

Bartezzaghi *et al.* (1994) focused on business processes and proposed a framework to model the lead time of any business process in order to support business process reengineering.

Vaughan (2004) studied the effects of lot sizing decisions on process lead time and safety stock inventories. In a similar study, Mikati (2010) analyzed the dependence of lead time on batch size using System Dynamics Modeling.

After the mid-1990s researchers began to address the lead time reduction concept for market mediation (Upton, 1995 and 1997; see De Treville, 2004). Articles in business press and lead time literature began to focus on the importance of speed-based advantages (Stalk, 1988; Schmenner, 1988; Stalk and Hout, 1990; Holmström, 1995; Schmenner, 2001). Stalk (1988, p.

42) named time to be the cutting edge advantage: *'As a strategic weapon, time is the equivalent of money, productivity, quality and even innovation'*, and underscored how managing time has enabled the Japanese industry not only reduce costs, but also to offer broad product lines and cover more market segments. Stalk (1988) also highlighted the possibility of establishing response time advantages as a winning competitive strategy based on success stories of the Japanese industry's time-based strategies.

In his article, *'The Merit of Making Things Fast'*, Schmenner (1988) placed increasing importance on speed-based advantages. Later, Schmenner (2001) explained how emphasizing focus on management of flow and speed could provide companies with higher productivity, based upon his *'Theory of Swift, Even Flow'* (De Treville *et al.*, 2004, p. 618).

Later, a group of researchers led the academic interest on the concept of using speed and lead time reduction to gain competitive advantage. This initiated the emergence of speed business strategies and the time-based competition concept highlighted by several researchers (Stalk, 1988; Stalk and Hout, 1990; Blackburn, 1991; Suri, 1994 and 1998; De Treville *et al.*, 2004).

Blackburn (1991) mentioned *'time-based competition'* as the next battleground in industrial competition. In their book *'Competing against time: How time-based competition is reshaping global markets'* Stalk and Hout (1990) discussed the urgent need for time-based capabilities based on the changing needs of a dynamic business environment. Later, Stalk *et al.* (1992) provided further discussion on the competitive power of speed-based strategies, which were based on the success stories of Wal-Mart, Kmart, and Canon (Stalk and Hout, 1990; Stalk *et al.*, 1992). In a similar direction, Holmström (1995) highlighted the criticality of speed and efficiency for manufacturing industries. Kumar and Motwani (1995) proposed a strategic framework for assessing time-based competitive advantage in manufacturing firms.

Tersine and Hummingbird (1995) centered lead time reduction into the core of customer oriented competitive strategy. The researchers highlighted the paramount importance for customers and noted how reducing lead time can provide quick response advantages (e.g. improved customer service, reduced response times, satisfying customers' expectations on time, delivering products/services faster than competitors and attracting new customers, etc.) to succeed in existing markets and to penetrate new markets.

One of the well-known comprehensive overviews of lead time reduction principles is Hopp and Spearman's (2006) *Factory Physics*. Based on the principles of the queuing theory, Hopp and

Spearman (2006) defined a set of mathematical relationships, principles and rules that determine the lead time. Basically these sets of rules formalize relationships and interactions of bottleneck utilization, lot sizes and variability with lead time (De Treville *et al.*, 2004). Based on these mathematical rules, Hopp and Spearman (2006) suggested practical, inexpensive and effective strategies for reducing lead times: *Looking for WIP* (the impact of buffer stocks vs. excess inventories), *keeping things moving* (i.e. splitting jobs, sharing transfer batches, queue control), *synchronizing production* (i.e. dispatching rules), *smoothing the work-flow* (i.e. leveling work release, establishing a uniform workflow and rationalizing line balancing) and *elimination of variability* (i.e. reducing rework, improving machine reliability and planning for yield losses).

Following this, Suri (1994 and 1998) introduced a queuing theory-based manufacturing strategy: ‘*Quick Response Manufacturing*<sup>1</sup>’ (QRM). Suri developed QRM as a companywide strategy for reducing lead times and by providing rapid response to customers. According to Suri (1994), QRM is an efficient, competitive strategy for managing high variability, low-volume or custom-engineered products, helping to improve product and service quality, and providing significant cost advantages. Using the QRM concept, Suri successfully integrated factory physics and lead time reduction principles into numerous real-life manufacturing applications (e.g. the industrial cases of John Deere, Rockwell Collins, Danfuss, Varco Drilling, Trans-Coil, Inc., E.J. Basler Co., Suri, 1994 and 1998) (De Treville *et al.*, 2004; Reiner, 2009 and 2010).

According to De Treville *et al.* (2004), by introducing Factory Physics and Quick Response Manufacturing principles Hopp and Spearman (2006) and Suri (1994 and 1998) represented ‘the first comprehensive application of lead time reduction principles (and underlying mathematical relationships) to the general theory of operations management’ (De Treville *et al.*, 2004, p. 619).

Today, lead time related mathematical relationships as well as the queuing-theory based software has been widely used to better understand and master lead time reduction principles and underlying dynamics (Suri *et al.*, 1986 and 1993; Suri *et al.*, 1995; Rabta, 2009; Rabta *et al.*, 2009). For the recent development of lead time literature reference is made to Reiner (2009) and Reiner (2010).

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<sup>1</sup> Quick Response Manufacturing should not to be confused with the supply chain strategy Quick Response (QR) which is a particular model for a particular market or industry (i.e. fashion market, apparel industry, textile industry; Hammond and Kelly, 1991). Quick Response Manufacturing is a companywide strategy which is applicable to wide range of business sectors.

## 2.2 The theoretical frame of lead time reduction

Reducing lead time is possible through understanding factors that determine the lead time. Primarily, three factors play a role in the average length of lead times: *Bottleneck utilization, lot sizes and variability* (as mentioned by Avanzi *et al.*, 2004, p. 3). System dynamics and factor interactions (i.e. resource interactions) also have a considerable impact on lead time (based on the mathematical laws of Factory Physics, Hopp and Spearman, 2006; Sterman, 2000 and 2001).

### i) Bottleneck utilization and lead time relation:

In a discrete production system the product units move through a sequence of stations where manufacturing/assembly operations are performed. Each station is responsible to perform a subset of tasks which are required to manufacture the entire product (Scholl and Klein, 1999, p. 721). Every station processes an item or a group of items within a given cycle time. Cycle time is defined as the time interval (average time) between completion of two successive units which is equal to the reciprocal value of the output rate. The utilization of a station is commonly defined as the long-run fraction of the average time the station is busy. Namely, utilization can be defined as the ratio of the average arrival rate over the average production rate of the system (system capacity). The station with the lowest throughput capacity (or whose capacity is equal to or less than the demand; Koo *et al.*, 2007) is commonly defined as the bottleneck station. In Figure 2.1 (*shown below*) a simple production line is illustrated where each station ( $S_i$ ) performs a single task ( $T_i$ ) by a unit processing time of  $t_i$  seconds.

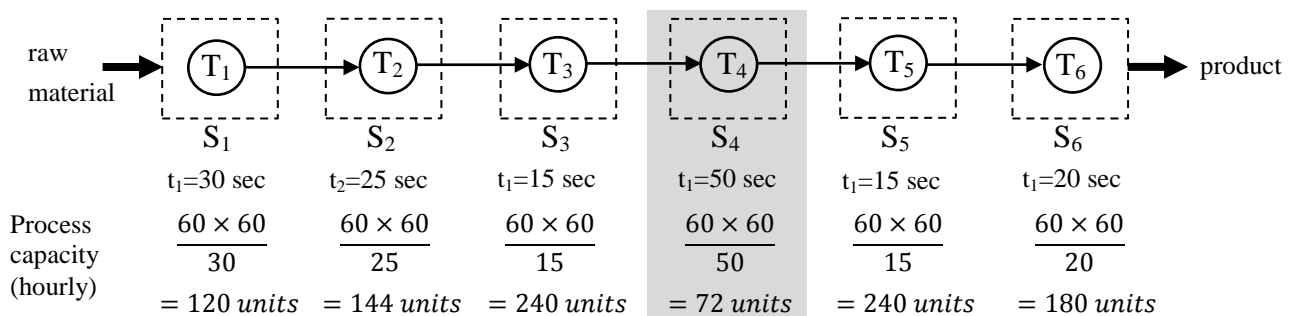


Figure 2.1: A sample process with the bottleneck station.

In this production line the Station 4 is the bottleneck station with the lowest throughput rate per hour. Performance at this station is critical, as system throughput is directly related to the capacity of the bottleneck station. Idle time, or time wasted in the bottleneck station, negatively impacts the entire system performance.

*Law of Utilization: If a station increases utilization without making any other changes, the average WIP and cycle time will increase in a highly nonlinear fashion (Factory Physics, Hopp and Spearman, 2006).*

Based on the law of utilization, increasing bottleneck utilization results in an exploded average lead time (Avanzi *et al.*, 2004) and work-in-progress inventories (Little's Law, Little, 1961) (*see Figure 2.2, shown below*):

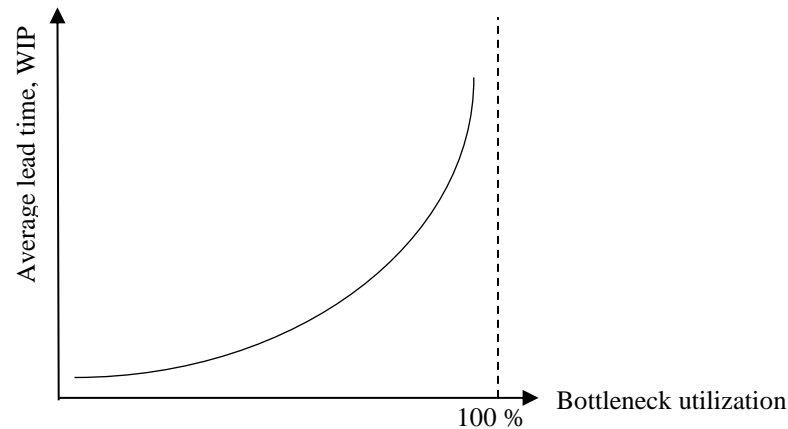


Figure 2.2: Bottleneck utilization – lead time relation  
(Source: Anupindi *et al.*, 1999; Hopp and Sterman, 2006).

Suri (1998), Anupindi *et al.* (1999) and Hopp and Spearman (1990 and 2006) demonstrated that the significant levels of performance and improved productivity are achievable reducing utilization at the bottleneck station. This can be achieved by reducing the workload (demand) on that station, increasing capacity (i.e. adding more resources, such as labor or equipment) or adding a capacity buffer.

Installing a capacity buffer at the bottleneck station prevents long lead times (Avanzi *et al.*, 2004). In this regard, buffers are not excessive inventory as having them is important to protect the throughput (Hopp *et al.*, 1990, p. 79). In addition, preventing excessive capacity utilization helps to maintain short lead times; since keeping the utilization level high at non-bottleneck workstations will result in exploded bottleneck utilization. Therefore, avoiding over utilization and maintaining moderate utilization assists in reducing lead time (Avanzi *et al.*, 2004). Conversely, cost allocation systems penalize capacity buffers and keeping utilization low at non-bottleneck stations (Avanzi *et al.*, 2004; De Treville and Ackere, 2006).

Systematic and sequential elimination of bottlenecks optimizes throughput and increases capacity. Along with the improvement of lead time performance, the system is capable of

responding to more customer requests at a time. As new demands occur, new bottlenecks emerge as a new target for further improvements. The lead time reduction process continues as a loop, consistent with the continuous improvement concept (Tersine and Hummingbird, 1995) (see Figure 2.3, shown below):

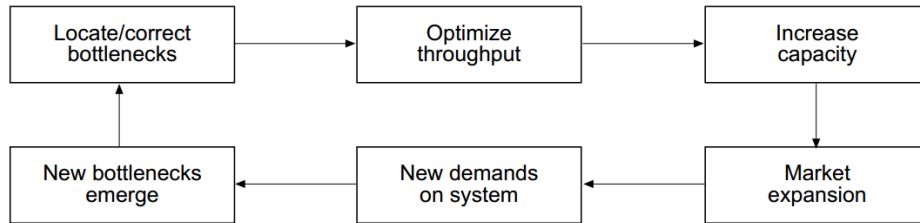


Figure 2.3: The continuous mechanic of bottleneck optimization based improvements (Source: Tersine and Hummingbird, 1995, Figure 3, p. 13).

In Section 5.2 to 5.5 (on pages 100 – 113), further theory on bottleneck optimization and related impacts on over performance will be explained along with an industrial example.

## ii) Lot size and lead time relation:

The reason behind batching work is related to machine setups and transportation operations (Karmarkar, 1987; Karmarkar *et al.*, 1985). Batching can be useful when multiple products are processed on the same machine and switching from one product type to the other necessitates the setup of the operation. On the other hand, batching is a source of variability, which has an impact on process flow time (Hopp and Spearman, 2006). For this reason, it is essential to understand the components of flow time:

$$\text{flow time} = \text{run time} + \text{setup time} + \text{move time} + \text{queue time} + \text{wait-for-parts time} + \text{wait-to-move time} \text{ (as defined by Hopp } et al.^2, 1990).$$

While setup time and unit run time are independent of batch size; run time, queue time and waiting-for-parts time are batch size dependent. Relatively small batch sizes increase the number

<sup>2</sup> Hopp *et al.* (1990, p. 80) defined sub-components of flow time as follows (in order keep the consistency, we use the same terminology as the authors used): *run time*: total processing time at work centers required to complete the job (all pieces in the batch); *setup time*: the sum total of all of the internal setups involved in processing the job; *move time*: time required to move the job between work centers; *queue time*: time spent waiting in queue for work center to become available; *wait-for-parts time*: time spent waiting for other subassemblies so that an assembly operation can begin, *wait-to-move time*: time spent waiting for other parts in a batch to be completed so that the batch can be moved to next work center.

of setups needed per batch; the total setup time is relatively high for small batch sizes. If proper batch sizes are selected, batching reduces the number of setups, setup time and setup costs.

Setup time reduction is important for increasing capacity and reducing flow time variance. According to Hopp *et al.* (1990) there may be cases where setup times cannot be reduced to insignificant levels and large batch sizes may be required to achieve the capacity needed. On the other hand, using very large lot sizes create more waiting; which results in an increase in queue time and waiting-for-parts time since pieces in the queue have to wait until the machine is available again. Furthermore, all pieces in a batch have to wait until the last item is processed. As a result, this forces the entire lot to wait, which is a significant increase in the wait time (Hopp and Spearman, 2006; Poiger *et al.*, 2010). Lot size - flow time interaction is shown in Figure 2.4 (*shown below*):

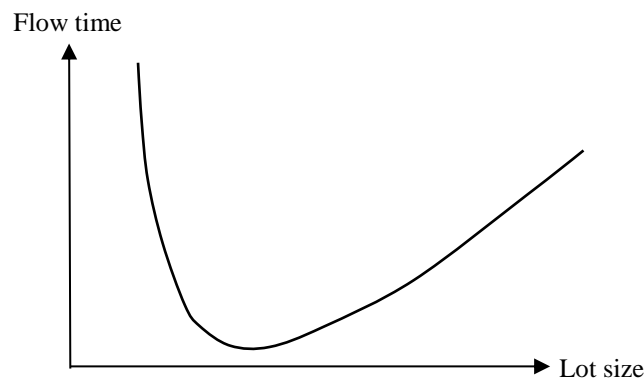


Figure 2.4: Lot size – flow time interaction  
(Based on Poiger *et al.*, 2010, Figure 6, p. 294 and Mikati, 2010, Figure 3, p. 7).

Batch size selection is a trade-off between setup times and waiting (waiting-in-queues and waiting-in-batch for parts). Targeting improvement efforts to reduce the flow time associated with these components makes sense (Hopp *et al.*, 1990). In fact, significant lead time improvements are achievable by optimizing the batch size (Mikati, 2010; Hopp and Spearman, 2006; Koo and Koh, 2007; Vaughan, 2004). In Section 6.1 (*on page 118*), further theory on batch size optimization and related performance impacts will be discussed along with an industrial example.

### iii) Variability and lead time relation:

Increasing system variability always degrades lead time performance:

*Law of Variability I: Increasing variability always degrades the performance of a production system* (Factory Physics, Hopp and Spearman, 2006).

In a production system variability is related to both production (processing rate) and arrival (demand; interarrival times) processes. As the coefficient of variation<sup>3</sup> increases, either for processing or interarrival times, lead time increase<sup>4</sup>.

Quality issues, rework, machine down times, worker absenteeism and the inconsistency of production methods all have a considerable impact on the mean and variance of flow time (Hopp *et al.*, 1990). If variability in a production system cannot be reduced, it can be buffered by some combination of inventory, capacity, and time (based on the second law of variability, Factory Physics). In this direction, strategies proposed for managing variability include reducing rework, improving machine reliability, better planning/scheduling, reduction of setup time, and pooling of customer demand or resources (Hopp and Spearman, 2006; Cattani and Schmidt, 2005; De Treville *et al.*, 2004; Suri, 1998).

Quality controls could help to reduce rework, rejections and time consumption. Particularly quality checks performed before bottleneck station, lengthy operations or the processing of large lots help early detection of problems and prevent the loss of time. Improving machine reliability and reducing machine downtime also reduces flow time. Reducing machine unavailability at the bottleneck is especially critical in terms of the strong impact that bottleneck resources have on mean and variation of flow time (Christensen *et al.*, 2007; Hopp *et al.*, 1990). Improving machine reliability also prevents keeping more buffer stocks since long and frequent machine breakdowns require more buffer stocks compared to short and frequent ones.

Placing buffer inventories, especially at bottleneck stations, is one way to hedge the uncertainty (Shi and Men, 2003; Yamashita and Altiok, 1998). Carrying a safety inventory helps to reduce stock outs and assists in maintaining a certain service level and improves customer satisfaction (Battini *et al.*, 2009). However, keeping an extra inventory is not free. Indeed this is a trade-off between the safety inventory level, related service level and stock keeping costs. Keeping fewer

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<sup>3</sup> *Coefficient of variation* is the most common measure for the variability of a random variable, which is defined by the ratio of its standard deviation to its mean; or equivalently the squared coefficient of variation.

<sup>4</sup> This can be illustrated using a simple G/G/m-model (Bolch *et al.*, 2006, pp. 244 and 269):

$$T_i = T_p \cdot \frac{\rho^{\sqrt{2(m+1)}-1}}{m(1-\rho)} \cdot \frac{c_i^2 + c_p^2}{2} \quad (2.1)$$

$$T = T_p + T_i \quad (2.2)$$

where  $T$  is average flow time,  $T_i$  is average waiting time,  $T_p$  is average service time of a server,  $\rho$  is the utilization,  $c_i$  is interarrival time variation coefficient,  $c_p$  is service time variation coefficient and  $m$  is number of servers.

inventories might be tempting in terms of reducing inventory costs; however, the stock out risk will also increase under long lead times, high demand and delivery variability<sup>5</sup>.

The pooling principle, pooling of customer demands or resources, allows better management of variability and aids the achievement of operational improvements (Cattani and Schmidt, 2005). The pooling of resources is used to reduce the number of workers (assigned to a task/station) by replacing this workforce with fewer but highly-skilled employees (can be assigned to several tasks/stations). In theory, the waiting time in the queues is expected to decrease. However, levels of specialization help hedge variability, but results in increased labor costs. Therefore, the extra investment would be needed for a highly-skilled workforce has to be compensated for with cost reductions and profit increases through lead time reductions.

## 2.3 Managerial behavior and lead time reduction

Although the relationships between lead time and related factors is well defined as a set of mathematical laws, either their application in a manufacturing environment is less emphasized or the implications of these rules are not very highly regarded (Suri, 1998).

According to Suri (1998), the principles of factory physics are less understood, along with a common belief that reducing lead time is costly or difficult. Managers tend to ignore the implications of related mathematical laws and pay less attention to the relationship between lead time and related factors. As a result, managers take counterproductive actions that result in an increase in lead time. Some of these mistakes increase utilization and keep resources as busy as possible, increase lot sizes, ignore variability and disregard resource interactions and system dynamics (Avanzi *et al.*, 2004; De Treville and Ackere, 2006).

In addition, the cost allocation system and traditional performance measurement frameworks also play a great role in misguiding managers and shading lead time reduction initiatives (Bititci *et al.*, 2000 and 2002; Neely *et al.*, 2005; Folan and Browne, 2005). Even though capital and time investments are required for reducing lead time, such systems do not reward investing in the

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<sup>5</sup> This can be illustrated using reorder point ( $s$ ) and the safety inventory ( $I_s$ ) formulas of Continuous Review Policy:

$$s = L \cdot \mu_D + I_s \quad (2.3)$$

$$I_s = z \cdot \sigma_D \sqrt{L} = z \sqrt{\mu_L \alpha_D^2 + \mu_D \alpha_L^2} \quad (2.4)$$

where  $L$  is replenishment lead time (delivery time);  $\mu_L$  is mean delivery time,  $\alpha_L^2$  is delivery time variance;  $\alpha_D^2$  is variance of demand (normally distributed  $N(\mu_D, \alpha_D)$ );  $z$  is the safety factor: the threshold value prevents falling into stock out by providing a certain amount of inventory for a given service level (Silver *et al.*, 1998; Nahmias, 2005).

reduction of setup times or variability, and penalize for keeping extra capacity buffers or keeping utilization at moderate levels (Avanzi *et al.*, 2004; De Treville and Ackere, 2006).

Such systems encourage managers to increase resource usage and boost utilization in order to hit production targets. For them, squeezing employees to work faster and harder is the correct strategy to accelerate production. Furthermore, most managers may choose to cut time and efforts for improving lead time in order to save time for extra work. High utilization and the cutting down of improvement efforts may secure the desired throughput increase, but this causes further and greater problems. In fact, by increasing utilization excess, capacity is wasted instead of being used to hedge uncertainties or make improvements, create growth, etc. The system becomes even less flexible and capacity and performance related problems begin to emerge (Repenning and Sterman, 2001; Sterman *et al.*, 1997; Oliva and Sterman, 2001 and 2010).

Workers operating at high rates of utilization have less time and place less emphasis on flow are less motivated to eliminate delays, reduce quality issues, reduce the amount of rework, machine downtimes or setup times. In the long-term, overall performance is affected in terms of decreased capability, increased lead and response times, reduced labor motivation, the erosion of service quality, increased costs and turnover rate, reduced profitability and the gradual loss of customers and market shares. Distorted performance leads to even further capacity gaps creating further work pressure on capacity in a snowball effect ('better-before-worse' situation). Keating *et al.* (1999), Repenning and Sterman (2001) and Oliva and Sterman (2001 and 2010) analyzed the internal dynamics of this dilemma. Another wrong mindset is using large batch sizes in order to increase capacity and reduce setup costs. However, large batch sizes may lead to increased lead times and costs which reduces responsiveness (Karmarkar, 1987; Karmarkar *et al.*, 1985; Suri, 1998). This type of mindset is contrary to the lean principles which favor creating and keeping capacity.

Managers ignore the long-term consequences of lead time reduction strategies; and their multiple effects on overall performance are usually disregarded. In fact, effective lead time reduction has an impact on market-oriented performance (Ittner and Larcker, 1998; Reiner, 2005). Actually, lead time reduction strategies provide several opportunities for responding to consumer imperatives as shown in Figure 2.5 (*on page 21*) (Tersine and Hummingbird, 1995):

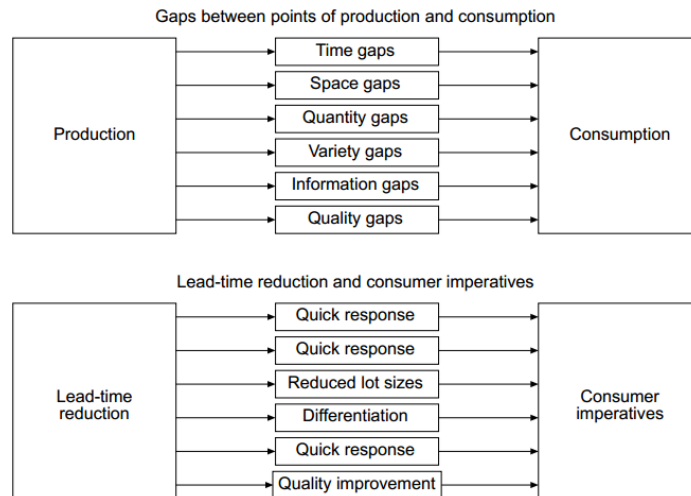


Figure 2.5: The relation between lead time reduction and consumer imperatives  
(Source: Tersine and Hummingbird, 1995, Figure 43, p. 15).

Lead time reduction strategies target closing the gaps between production and consumer needs while improving the consumers' satisfaction. For instance, providing a quick response to consumers' needs through lead time reduction eliminates time, space and information gaps. Optimization of lot sizes and reduction of setup times permits variety in response to consumer needs while closing quantity and variety gaps. The elimination of scrap, rework, downtime and increasing machine reliability improves quality. Furthermore, improving lead time leaves more time and capacity for continuous improvement initiatives while closing quality gaps (Tersine and Hummingbird, 1995, pp. 14-15; Stalk and Hout, 1990).

## 2.4 Performance measurement and management literature

'Performance measurement is the process of quantifying the efficiency and effectiveness of actions; and a performance measurement system is the set of metrics used to quantify both the efficiency and effectiveness of these actions' (based on a definition by Neely *et al.*, 2005, p. 1229).

The origin of the literature covered here extends back to late 1980s where the need for 'integrated, balanced, improvement-oriented and dynamic' performance measurement systems emerged (Bititci *et al.*, 2000, p. 693; Kaplan, 1990; Russell, 1992).

Until the 1980s, traditional performance measurement systems were regularly used for monitoring, controlling and evaluation purposes. These systems intensively relied upon cost accounting systems. Thereby, these systems were primarily financially-oriented; as they were

heavily reliant upon cost and efficiency measures (Anderson and McAdam, 2004; Neely *et al.*, 1995).

Following changes in the market, individual use of financial performance measures became insufficient to meet the needs of today's manufacturing environment (Bititci, 1994, p. 16). Traditional measurement frameworks became insufficient to capture the real drivers of the business (Wongrassamee *et al.*, 2003). Furthermore, traditional measures were misleading managers by providing the false impression of being useful and correct, but in fact, they were proving to provide a limited and misleading image of performance (Medori and Steeple, 2000). Several studies heavily criticized the inadequacy of traditional measures (Kaplan, 1988; Ghalayini *et al.*, 1997; Medori and Steeple, 2000; Neely *et al.*, 2005; Neely, 2005). The discussion of Bititci *et al.* (2006), Bititci (1994), Neely *et al.* (1995) and Ghalayini and Noble (1996) are also referred to regarding the deficiencies of traditional performance frameworks.

The limitations of traditional performance measures vary. One main disadvantage is their high dependency on classical ABC-based cost accounting measures, which can be insufficient to cover all drivers of cost (Ghalayini and Noble, 1996). According to Kaplan (1990, p. 35), such local performance measures or volume-based measures are harmful; as they conflict with attempts to improve quality, reduce lead times, reduce inventories and increase flexibility.

Traditional performance measures are also criticized and seen to be lagging metrics; for not being aligned with the corporate strategy and lacking strategic focus (Neely, 1999). Measures such as cost, profit or throughput may encourage short-termism, leading to myopic, sub-optimal solutions (Anderson and McAdam, 2004). For instance, profit without having the integration of other measures can lead to myopic interpretation of actual performance. As Globerson (1985) explained, profit alone does not necessarily indicate the source of problems or show where might be the fruitful areas to improve. Greedy cost reduction goals may gradually encourage managers to rely on short-term earnings; leading to weak decisions, causing more harm than good (Sterman *et al.*, 1997). This negatively impacts long-term improvement targets while distorting responsiveness and flexibility (Neely *et al.*, 2005); efficiency and effectiveness (Tung *et al.*, 2011).

Another criticism surrounds the limited adaptability of traditional measures with the continuous improvement philosophy (Kaplan and Norton, 1992). According to Fisher (1992, p. 21), financial standards negatively affect employee motivation and the success of related improvement programs. Their relevance to practice is limited, as financial metrics can be insufficient to truly show the effects of improvement programs. As Suri (1998) mentioned, such measures are

insufficient to realistically reflect complete cost-based improvements achieved by the reduction of lead time. Furthermore, quantification of some non-financial improvements in terms of pure financial measures might be incorrect or impractical (i.e. evaluating the effect of kaizen improvements on internal satisfaction).

Traditional measures do not have an external customer-oriented focus; as in some cases it is impossible to evaluate and improve customer-oriented company strategies (Kaplan and Norton, 1992).

A final criticism of traditional measures is related to time-based performance. The popularity of time-based measures caused misperceptions. Some managers believed that the individual use of metrics such as cycle time, lead time or delivery time would be enough to improve performance. However, not integrating such measures with non-time based performance (i.e. service quality, customer satisfaction/dissatisfaction, related penalties/costs and related effects on future sales) may lead managers to have an incorrect overview of company performance. This highlights the importance of integrating the use of time-based and non-time based measures (Ghalayini and Noble, 1996).

Starting in late 1970s and early 1980s, the arrival of Japanese manufacturing systems (just-in-time, lean manufacturing and continuous improvement programs) initiated an increasing awareness of the performance measurement concept. Being customer focused became an important competitive power, as opposed to being cost-oriented (Firat and Venkatesh, 1993; Firat *et al.*, 1995). As the importance of customer satisfaction was raised (Rust and Zahorik, 1995; Rust *et al.*, 2010), providing a quick response to customer needs became a competitive drive. This has forced many organizations to differentiate themselves from their competitors by capturing more critical aspects of customers (Ittner and Larcker, 1998 and 2003). Companies started leaving low-cost production strategies and started shifting to advanced strategies in order to improve responsiveness, quality and customer services and provide higher quality customer satisfaction (Ittner and Larcker, 1998).

This motivated companies' growing interest on customer and market oriented non-financial measures (i.e. service quality, service flexibility, order/delivery lead time, customer responsiveness, customer satisfaction, customer loyalty and many others; Neely, 1999; Ghalayini and Noble, 1996). As Medori and Steeple (2000) stated, there are several advantages to integrating non-financial measures into performance measurement. Compared to financial measures, non-financial measures are consistent with the long-term company strategy. They

provide more precise information for the management team while having a wider focus on both internal and external goals. They are flexible and adaptable to the changing needs of the market; and are compatible with the continuous improvement philosophy (Medori and Steeple, 2000, p. 521). Traditional and non-traditional performance measures are compared in Table 2.1 (*shown below*):

Table 2.1: A comparison between traditional and non-traditional performance measures <sup>(\*)</sup>

Characteristic	Traditional performance measures	Non-traditional performance measures
<i>Basis of system</i>	Outdated traditional accounting standards	Company strategy
<i>Types of measures</i>	Mainly financial	Mainly non-financial: operational, customer-oriented and financial;
<i>Audience</i>	Middle and top managers	All employees
<i>Frequency</i>	Lagging (weekly or monthly)	Real-time (hourly or daily) – Dynamic
<i>Linkage with “reality”- real-life usage</i>	Difficult, misleading, indirect	Simple, easy to use, accurate, direct
<i>Acceptance - shop floor relevance</i>	Neglected at the shop floor	Frequently used at the shop floor
<i>Format</i>	Fixed	Flexible/variable – depends on needs
<i>Local-Global relevance</i>	Static, non-varying	Dynamic, situation structure dependent
<i>Stability – (non)changing over time</i>	Static, non-changing	Dynamic, change over time as the need change
<i>Purpose</i>	Monitoring and controlling	Supporting process/performance improvement
<i>Support for new improvement approaches (JIT, TQM, CIM, FMS, etc.)</i>	Hard to adapt	Applicable
<i>Effect on continuous improvement</i>	Impedes / hinders	Supports

<sup>(\*)</sup> Source: Ghalayini *et al.* (1997), Table 1, p. 210 and Ghalayini and Noble (1996), Table I, p. 68.

Following these changing needs, the classical performance measurement concept has shifted its focus from measuring and controlling to supporting continuity and the improvement of performance (Santos *et al.*, 2007 and 2008). Thereby, functions such as being customer-oriented, having a long-term orientation and supporting continuous improvement became important. Performance frameworks were required to cover various aspects of the business needs (Wongrassamee *et al.*, 2003; Ghalayini and Noble, 1996). Thus, having an integrated view of several performance dimensions became a necessary condition (Ghalayini *et al.*, 1997). Neely *et al.* (1995) highlighted this changing trend as shown in Table 2.2 (*shown below*). Gradually, this led to an emerging need for improved performance measurement systems (Bititci and Turner, 2000). A new generation of performance frameworks was designed to facilitate interactions and causal relationships between elements of performance while addressing systems dynamically (Bititci *et al.*, 2000; Neely *et al.*, 1995).

Table 2.2: The main changes and trends in development of performance measurement systems <sup>(\*)</sup>

Traditional performance measurement systems	Innovative performance measurement systems
Based on cost/efficiency	Value-based
Trade-off between performances	Performance compatibility
Profit-oriented	Customer-oriented
Short-term orientation	Long-term orientation
Prevalence of individual measures	Prevalence of team measures
Prevalence of functional measures	Prevalence of transversal measures
Comparison with standard	Improvement monitoring
Aim at evaluating	Aim at evaluating and involving

<sup>(\*)</sup> Source: Anderson and McAdam (2004), Table III, p. 476; Neely *et al.* (1995).

## 2.5 Recent developments of integrated performance measurement systems

Current performance measurement trends have shifted towards better-structured and integrated performance measurement systems. A new generation of frameworks is using balanced and well-integrated measures while dynamically addressing causal relationships between elements of performance systems (Bititci *et al.*, 2000; Neely *et al.*, 1995; Bititci, 1994). Integrated performance measurement ensures '*integration of business objectives, business strategies, functional strategies and personal objectives*' (see Figure 1, Bititci, 1994, p. 17).

In recognition of the need for being integrated, dynamic and long-term orientated, a number of performance measurement frameworks have been developed.

Neely *et al.* (2005 and 2000), Neely (2005), Bititci *et al.* (2012, 2006, 2002 and 2000), Nudurupati *et al.* (2011), Taticchi *et al.* (2010), Santos *et al.* (2007), Folan and Browne (2005), Bourne *et al.* (2000) and Ghalayini *et al.* (1997 and 1996) provided a detailed perspective and an extended literature review on performance measurement systems. Surely, each performance framework has advantages and limitations. Here, some of the integrated performance measurement frameworks, which have become popular over the years, are highlighted:

- The Du Pont Analysis, ROI (or ROA) and ROE Ratios (Kaplan, 1984; Neely *et al.*, 2005).
- The Performance Measurement Matrix (Keegan *et al.*, 1989).
- The Performance Measurement Questionnaire (Dixon *et al.*, 1990).
- The Strategic Measurement Analysis and Reporting Technique (SMART) – Performance Pyramid (Cross and Lynch, 1989; Lynch and Cross, 1992).
- The Results and Determinants Framework (Fitzgerald *et al.*, 1991).
- The Balanced Scorecard (Kaplan and Norton, 1992, 1996 and 1997).
- The Pyramid of Organizational Development (Flamholtz, 1995; Flamholtz and Hua, 2002).
- The Cambridge Performance Measurement Design Process (Neely *et al.*, 1995, 1996a and 2005).
- The Integrated Dynamic Performance Measurement Systems (Ghalayini *et al.*, 1997).
- The Business Excellence Model of the EFQM (EFQM, 1999 and 2013).
- Integrated Performance Measurement System Reference Model (Bititci *et al.*, 1997; Bititci and Carrie, 1998; Bititci *et al.*, 1998 and 2000).
- Active Monitoring (Turner and Bititci, 1998; Bititci *et al.*, 1998).
- The Quantitative Model for Performance Measurement Systems (Suwignjo *et al.*, 1997 and 2000; Bititci *et al.*, 1998).
- The Integrated Performance Measurement Framework (Medori and Steeple, 2000).
- The Performance Prism (Neely *et al.*, 2000, 2001 and 2002).
- The Integral Framework for Performance Measurement (Rouse and Putterill, 2003).

### (I) The Du Pont Analysis

One of the oldest performance measurement systems was developed by Du Pont and is based on cost accounting theories and practices (Kaplan, 1984; Neely *et al.*, 2005). Du Pont developed a pyramid by linking accounting measures and financial ratios, such as Return On Assets (ROA), Return On Investment (ROI) and Return On Equity (ROE) (*see Figure 2.6, shown below*).

ROA is commonly used to evaluate the effective use of assets by measuring the ratio of profit margins (net income) to asset turnover (average total assets). ROI is used to evaluate the efficiency of an investment by comparing the ratio of profit and investment cost. ROE is the ratio of net income to a shareholder's equity, which shows the amount of profit generated with the money invested by shareholders (Grünberg, 2004; Bodie *et al.*, 2004; Groppelli and Nikbakh, 2000).

One of the advantages of Du Pont's model is its structure. Several financial measures of an organization are hierarchically linked. On the other hand, one of the major drawbacks is having a unilateral focus on financial measures (Rouse and Putterill, 2003). These measures have been criticized for being myopic and short-term oriented by several academics (Neely *et al.*, 2005).

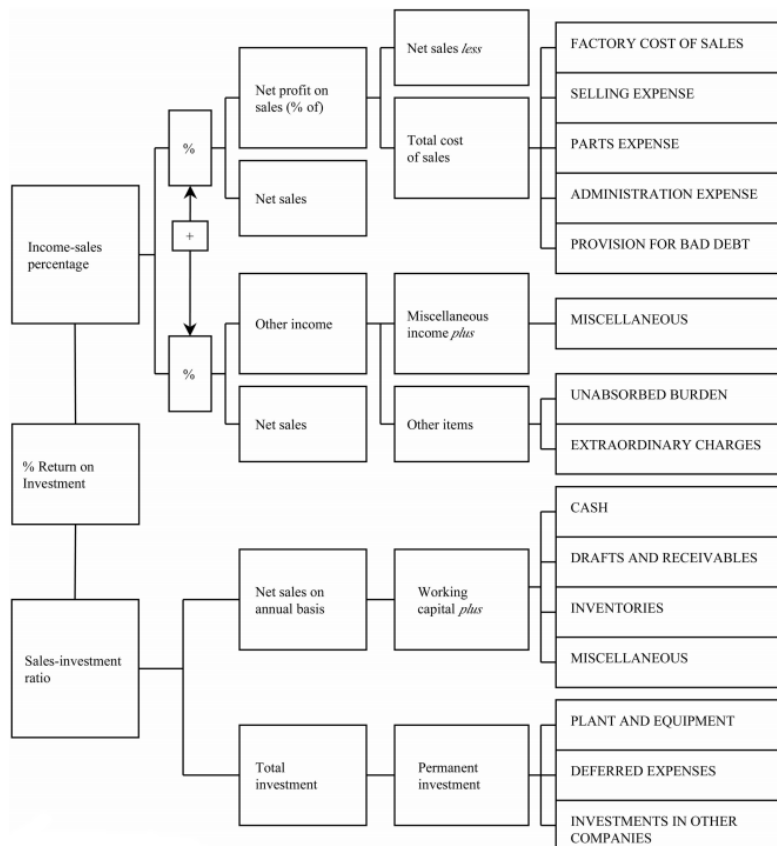


Figure 2.6: Du Pont's Pyramid of Financial Ratios (Source: Chandler, 1977; Neely *et al.*, 2000, Figure 3, p. 1124).

## (II) The Performance Measurement Matrix

The Performance Measurement Matrix of Keegan *et al.* (1989) integrates financial, non-financial internal and external business performances (see Figure 2.7, shown below). Financial measures are defined into two categories: *External cost metrics* (i.e. relative research expenditures and competition related costs) and *internal cost metrics* (i.e. design, development, production and material). Similarly, non-financial measures are defined into two categories: *External measures* (i.e. market related metrics, number of customers and the number of customer complaints) and *internal measures* (i.e. on time delivery, cycle time and throughput) (based on Anderson and McAdam, 2004).

The framework structure is based on the following measures: Quality, customer satisfaction, speed, product/service cost reduction and cash flow. These measures are integrated with business functions based on the hierarchy of an organization's cost drivers (Neely *et al.*, 2000). According to Neely *et al.* (2001) and Anderson and McAdam (2004), the main strengths of Keegan's matrix is its integrated structure; alongside its simplicity and flexibility. On the other hand, the matrix has been criticized for having a less detailed structure compared to the Balanced Scorecard of Kaplan and Norton (1992, 1996 and 1997). According to Neely *et al.* (2000), this is due to non-explicit links between business dimensions. Furthermore, its business performance has been criticized for being unrefined and somewhat generalized when compared to the Balanced Scorecard method (Folan and Browne, 2005; Bititci *et al.*, 2006).

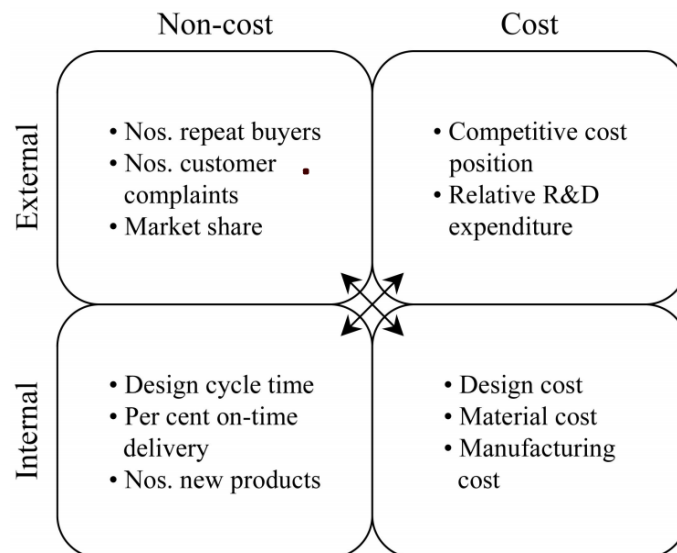


Figure 2.7: The Performance Measurement Matrix  
(Source: Keegan *et al.*, 1989; Neely *et al.*, 2000, Figure 1, p. 1122).

### **(III) The Performance Measurement Questionnaire (PMQ)**

The PMQ was created by Dixon *et al.* (1990) to serve as a decision tool for managers. Dixon *et al.* (1990) used a structured auditing questionnaire to check the compatibility of a firm's performance in accordance with the continuous improvement concept (Neely *et al.*, 1995). The main goal of the PMQ is to identify the improvement needs of an organization and the limits of selected performance measures. The PMQ is used to assess and compare actual performance with the competitive priorities of the company (Ghalayini and Noble, 1996).

The PMQ's strengths are in its functionalities and analysis capabilities. Four different types of analyses are defined: *Alignment*, *congruence*, *consensus* and *confusion* analysis (Neely *et al.*, 1995; Ghalayini *et al.*, 1997). The variety of analyses helps managers remain consistent between the firm's strategy and related measures. The manager can also identify areas requiring improvement and estimate the limits of improvement actions (Ghalayini and Noble, 1996). However, the PQM has been criticized for having a missing link to the continuous improvement concept. Furthermore, the PQM has been defined as a tool as opposed to an inclusively integrated performance measurement system (Ghalayini *et al.*, 1997).

### **(IV) The Strategic Measurement Analysis and Reporting Technique (SMART)**

SMART (also known as *The Performance Pyramid*) was developed to eliminate the myopic focus of traditional performance management systems (Cross and Lynch, 1989; Lynch and Cross, 1992) and has a wider vision. This method aggregates the strategic objectives and operational performance of an organization using a pyramidal structure. This pyramidal structure is composed of four levels, of which, corporate vision/strategy is at the top. At the second level, all strategic business units are positioned. The strategic objectives (market and financial objectives) of this level are in close connection with the first level. The third level focuses on business operating units where the market and financial objectives of the second level are linked with customer satisfaction, flexibility and productivity measures. At the final level, measures of quality, delivery, process time and cost are positioned. The final level focuses on departments, work centers and related operations. The pyramidal structure of SMART is shown in Figure 2.8 (*shown on page 29*).

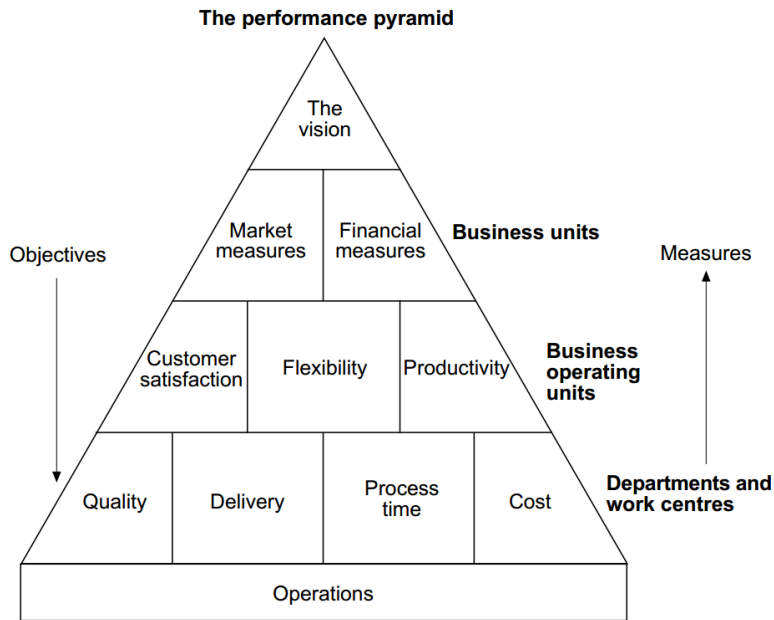


Figure 2.8: The Performance Pyramid  
 (Source: Lynch and Cross, 1992; Ghalayini and Noble, 1996, Figure 5, p. 74).

This hierarchical structure is one of SMART’s strengths. Several corporate objectives are linked with operational performance measures (Neely *et al.*, 2000). Business levels are efficiency integrated with each other. SMART can support both strategic business levels (Ghalayini and Noble, 1996; Rouse and Putterill, 2003) and low-level business units (Anderson and McAdam, 2004). There is an explicit distinction between external and internal measures. However, SMART has been criticized for missing a mechanism for the identification of critical performance measures (Ghalayini *et al.*, 1997). Continuous improvement integration is also limited. SMART has also been criticized for providing limited detail on measures (i.e. form, structure and development related information) (Anderson and McAdam, 2004).

**(V) The Results and Determinants Model**

The Results and Determinants Model (Fitzgerald *et al.*, 1991) has a structure composed of six major performance dimensions and two conceptual categories. The *results* category covers financial and competitiveness/market related measures. The *determinants category* covers service quality, flexibility, resource utilization and innovation as shown in Figure 2.9 (see page 30).

The Results and Determinants Model integrates lagging indicators (*results*) as a function of leading indicators (*determinants*) (Neely *et al.*, 2000). According to Folan and Browne (2005) this clear distinction is one of the main strengths of the method compared to other methods (i.e. ‘The Performance Measurement Matrix’ of Keegan *et al.*, 1989).

	Dimension of performance	Type of measure	
RESULTS	Competitiveness	Relative market share and position Sales growth Measures of the customer base	LAGGING INDICATORS
	Financial performance	Profitability Liquidity Capital structure Market ratios	
DETERMINANTS	Quality of service	Reliability Responsiveness Aesthetics/appearance Cleanliness/tidiness Comfort Friendliness Communication Courtesy Competence Access Availability Security	LEADING INDICATORS
	Flexibility	Volume flexibility Delivery speed flexibility Specification flexibility	
	Resource utilization	Productivity Efficiency	
	Innovation	Performance of the innovation process Performance of the individual innovations	

Figure 2.9: The Results and Determinants Model  
(Source: Brignall *et al.*, 1991, Table 1, p. 36; Neely *et al.*, 2000, Figure 2, p. 1123).

## (VI) The Balanced Scorecard (BSC)

The Balanced Scorecard of Kaplan and Norton (1992, 1996 and 1997) is one of the most frequently cited and adopted performance measurement frameworks (Neely *et al.*, 2005 and Taticchi *et al.*, 2010). The BSC has an integrated structure, which covers both financial (i.e. sales, revenue, ROI and cash flows) and non-financial measures (i.e. customer satisfaction and delivery performance, etc.). This structure is shown in Figure 2.10 (*see page 31*). Regarding each performance measure, this method uses a simple question to identify performance needs:

- Customer perspective: *'How do customers see us?'*
- Internal perspective: *'What must we excel at?'*
- Innovation and learning perspective: *'Can we continue to improve and create value?'*
- Financial perspective: *'How do we look to shareholders?'*

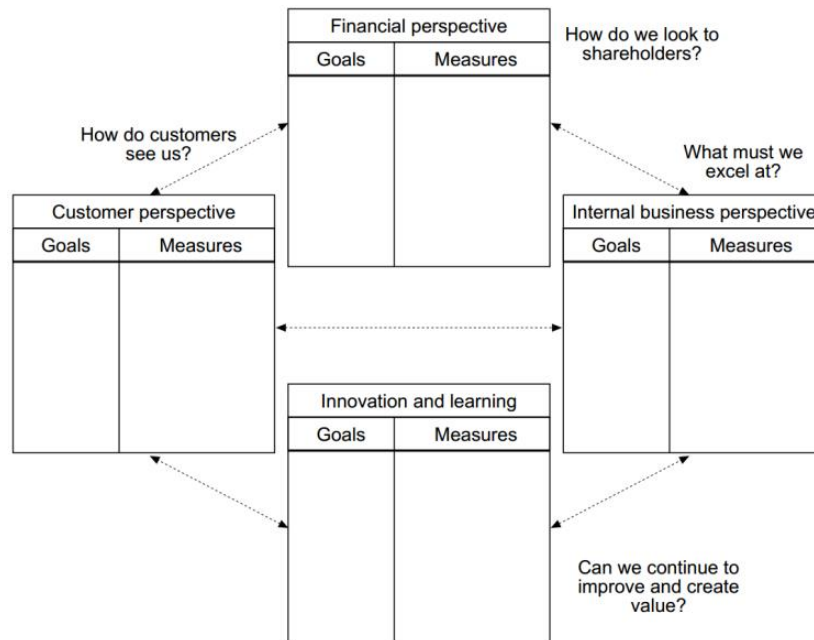


Figure 2.10: The Balanced Scorecard  
 (Source: Kaplan and Norton, 1992, p. 72).

According to Kaplan and Norton (1992, 1996 and 1997), this method provides a balanced view of performance while integrating corporate values, operational objectives, customer satisfaction and shareholder value. In this way, strategic, operational and financial measures are linked and categorized using four perspectives: *Internal business perspective*, *customer perspective*, *financial perspective* and *innovation/learning perspective*.

The *financial perspective* measures the success of the business in terms of Return On Investments. The *customer perspective* measures the success of business based on customer satisfaction, customer loyalty and the word-of-mouth effect. The *internal business perspective* measures the success of internal operations and processes. The *innovation and learning perspective* measures the success of the business by comparing innovations and developments with competitors (Kaplan and Norton, 1996). This framework uses four stages. The first stage, *translating the vision*, is about clarification of effective integration of the firm's strategy, vision and related goals to lower operational levels. The second stage, *communicating and linking*, is about linking top-level managerial elements to all sub-levels and related divisional goals. The third stage, *business planning*, is about integrating business and financial planning. The final stage, *feedback and learning*, provides strategic capability by reviewing the related results (Folan and Browne, 2005).

One of the main strengths of the BSC is its integrated structure with the use of four performance perspectives (Neely *et al.*, 2000). The vision of the BSC provides managers with a harmonized focus while preventing myopic focus on a single type of performance dimension (Ghalayini and Noble, 1996; Ghalayini, Noble and Crowe 1997). The Balanced Scorecard can provide organizations with a comprehensive strategic plan through improved communications and feedback mechanisms.

On the other hand, the BSC has been criticized for missing competitiveness and success related dimensions (Kennerley and Neely, 2002; Neely *et al.*, 1995). According to Ghalayini *et al.* (1997) the BSC has a general perspective; it does not provide clear recommendations. Thus, it is not useful at operational level. According to Pavlov and Bourne (2011) this method's effectiveness is highly dependent on how it is implemented. Moreover, the BSC has been criticized for lacking the following measures: Product quality, service quality and employee satisfaction (Kennerley and Neely, 2002). Furthermore, innovation, learning and customer oriented measures have been criticized for being weakly developed (Purbey *et al.*, 2007).

Since the early 1990s, the BSC has spread through several industries and adopted by many companies. Geuser *et al.* (2009, p. 93) stated that according to a study conducted by Bain & Company in 2005, 57% of 960 executives of international companies were using the BSC (Rigby, 2005, p. 13). In 2007, the percentage increased to 66% while covering 1221 international firms (Rigby, 2007, p. 14). According to Bain & Company the BCS has been reported as the most widely used and adopted management tool of 2008 and 2010 (Bain & Company, 2013). During recent years, the BSC has evolved from a performance measurement tool to a comprehensive strategy execution tool. Various generations of the BSC have emerged. Cobbold and Lawrie (2002) classified three distinct types among the variations of BSC. The first generation is a balanced scorecard design, which is the original BSC of Kaplan and Norton (1992). The development of the second generation BCS is based on the introduction of causality between the four perspectives of the first generation BSC. The second generation uses 'Strategic Linkage Modeling' along with strategy maps to distribute the strategic objectives across the four measurement perspectives of the original BSC method. In this way, the cause-effect links are established among these objectives for each perspective. The third generation of Balanced Scorecard refines the second generation designs and includes better translation of the strategy into long-term strategic goals while providing increased strategic relevance and improved functionality (Cobbold and Lawrie, 2002). The development of the BSC has initiated the adaptation of balanced performance approaches within the public sector, health and social care (Johnsen, 2001; Moullin, 2004; Moxham and Boaden, 2005 and Greatbanks and Tapp, 2007).

Recent BSC variations have been much more focused on economic and social issues alongside the concept of sustainability within organizations (Chalmeta and Palomero, 2010; Schaltegger and Lüdeke-Freund, 2011).

**(VII) The Pyramid of Organizational Development**

The Pyramid of Organizational Development model was developed by Flamholtz’s (1995). The model links organizational structure, organizational success and financial performance by using six factors: Corporate culture, management systems, operational systems, resource management, products, services and markets. These factors are aggregated as a holistic system which is shown in Figure 2.11 (*shown below*).

The main strength of the model is the pyramidal structure, which establishes a direct link between the organizational development and financial success of the organization. Moreover, the model successfully aggregates financial and non-financial performance dimensions. Based on this model, Flamholtz and Hua (2002) identified a significant relationship between the organizational success model and the financial success of the organization.

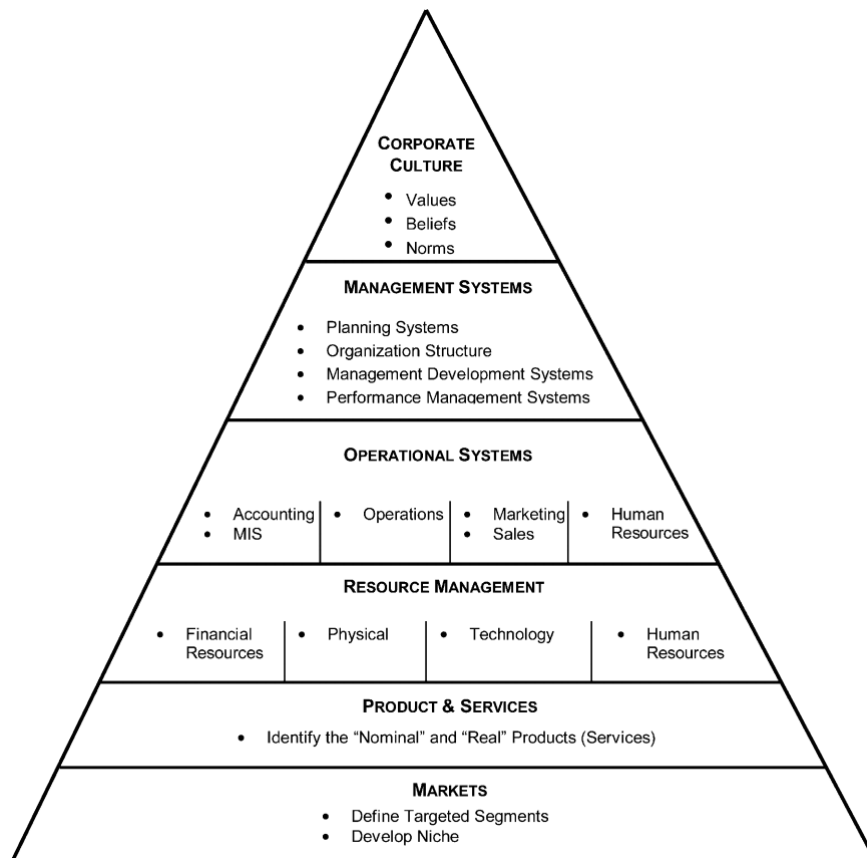


Figure 2.11: The Pyramid of Organizational Development: Six key building blocks of successful organizations (Source: Flamholtz and Hua, 2002, Figure 1, p. 75).

### **(VIII) The Cambridge Performance Measurement Design Process**

The Cambridge Performance Measurement Design Process was developed in order to improve the process design and implementation issues of performance measurement systems (Neely *et al.*, 1995). The performance management system concept is approached as an entity of individual measures. The framework focuses on complete integration of these individual measures, the performance measurement system and the environment as shown in Figure 2.12 (*shown below*):

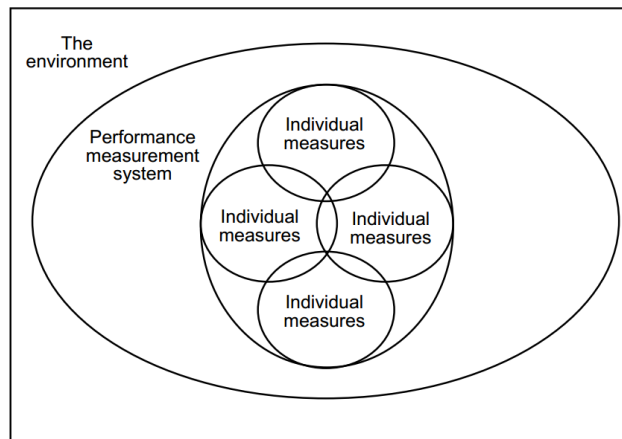


Figure 2.12: The Performance Measurement System Design Framework  
(Source: Neely *et al.*, 1995, Figure 1, p. 81).

According to Neely *et al.* (1995, p. 1256), the main contribution of this study is the clear and coherent knowledge provided regarding two concepts: *'How all internal, external, financial and non-financial elements have been integrated'* and *'how the link between strategy and measures has been established.'* The framework can assist managers in resolving conflicting issues between performance measures while at the same time, maintaining a proper balance between external and internal measures. In this way, managers can decide what to measure and how to measure by eliminating measurement related inconsistencies (Neely *et al.*, 1995, 1996a and 2005).

### **(IX) The Integrated Dynamic Performance Measurement Systems (IDPMS)**

IDPMS was designed to integrate performance measures across managerial and operational levels (Ghalayini *et al.*, 1997). Three principal functions are considered: (i) management; (ii) process improvement activities (management level and shop floor level); and (iii) operational activities at the factory shop floor. In this regard, three critical links have been defined across these functions: (a) *the management – factory shop link*; (b) *the management – process improvement team link*; and (c) *the process improvement team – factory shop floor link*.

The first link is critical in terms of maintaining the flow of information from the shop floor to management. The second link is critical in terms of ensuring the continuity and efficiency of improvement activities. By establishing information flow between management and teams, improvement decisions and performance achievements can be better controlled. In this way, prediction and planning of improvement activities can be accurately undertaken. The final link ensures the continuity and dynamic update of performance standards.

This sophisticated integration mechanism of the IDPMS is established through three tools: The ‘*performance measurement questionnaire*,’ the ‘*half-life concept*’ and the ‘*Modified Value-Focused Cycle Time – MVFCT*,’ as seen in Figure 2.13 (shown below).

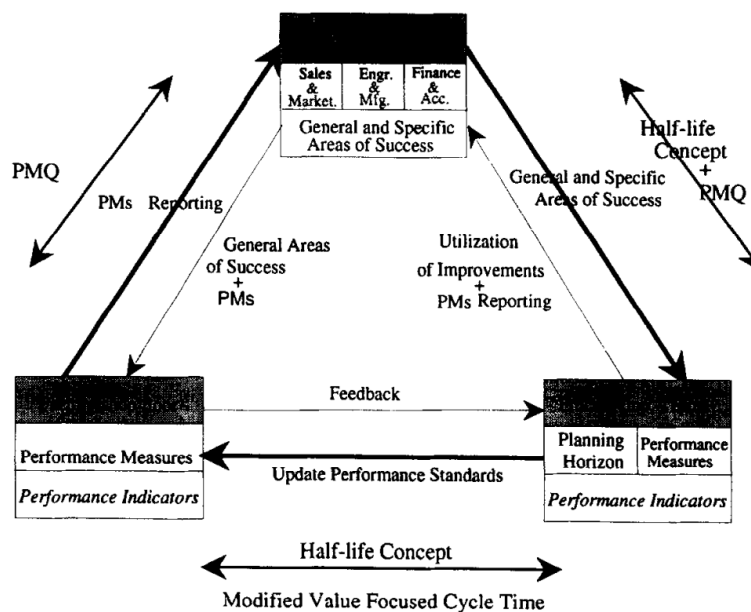


Figure 2.13: The Integrated Dynamic Performance Measurement Systems (Source: Ghalayini *et al.*, 1997, Figure 1, p. 211).

The half-life concept helps furnish process improvement activities systematically and continuously over a determined time horizon. The MVFCT acts as a barrier between cost reduction goals and operational performance measures while preventing any sub-optimal, myopic operational performance. According to the authors, one of the strengths of the method is the integration of different performance factors. The dynamic reporting of performance achievements is also a strength. In this way, the method helps improvement teams to identify continuous improvement opportunities. Contrarily, one of the weaknesses of the IDPMS is the missing marketing measures and marketing related strategies. Impacts of operational improvements on customer satisfaction have not been considered (i.e. the impact of lead time reduction on

customer satisfaction). Furthermore, the related effects on financial performance have also been missed (i.e. the impact of increased customer satisfaction on penalty costs and revenue, etc.).

### **(X) The Business Excellence Model of the EFQM**

The Business Excellence Model of EFQM (EFQM, 1999 and 2012) is a comprehensive, systematic framework, which links key performance metrics and a company's long-term strategic goals. The core of EFQM is based on self-assessment and continuous improvement of performance. The Business Excellence framework consists of two sets of performance factors: *Enablers* and *results*. The EFQM provides systematic analysis capabilities, which provide efficient identification of improvement opportunities. There are five enablers (leadership, people management, policy and strategy, resources and processes); and four results (people satisfaction, customer satisfaction, impact on society and business results), which are defined in the framework where results are used to link enablers to future success. This structure is illustrated in Figure 2.14 (*shown on page 37*).

The EFQM has been criticized for its limited instructions as to how those nine criteria should be integrated into the self-assessment process. As a result of this, the EFQM has been defined as a non-prescriptive approach (Wongrassamee *et al.*, 2003). According to Neely *et al.* (2000), performance terms are not well defined and limited definitions may lead to confusion. Thus, the EFQM has been also criticized for its vagueness in relation to operationalization. Despite all of these criticisms, the EFQM model has been quite popular. It has been utilized as base reference model for the European Quality Awards and has also been used as a self-assessment/improvement guide by numerous companies (i.e. Xerox, International Computers Limited, Rover, Royal Mail, TNT Express, GlaxoSmithKline, AB Electrolux, British Telecommunications, Ciba-Geigy, Dassault Aviation, Fiat Auto, KLM, Nestlé, Philips, Renault, Robert Bosch, Sulzer and Volkswagen) (EFQM, 2012; Neely, 1999).

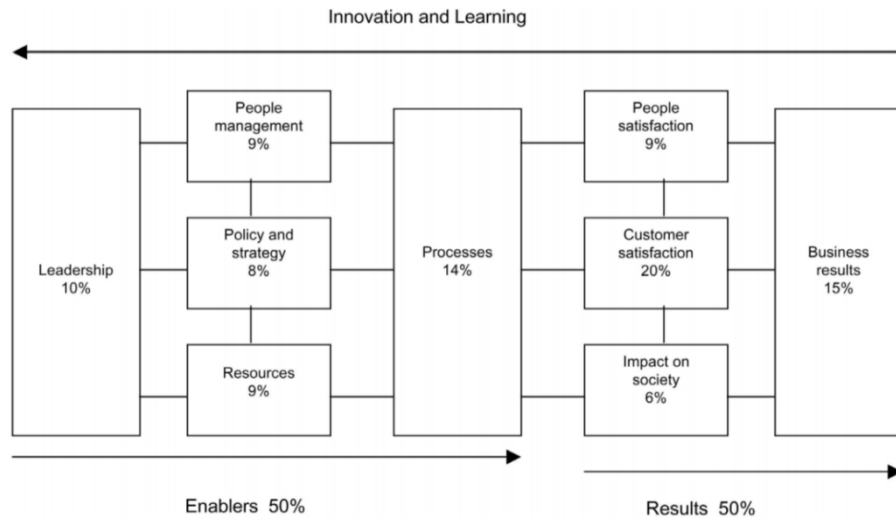


Figure 2.14: The Business Excellence Model  
 (Source: EFQM, 2012; Wongrassamee *et al.*, 2003, Figure 1, p. 16).

### (XI) The Integrated Performance Measurement System (IPMS)

The IPMS is a development guide with a focus on structure and metric-to-metric relationships of performance measurement systems (Bititci *et al.*, 1997). The IPMS was developed to quantify and model the relationships between performance measures. This system proposes a group of tools and techniques: A reference model, an audit method and a development guide. The overall structure of the IPMS is shown in Figure 2.15.1 (*shown on page 38*).

According to Bititci *et al.* (1997) the IPMS framework is capable of integrating various business concepts into a unified structure. The main functionality of the framework is defined using five actions: (i) *policy deployment* (the deployment of top level objectives: Corporate/stakeholder level and policies through the entire organization); (ii) *competitive criteria and benchmarking* (business positioning and the determination of key competitive factors); (iii) *process orientation* (the management of key business processes and performance); (iv) *normative planning* (measurement methodology related); and (v) *active monitoring* (the usage of proactive measures instead of reactive measures).

The IPMS deploys business objectives and policies amongst the organization while, at the same time, maintaining diffusion of each strategy into business elements (*see Figure 2.15.2 on page 38*). In this direction, four business levels are defined: *Corporate level*, *business unit level*, *business process level* and *activity level*. At each level, five factors are considered: *Stakeholders*, *control criteria*, *external measures*, *improvement objectives* and *internal measures* (based on Figure 4 and Figure 5, p. 528, Bititci *et al.*, 1997) (*see Figure 2.15.3 on page 38*).

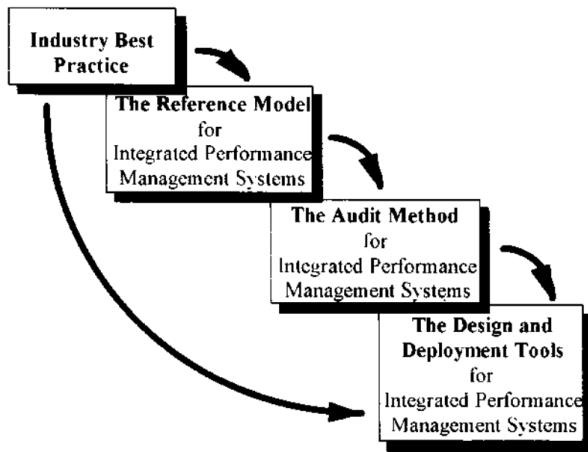


Figure 2.15.1: Concept & Objectives of IPMS Project (Source: Bititci *et al.*, 1997, Figure 1, p. 523).

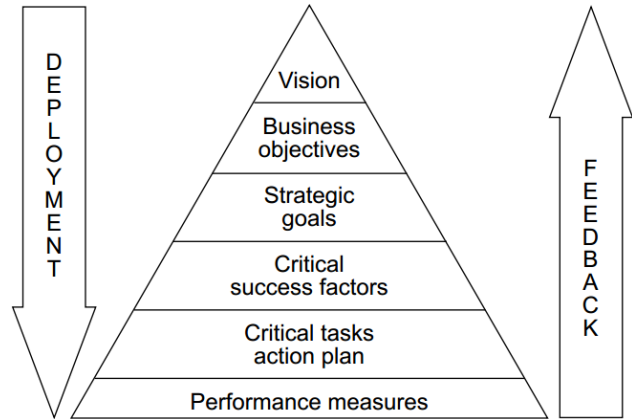


Figure 2.15.2: Closed Loop Deployment & Feedback System (Source: Bititci *et al.*, 1997, Figure 2, p. 524).

The IPMS contributes to the development of performance measurement literature by demonstrating the need for dynamic, integrated management systems. The authors provided explicit details regarding the deficiencies of static performance measures (Bititci *et al.*, 2000). The approach provided in this study is a pioneer, in a way, to accept and design performance management process as a closed-loop system. In this way, comprehensive feedback gathering, evaluation and deployment mechanisms are maintained and integrated into the performance measurement process (Bititci and Carrie, 1998; Bititci *et al.*, 1998 and 2000).

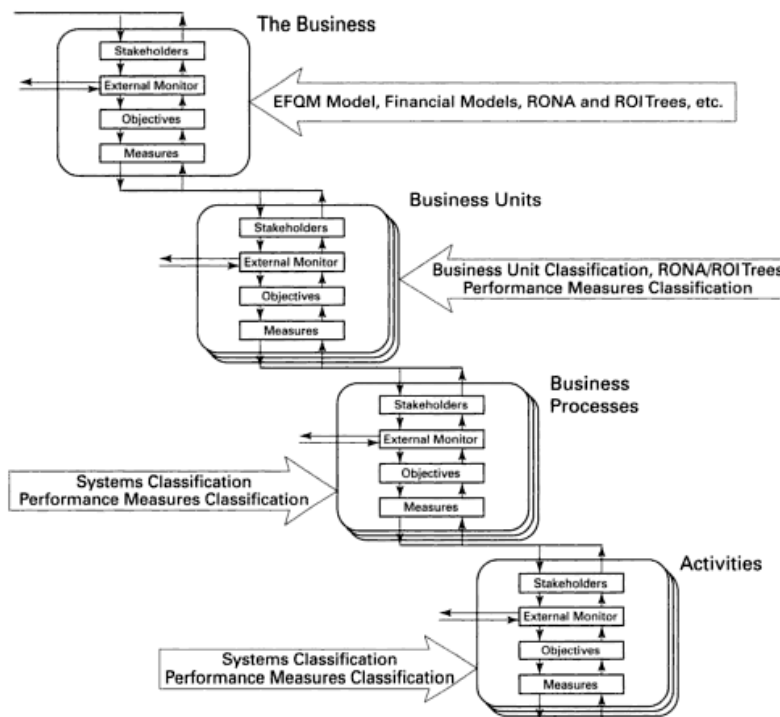


Figure 2.15.3: A reference model for Integrated Performance Measurement Systems (Source: Bititci *et al.*, 1997, Figure 5, p. 529; Bititci *et al.*, 2002, Figure 11.2, p. 183).

## (XII) Active Monitoring

Active Monitoring (Turner and Bititci, 1998; Bititci *et al.*, 1998) has been designed for the active monitoring of business processes and performance. The Active Monitoring approach has been tested against various business processes (i.e. operational, support and managerial) and has succeeded in maintaining business process reliability (based on Bititci *et al.*, 2000).

## (XIII) The Quantitative Model for Performance Measurement Systems (QMPMS)

The QMPMS focuses on investigating, modeling and quantifying performance measurement interactions and relations. In this direction, the QMPMS project has contributed to the development of integrated performance measurement literature (Suwignjo *et al.*, 1997 and 2000; Bititci *et al.*, 1998).

## (XIV) The Integrated Performance Measurement Framework (IPMF)

The IPMF is a strategic planning framework and was been designed to address both financial and non-financial performance dimensions (Medori and Steeple, 2000). The framework is used to analyze existing measurement systems and identify critical performance issues. The evaluation of the system and the selection of measures is based on six competitive priorities: *Quality, cost, flexibility, time, delivery* and *future growth*. These priorities are linked with a company's success factors, strategic targets and competitive priorities. The design of IPMF is based on a six-stage structure as illustrated in Figure 2.16 (*shown below*):

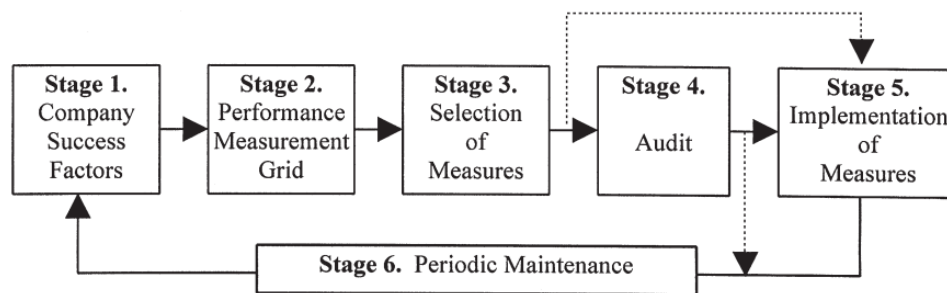


Figure 2.16: The Integrated Performance Measurement Framework  
(Source: Medori and Steeple, 2000, Figure 1, p. 523).

The structure of the IPMF is one of its strengths. According to the authors, the method is capable of capturing any specific information, at any performance level. The method also provides a thorough examination of a company's existing measurement system while helping to identify obsolete measures, performance gaps and missing non-financial measures. The framework has been empirically tested using action research methodology by involving medium and large-sized manufacturing companies. According to the authors, the IPMF has succeeded in improving company performance measurement systems whilst at the same time increasing internal satisfaction and trust.

### **(XV) The Performance Prism (PP)**

The Performance Prism is an extensive and innovative performance measurement framework. According to Neely *et al.* (2001 and 2002), the Performance Prism has been defined as the second-generation of existing frameworks (Anderson and McAdam, 2004; Neely, 2002). The framework addresses five main components of an organization: *Stakeholder satisfaction, strategies, processes, capabilities* and *stakeholder contribution*. Each component establishes one facet of a virtual prism. *Stakeholder satisfaction* and *stakeholder contribution* has been stated to be the top and bottom facets. The remaining measures have been stated to be the side facets. The stakeholders and organizations have been integrated reciprocally (*see Figure 2.17 on page 41*). The first facet focuses on the identification of a stakeholder's needs and the improvement of their satisfaction. The second facet concentrates on strategies, whereas the third facet focuses on the identification of related processes (i.e. product development, demand generation and fulfillment, enterprise planning and management) in connection with strategies. The fourth facet is related to the capabilities (i.e. people, practices, technology and infrastructure) of an organization, which are highly critical to execute and improve business processes. Thus, this facet focuses on the exact identification of organizational capabilities. Each facet has a target question (Neely *et al.*, 2001, pp. 6-7):

- *'Who are the important stakeholders in your organization and what do they want and need?'*
- *'What are the strategies we require to ensure the needs of our stakeholders are satisfied?'*
- *'What are the processes we have to put in place to allow our strategies to be delivered?'*
- *'What are the capabilities we require to operate our processes?'*

As Neely *et al.* stated, those key questions help management teams to focus and better identify their needs. The final facet is about the reciprocal and symbiotic relationship between the stakeholders and the organization. According to Neely *et al.* (2001), one unique feature of the Performance Prism is the establishment of this reciprocal relationship. Since several measurement frameworks are missing the reciprocity between the stakeholders and the organizations (Neely *et al.*, 2001).

According to Neely (2002), the framework addresses several shortcomings of the traditional measurement frameworks. The framework's principal strength is the logical aggregation of the five organizational components through a three-dimensional framework. The framework implies a comprehensive and balanced picture through integrating financial and non-financial measures; internal and external measures; and effectiveness and efficiency measures. Furthermore, the model creates awareness on multiple facets of performance and encourages managers to establish a link between these performance dimensions (Neely, 2002). Another contribution is the

innovative way of addressing stakeholders. The framework is flexible enough to provide either a broad or narrow perspective of performance (Anderson and McAdam, 2004).

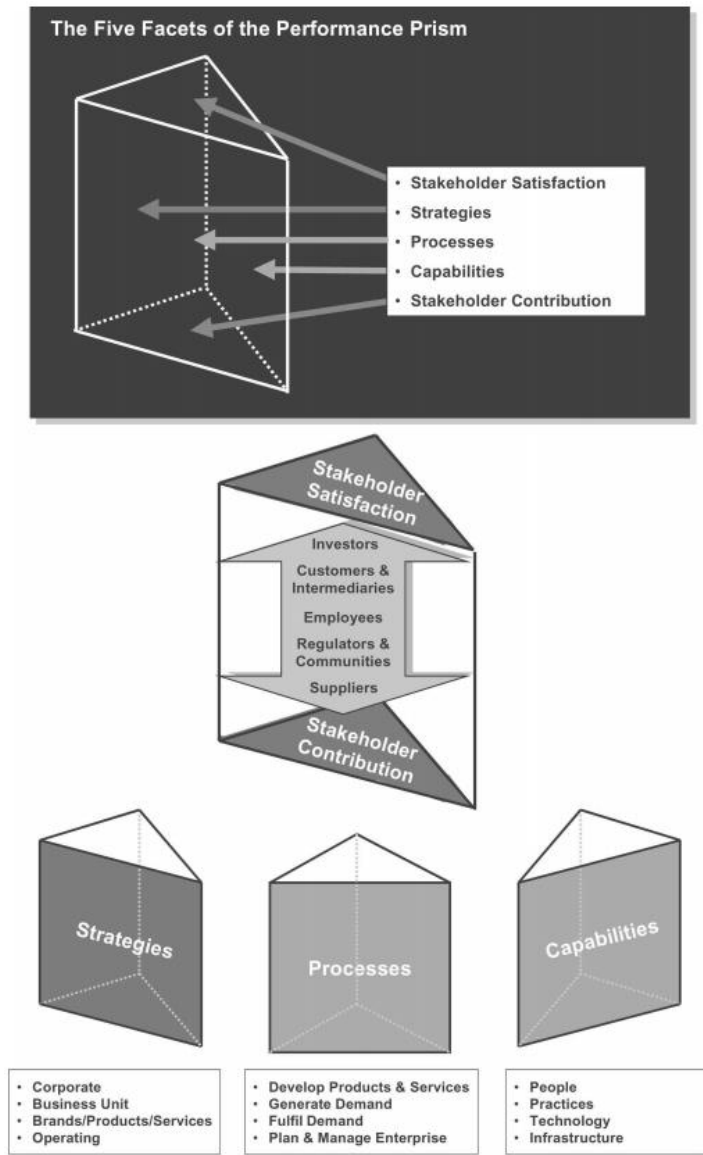


Figure 2.17: The Performance Prism  
(Source: Neely *et al.*, 2001, Appendix, p. 12).

### (XVI) The Integral Framework for Performance Measurement (IFPM)

IFPM (Rouse and Putterill, 2003) integrates *performance measurement*, *performance analysis* and *performance evaluation* functions under a single framework. The core of the framework covers process related elements, performance norms and measures. This core is encapsulated via several concentric circles. The first circle integrates *planning*, *evaluation*, *resource utilization* and *achievements*. The second circle integrates *organizational culture/structure*, *objectives* and

resource capacity, which are important factors in terms of organizational objectives and strategic outcomes. The final circle completes the overall framework while forming an interface between stakeholders' expectations, the organization's visions/goals, contributions and benefits as shown in Figure 2.18 (shown below):

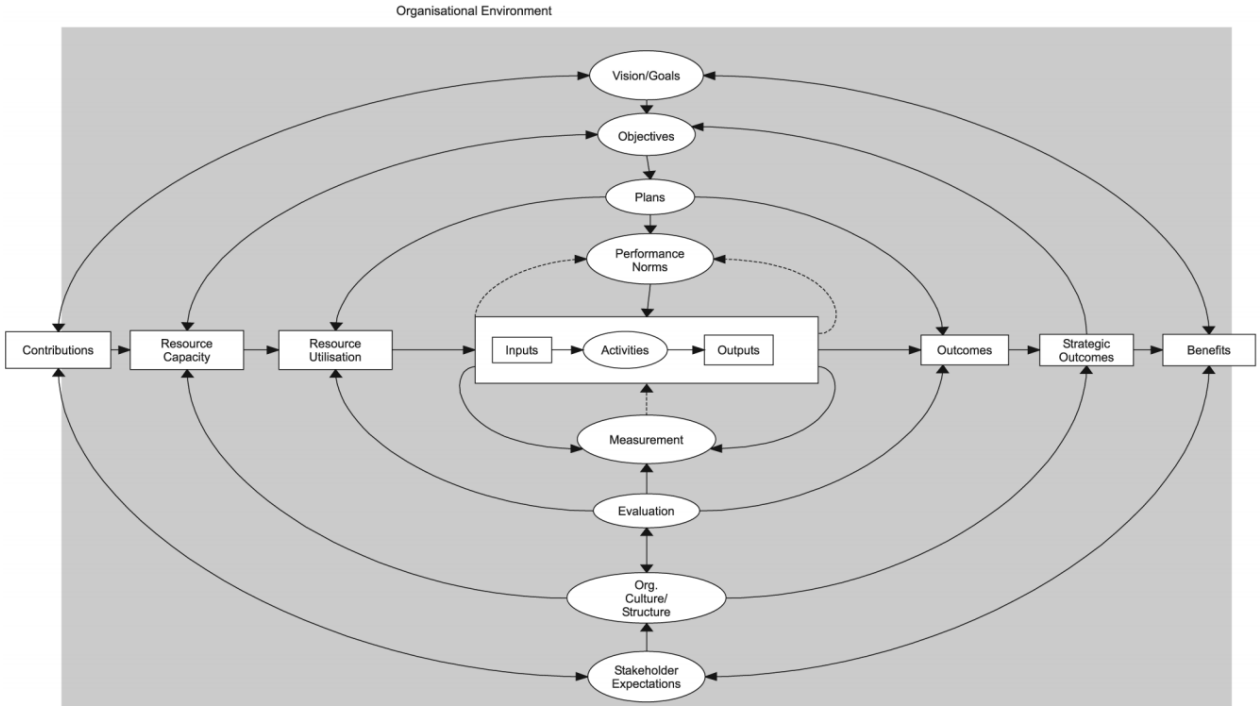


Figure 2.18: Complete view of the Integral Framework (Source: Rouse and Putterill, 2003, Figure 4, p. 799).

Integration amongst these levels has been established through a set of principles and by following a systematic structure. This is one of the main strengths of the method. In this way, the IFPM addresses both micro and macro levels, whilst at the same time provides a holistic view (Rouse and Putterill, 2003).

Bititci *et al.* (2000) summarized existing integrated performance measurement frameworks while highlighting the core functionalities required of a dynamic performance management system.

Table 2.3 (shown on page 43) a brief summary of the major performance measurement frameworks is provided and in Table 2.4 (shown on page 44), selected functionalities of existing methods based on the comparison criteria of Bititci *et al.* (2000) are compared.

Table 2.3: A comparison of major performance measurement frameworks<sup>(\*)</sup>

Framework	Performance dimensions	Framework typology	Link/suggestion to other measurement processes	Sustainability link/extension
The Du Pont Analysis (Kaplan, 1984; Neely <i>et al.</i> , 2005)	Return On Equity (ROE) and Return On Investment (ROI); profitability, financial efficiency and financial leverage factors, etc.	Structural	-	Yes
The Performance Measurement Matrix (Keegan <i>et al.</i> , 1989)	Costs external (i.e. competition and R&D); costs internal (i.e. design, material and production); non-financial internal environment (i.e. cycle time, on-time delivery and throughput); and non-financial external environment (i.e. number of customers, customer satisfaction and market share). <sup>(*)</sup>	Structural	No <sup>(*)</sup>	
The Performance Measurement Questionnaire (Dixon <i>et al.</i> , 1990)	Internal control, external control; alignment analysis, congruence analysis, consensus analysis and confusion analysis.	Structural	-	
Strategic Measurement Analysis and Reporting Technique (SMART) – Performance Pyramid (Cross and Lynch, 1989; Lynch and Cross, 1992)	Corporate vision/strategy; business unit: Market objectives, financial objectives; Business Operation System: Customer satisfaction, flexibility and productivity; Department and work center: Operational objectives, quality, delivery, cycle time and waste; Operations: Operational priorities. <sup>(*)</sup>	Structural	No <sup>(*)</sup>	
The Results and Determinants Framework (Fitzgerald <i>et al.</i> , 1991)	Results (financial performance and competitiveness); determinants (quality, flexibility, resource utilization and innovation). <sup>(*)</sup>	Structural	No <sup>(*)</sup>	
The Balanced Scorecard (Kaplan and Norton, 1992, 1996 and 1997)	Financial, internal business, customer perspective, innovation and learning. <sup>(*)</sup>	Structural – supported by procedural framework	No <sup>(*)</sup>	Yes
The Pyramid of Organizational Development (Flamholtz, 1995)	Organizational development/success factors (corporate culture, management systems, operational systems, resource management, product and services and markets); financial performance (EBIT), and profitability.	Structural	Yes	
Cambridge Performance Measurement Design Process (Neely <i>et al.</i> , 1995, 1996 and 2005)	Internal, external, financial and non-financial elements.	Structural	Yes	
The Integrated Dynamic Performance Measurement Systems (Ghalayini <i>et al.</i> , 1997)	Financial measures (i.e. sales, market shares and profits), operational measures (i.e. on-time delivery, cycle-time variability and machine breakdowns, etc.), management, corporate strategy and shop-floor activities/performance.	Procedural	No	
The EFQM Excellence Model (EFQM, 1999 and 2013)	Enablers (leadership, people management, policy and strategy, resources and processes); results (people satisfaction, customer satisfaction, impact on society and business results). <sup>(*)</sup>	Structural	No <sup>(*)</sup>	Yes
Integrated Performance Measurement Systems Reference Model (Bititci and Carrie, 1998; Bititci <i>et al.</i> , 1997, 1998 and 2000)	Key factors: Stakeholders, control criteria, external measures, improvement objectives and internal measures. Hierarchical levels: Corporate, business unit, business processes and activities.	Procedural	Yes (Requirements for as integrated performance measurement framework)	Yes
The Integrated Performance Measurement Framework (Medori and Steeple, 2000)	Quality, cost, flexibility, time, delivery and future growth.	Procedural		
The Performance Prism (Neely <i>et al.</i> , 2000, 2001 and 2002)	Stakeholders satisfaction, strategies, processes, capabilities and stakeholder contribution. <sup>(*)</sup>	Structural	No <sup>(*)</sup>	Yes
Internal Framework for Performance Measurement (Rouse and Putterill, 2003)	Structure, processes, input, output, outcome and potential others. <sup>(*)</sup>	Structural	Yes (principles) <sup>(*)</sup>	Yes

<sup>(\*)</sup> Source: Folan and Browne (2005) Table 2, p. 667; Anderson and McAdam (2004), Table II, pp. 470-471.

Table 2.4: A comparison among selected performance measurement frameworks (\*)

Requirement <sup>6</sup>	PMM	PMQ	SMART	RDF	BSC	POD	CPMS	IDPMS	EFQM	IPMS	AM	QMPMS	IPMF	PP	IFPM
External control system	×	×	×	×	×	×	×	×	✓	✓	×	×	×	✓	✓
Review mechanism	Ltd	×	×	×	×	×	✓	×	Ltd	×	×	×	✓	Ltd	✓
Casual relationships	Ltd	×	✓	Ltd	✓	✓	✓	×	✓	✓	×	✓	×	✓	Ltd
Quantify critically	×	×	×	×	×	✓	×	×	Ltd	×	×	✓	×	×	×
Internal control system	×	×	×	×	×	×	Ltd	×	✓	×	✓	×	✓	✓	✓
Look-ahead mechanism	×	×	×	×	×	×	×	×	✓	×	✓	×	Ltd	×	×

(\*) Adopted from Table I, p. 699, Bititci *et al.* (2000).

#### Abbreviations

PMM: The Performance Measurement Matrix (Keegan *et al.*, 1989);

PMQ: The Performance Measurement Questionnaire (Dixon *et al.*, 1990);

SMART: The Strategic Measurement Analysis and Reporting Technique (Cross and Lynch, 1989; Lynch and Cross, 1992);

RDF: The Results and Determinants Framework (Fitzgerald *et al.*, 1991);

BSC: The Balanced Scorecard (Kaplan and Norton, 1992, 1996 and 1997);

POD: The Pyramid of Organizational Development (Flamholtz, 1995; Flamholtz and Hua, 2002);

CPMS: The Cambridge Performance Measurement Design Process (Neely *et al.*, 1995, 1996a and 2005);

IDPMS: Integrated Dynamic Performance Measurement Systems (Ghalayini *et al.*, 1997);

EFQM: The Business Excellence Model of the EFQM (EFQM, 1999 and 2012);

IPMS: Integrated Performance Measurement Systems Reference Model (Bititci and Carrie, 1998; Bititci *et al.*, 1997, 1998 and 2000);

AM: Active Monitoring (Turner and Bititci, 1998; Bititci *et al.*, 1998);

QMPMS: Quantitative Model for Performance Measurement Systems (Suwignjo *et al.*, 1997 and 2000; Bititci *et al.*, 1998);

IPMF: The Integrated Performance Measurement Framework (Medori and Steeple, 2000);

PP: The Performance Prism (Neely *et al.*, 2001 and 2002);

IFPM: The Internal Framework for Performance Measurement (Rouse and Putterill, 2003).

<sup>6</sup> Requirements briefly refer to the core requirements of dynamic performance measurement systems. According to Bititci *et al.*, 2000:

*An external control system* refers to the continuous monitoring of developments and changes in the external environment;

*Review mechanism* refers to the use of information provided by the internal and external monitors, objectives and priorities in order to modify, set or decide internal objectives and priorities; namely a feedback mechanism;

*Casual relationships* is about facilitating integrated relationships between measures;

*Quantify criticality* refers to a system's capability of quantifying casual relationships;

*Internal control system* refers to successful deployment/prioritization of revised and updated objectives to the related organizational position;

*The look-ahead mechanism* is linked to having a focus on future performance.

## 2.6 Future trends in performance measurement system development

Beginning in the 1980s, the concept of performance measurement has changed rapidly. Over the years, the complexity has shifted from performance recommendations towards an organizational and dynamic structure, where multiple performance dimensions have been integrated. According to Folan and Browne (2005) and Pavlov and Bourne (2011), the future of performance measurement is evolving into inter-organizational performance management systems where organizations are evaluated as complete dynamic entities while considering both internal and external impacts. The evolutionary process of performance measurement is shown in Figure 2.19 (shown below):

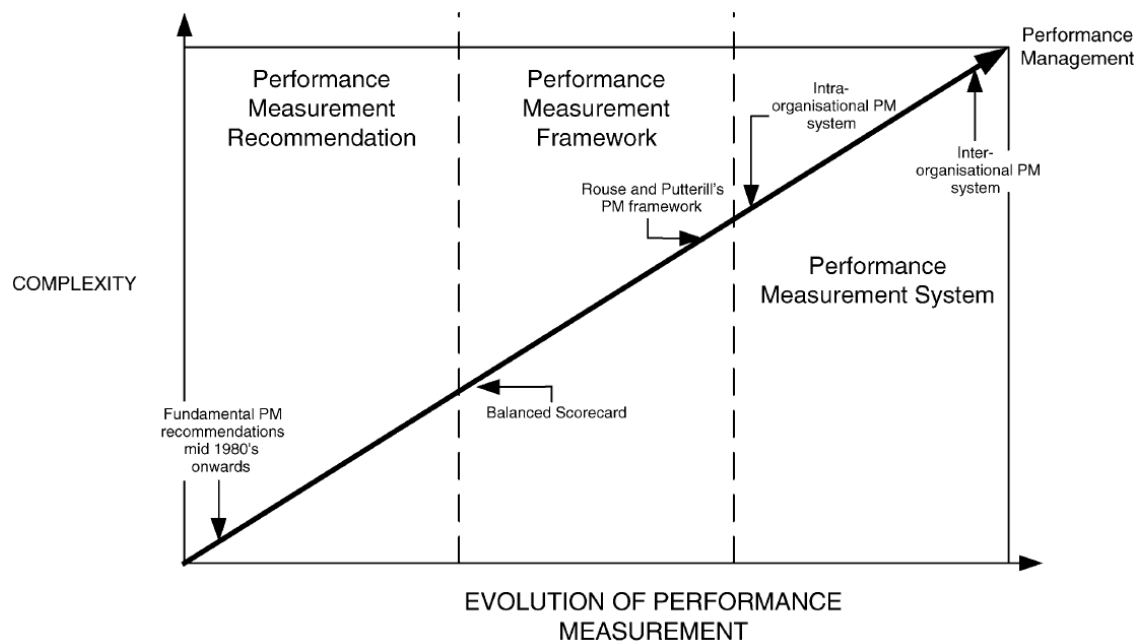


Figure 2.19: The evolutionary process of performance measurement  
(Source: Folan and Browne, 2005, Figure 3, p. 675).

The amount of performance management literature is somewhat extensive and is still currently under development. The limitations of the traditional measurement frameworks led the researchers to focus on multi-dimensional and dynamic performance management systems with integrated features. Moreover, there is an increasing interest in market-oriented performance frameworks and related external indicators, such as service quality and customer satisfaction. Neely (2005) identified that market-oriented indicators such as customer satisfaction and market orientation are one of the most used measures among other influential performance metrics (Based on a study covering 6,618 papers published in 546 journals) (see Figure 2.20 on page 46).

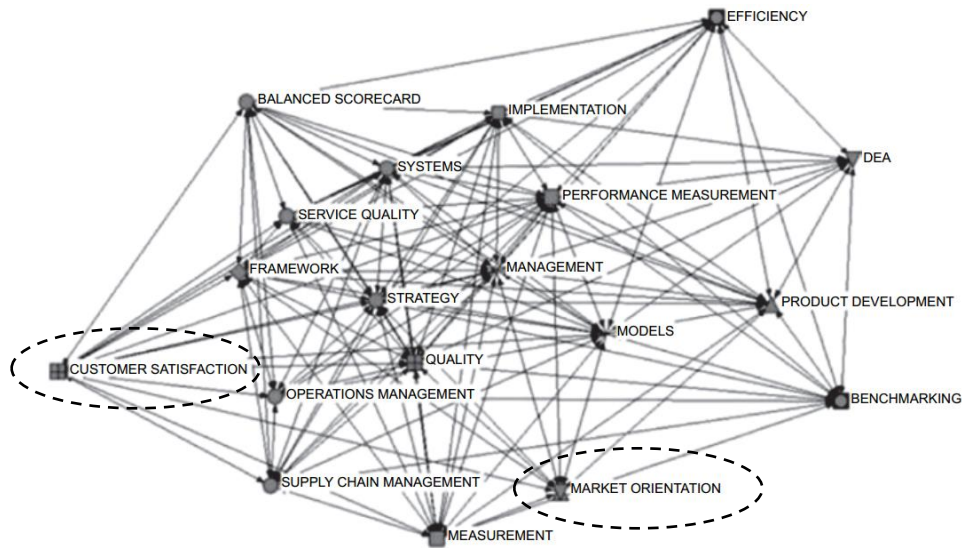


Figure 2.20: Keyword analysis based on most influential works  
 (Source: Taticchi *et al.*, 2010, Figure 6, p. 9).

A considerable amount of performance measurement literature surrounds the development of performance measurement systems and metrics for supply chains (Shepherd and Günter, 2006, pp. 244-246). In recent years, supply chain improvement and the evaluation supply chain performance has received much attention from researchers. Neely (1999), Beamon (1999), Beamon and Chen (2001), Gunasekaran *et al.* (2001), Shepherd and Günter (2006) and Li and Kumar (2005 and 2007) provided a comprehensive overview of supply chain performance measurement systems while highlighting the importance of the topic and the emerging need for further developments in this field. The measurement and management of performance at supply chain level is complex compared to performance measurement at company level. The overall performance of the entire supply chain is affected by the performance of each member in the supply chain (i.e. supplier performance, buyer performance) (Tan *et al.*, 1999). In this regard, supply chain performance measurement is not only about improving performance within a company, but also about the assessment of factors outside of a company's boundaries where the scope is expanded from inter-company performance to inter-supply chain performance (Chen and Paulaj, 2004, p. 122).

Despite the popularity of performance measurement systems in supply chain management, related literature still lacks system thinking (Chan and Qi, 2003) and dynamic alignment of performance measurement systems over time (Bourne *et al.*, 2000). Recently, the majority of performance measurement systems for supply chains tend to be static rather than dynamic. Although this issue has been recently addressed (Akyuz and Erkan, 2010; Bititci *et al.*, 2005;

Jammerneegg and Kischka, 2005; Nudurupati and Bititci, 2005) there is still a gap in the literature. Greater attention from researchers should be paid to time based dynamic performance measurement systems for evaluating the performance at both supply chain and company level (Shepherd and Günter, 2006, pp. 243, 247 and 252). Although recent developments are surrounding the supply chain level, there is still need for further developments at the company level.

Another popular topic is the Sustainability Performance Measurement Systems (SPMS). The sustainability concept in performance management and measurement has been the subject of a growing amount of research (Searcy, 2012; Bititci *et al.*, 2011a and 2011b; Schaltegger *et al.*, 2011; Schaltegger and Wagner, 2006). According to Hubbard (2009, p. 117) the sustainability concept has dramatically changed and widened the scope of organizational performance measurement. The sustainability performance measurement links economic, environmental and social performance aspects with business performance and competitive strategy (Figge *et al.*, 2002). In this direction, sustainability performance measurement is distinguished from traditional performance management in terms of measuring the systems' ability to adapt to environmental, social and economic changes and continue its function over a long term (Searcy, 2012, p. 240).

Environmental and social aspects of performance management have been extensively discussed in academic literature. A number of methods have been proposed to cover sustainability issues (Singh *et al.*, 2012). Chee Tahir and Darton (2010) proposed *The Process Analysis Method* to measure and quantify the sustainability performance of business operations. Robert (2000) proposed a hierarchical model, *The System Model*, to link economic aspects of sustainable development with the elements and metrics of organizational performance (Hubbard, 2009). Some of the performance measurement systems, such as *Du Pont's Pyramid of Financial Ratios* and *Balanced Scorecard*, have already been applied to sustainability (Castro and Chousa, 2006, p. 324). One of the most extensively cited methods is the *Sustainability Balanced Scorecard Approach* where the classical four perspectives (i.e., financial, customer, internal process and learning and growth) of the Balanced Scorecard (Kaplan and Norton, 1992, 1996 and 1997) has been modified and extended to incorporate the sustainability concept (Searcy, 2012, p. 240; Schaltegger *et al.*, 2011; Sardinha and Reijnders, 2005; Figge *et al.*, 2002). Van Marrewick and Hardjono (2003) have focused on extending the quality process approach of the *Business Excellence Model* (EFQM, 1999 and 2012) in order to develop a sustainable measurement system based on quality management principles (Hubbard, 2009). The development of some performance measurement tools has been based on maintaining the sustainability of stakeholder relationships, which is related to corporate sustainability. According to Perrini and Tencati (2006,

pp. 296-298), a company's capability to continue operating over a long period of time depends on establishing and managing the relationship with stakeholders in an integrated way. During the last two decades, advanced integrated performance measurement frameworks, such as *The Performance Prism* (Neely *et al.*, 2000, 2001 and 2002), *The Integrated Performance Measurement System* (Bititci and Carrie, 1998; Bititci *et al.*, 1997 and 1998) and the *Integral Framework for Performance Measurement* (Rouse and Putterill, 2003) have been proposed to integrate the stakeholder's perspective to contribute to sustaining the long-term success and survival of companies (Garengo *et al.*, 1995, p. 31; Castro and Chousa, 2006, p. 326).

Existing sustainability performance evaluation systems have been criticized for mainly two aspects: (i) addressing predominantly environmental and social aspects, but putting less emphasis on the financial side; (ii) focusing on global sustainability, reporting and external functions, while putting less emphasis on internal processes and the practical aspects of performance measurement (Staniskis and Arbaciauskas, 2009, p. 43). Literature highlights the link between financial performance and environmental/social performance. However, Castro and Chousa (2006, pp. 322-323) draw attention to the paucity of existing performance frameworks, incorporating the impact of sustainability issues on financial performance. According to the authors, an integrated framework is required to integrate the social, environmental and economic performance of a company. According to Sigh *et al.* (2012) and Robert (2000, p. 243) most of the sustainability assessment methodologies focus on the development of various sustainability indices and composite indicators (see Sigh *et al.*, 2012 for a detailed overview of sustainability indices). However, a list of business sustainability indicators has been criticized for having no clear and detailed guidance for their implementation in practice (Veleva and Ellenbecker, 2001, p. 523). Environmental and social performance models have also been criticized for their subjectivity and lack of focus in helping identify performance changes and performance improvement options (Staniskis and Arbaciauskas, 2009, p. 45). According to Sardinha and Reijnders (2005, p. 74), sustainability performance evaluation systems should focus on a company's current and intended future performance with the goal of increasing effectiveness and maintaining the long-term durability of performance improvement. In this regard, rather than focusing on social and environmental aspects, this study focuses on maintaining long-term sustainability in terms of financial and operational aspects. The performance evaluation framework addresses sustainability in terms of incorporating financial aspects, operational efficiency and customer satisfaction in the long-term.

With regards to the development and design of next generation integrated performance management systems, several researchers have provided detailed insights into how the

framework development should be modified to answer the needs of performance measurement literature (Dixon *et al.*, 1990; Ghalayini and Noble, 1996; Bititci *et al.*, 2000; Santos *et al.*, 2002; Neely *et al.*, 2005; Neely, 2005; Neely *et al.*, 1996b). In this direction, we highlight some features and characteristics have been highlighted as they are related to the objectives of this research study:

- A performance measurement system should be a dynamic system (Bititci *et al.*, 2000) while at the same time be responsive to changes in the system (Gregory, 1993; Ghalayini *et al.*, 1997).
- Casual relationships between performance metrics should be covered (Ittner and Larcker, 2003).
- A performance measurement system should involve short-term and long-term measures. Since relying on static performance measurement systems has negative effects on the responsiveness of the organization (Bititci *et al.*, 2000; Ghalayini *et al.*, 1997).
- A performance measurement system should provide a rapid response to changes in the organizational environment (Bititici *et al.*, 1997; Medori and Steeple, 2000).
- A performance measurement system should focus on internal organization as well as external environment. Therefore, performance measurement systems are required to be internally and externally responsive (Gomez *et al.*, 2011; Folan and Browne, 2005; Maskell, 1991).
- External comparisons and non-financial targets should be considered as a part of the performance measurement activity (Neely *et al.*, 2005, p. 1249).
- A performance measurement system should be a strategic framework while covering multiple decision criteria and various performance factors at different levels of the organizational hierarchy (Folan and Browne, 2005; Grünberg, 2004; Ittner and Larcker, 2003; Ghalayini *et al.*, 1997; Neely *et al.*, 1995).
- In this direction, performance measurement design should shift its focus from tangible assets to intangible assets. Assets such as *customer relationships*, *innovative services*, *responsive operational processes*, *motivation* and *satisfaction* are the major source of competitive advantage (Anderson and McAdam, 2004). Thus, a performance measurement system should

have a customer-oriented focus and should target improving customer satisfaction and increasing customer loyalty (Folan and Browne, 2005; Band, 1990).

- Both financial and non-financial performance dimensions should be covered. Since non-financial measures affect future financial results (Ittner and Larcker, 2003; Maskell, 1991; Kaplan and Norton, 1996). Explicitly, time should be included as a strategic performance measure (Ghalayini and Noble, 1996).
- Performance measurement should be long-term oriented and focus on future performance (Santos *et al.*, 2007). Because current measures and practices are mostly short-term oriented and do not support the improvement of future performance (Ghalayini and Noble, 1996).
- A performance measurement system should have a continuous review mechanism in order to observe changes in the system and provide an early warning for potential problems (Folan and Browne, 2005; Band, 1990). Most of the current performance practices have a limited revision mechanism (Bititci *et al.*, 2000).
- A performance measurement system should support the continuity of improvements. Most methods do not have a continuous improvement mechanism (Maskell, 1991; Kaplan and Norton, 1992 and 1997; Neely *et al.*, 1997; Medori and Steeple, 2000; Folan and Browne, 2005).

## Chapter 3

# Theoretical Framework

### 3.1 Theory foundation and perspective

Most performance measurement frameworks in literature either indicate a very general perspective of performance or have a certain diversification on a specific set of measures (Grünberg, 2004):

- Some of these frameworks have a focus on operational measures (Bilberg *et al.*, 1994; Waters, 1999; Reiner *et al.*, 2006; Gunasekaran *et al.*, 2001);
- A group of studies covers only customer-oriented measures (Bhagwat and Sharma, 2007; Reiner, 2005; Reiner and Natter, 2007; Beamon, 1999; Gunasekaran *et al.*, 2001);
- Some other frameworks only use financial measures (Ketchen *et al.*, 2008; Gong, 2008; Kojima *et al.*, 2008; Cormican and Cunningham, 2007; Heshmati, 2000).

As Bhagwat and Sharma (2007) mentioned, *‘These methods offer relatively blunt tools that offer a one-dimensional view, of little help to practitioners’*. On the other hand, integrated performance frameworks combine and integrate several performance aspects while overcoming the myopic perspective of these performance measurement frameworks.

Today’s organizations are highly dynamic systems; and are part of non-stable, complex environment where certain factors interact dynamically. Thereby, performance management has become an evolving, learning, dynamic process (Gomes *et al.*, 2011). Companies need to cover all dimensions of the business in order to identify overall performance strengths and weaknesses, which are possible through an effective, integrated performance management system.

The first generation of integrated performance measurement frameworks was '*structural frameworks*'. It was not dynamic; and not adaptive to organizational changes and market conditions; it also lacked a feedback/learning mechanism (Ghalayini *et al.*, 1997; Folan and Browne, 2005; Gregory, 1993).

A modern performance measurement/management system is defined as: A '*balanced*' and '*holistic*' system (Neely, 2002; Taticchi *et al.*, 2010) of several performance dimensions and metrics (Kaplan and Norton, 1996) supported by a dynamic infrastructure, which allows continuous monitoring, reviewing, improvement of objectives and priorities (Bititci *et al.*, 2000).

There are only a few '*procedural frameworks*' where the measurement process is supported by feedback (*see Table 2.4 on page 44*). Only a handful of studies establish dynamic interactions and performance trade-off characteristics as a closed-loop performance measurement framework (Reiner, 2005; Bhagwat and Sharma, 2007; Gunasekaran *et al.*, 2001).

As Souza *et al.* (2000, p. 348) mentioned: "*As long as causal factors and their related roles in overall dynamics are identified and quantitatively measured, then it would be possible to reach significant performance improvements by the elimination or reduction of relevant dynamics.*"

What is missing is a dynamic, closed-loop, time-based framework that continuously improves performance measures based on feedback and modifications while being adaptive and responsive to changing organizational needs, strategy, market conditions and customer expectations over time (Neely *et al.*, 2000; Santos *et al.*, 2002; Anderson and McAdam, 2004; Grünberg, 2004; Li *et al.*, 2005 and 2007).

This framework development<sup>7</sup> is structured based on this fact. In this regard, it is accepted that the performance measurement is a simultaneous and continuous process. A dynamic, closed-loop performance management framework was designed, which is adaptive to changing customer satisfaction while covering performance interactions and trade-off characteristics.

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<sup>7</sup> Note: Fundamentals of model development is firstly introduced in: '*Evaluation of the Dynamic Impacts of Lead Time Reduction on Finance Based on Open Queueing Networks*', (Gläßer *et al.*, 2010a) as well as presented '*Evaluation of Financial Impacts of Lead-Time Reduction*' (Gläßer *et al.*, 2010b).

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## 3.2 Development of the theoretical framework

In this section the focus is mainly on operational, customer-oriented and financial performance dimensions by explaining the idea behind the model development.

An overview of the relevant input parameters of the framework is given in Table 3.1 (*shown below*):

Table 3.1: Parameters of the dynamic integrated performance evaluation framework

Parameter	Explanation
$W$	actual waiting time
$r_{int}$	annual interest rate
$A$	assumed worth of customers time
$c_{retention}$	average customer retention cost (per customer)
$\lambda$	average repurchase cycle
$t$	average waiting time
$b$	batch size
$T_o$	customer's expectation for the waiting time
$D$	demand
$\gamma$	effect of the expected waiting time on satisfaction
$r$	extend of customer's risk awareness in term of time
$h_k$	holding cost for product $k$
$c_i$	interarrival time variation coefficient
$ir$	investment ratio
$LC_l$	labor $l$ cost
$IC_m$	machine $m$ idle cost
$RC_m$	machine $m$ running cost
$MP$	market potential
$a$	marketing effectiveness
$Inv_k$	mean inventory level of product $k$
$B$	number of backorders during the production period
$NC_0$	number of customers at time $t=0$
$m$	number of machines (parallel resources)
$n_i$	number of labor
$N_k$	number of setups for product $k$ during the period (total demand / batch size)
$c_{penalty}$	penalty cost per backorder
$p$	price
$T_{pp}$	production period of one year in minutes
$r_t$	run time per piece
$\rho_m$	run utilization for machine $m$
$c_p$	service time variation coefficient
$c_{km}$	setup cost for a batch of product $k$ on machine $m$
$St_b$	setup time (batch)
$WIP_k$	total WIP for product $k$
$WLT_b$	waiting time for labor (batch)

### 3.2.1 Operational performance measurement development

Improving the overall performance is possible through effective reduction of lead time and understanding the relationship between lead time and related factors (Hopp and Spearman, 2000). However, lead time and related factor interactions are often misunderstood or misinterpreted (Suri, 1998; Reiner, 2010; De Treville *et al.*, 2006).

Many managers believe in keeping resource utilization high will accelerate production and increase throughput; or using large batch sizes in order to increase capacity and reduce setup costs. In fact, this type of managerial thinking ignores the functional dependencies between lead time, capacity utilization and variability (Karmarkar, 1987; Tersine and Hummingbird, 1995). Thereby, principles of Factory Physics and lead time related mathematical laws are included as a part of the model development. Furthermore, the principles of queuing theory and waiting line models (Eiselt and Sandblom, 2012) are used to model and analyze the waiting line system (i.e. customer arrival process, waiting of customers, service process, etc.).

During the modeling phase, a G/G/1 queuing system was used in which service times and inter-arrival times are general distributions (Bolch *et al.*, 2006, pp. 244-272).

Regarding the arrival and service processes, relevant input parameters are the production period ( $T_{pp}$ ), batch size ( $b$ ), the number of machines ( $m$ ), the inter-arrival time variation coefficient ( $c_i$ ), the service time variation coefficient ( $c_p$ ), setup time per batch ( $St_b$ ), run time per piece ( $r_i$ ), waiting time for labor for a batch ( $WLT_b$ ) (see Table 3.1 on page 53). Operational measures are given in Table 3.2 (see page 55).

Table 3.2: Operational measures

Parameter	Formulation	Explanation
$D$	$a + Bp$	demand for the multi-product case is defined as the function of price, where $\mathbf{a} = (a_1, \dots, a_n)$ is a vector of coefficients; $\mathbf{B} = [b_{ij}]$ is the matrix of price sensitivity (Talluri and Van Ryzin, 2005, p. 323)
$D_{UB}$	$\frac{T_{bb} \times m \times b}{St_b + (r_t \times b) + WLt_b}$	demand upper bound
$R_k$	$\frac{D}{T_{pp}}$	arrival rate for product $k$
$R_p$	$\frac{1}{\left(\frac{St_b}{b} + r + \frac{WLt_b}{b}\right)}$	production rate
$\rho$	$\frac{R_k}{R_p \times m} = \frac{D}{R_k \times m \times T_{pp}}$	utilization
$T_p$	$St_b + (r_t \times b) + WLt_b$	average processing time (batch)
$T_i$	$T_p \times \frac{\rho^{\sqrt{2(m+1)}-1}}{m(1-\rho)} \times \frac{c_i^2 + c_p^2}{2}$	average waiting time (batch)
$T$	$T = T_i + T_p$	average flow time (batch)
$T_{base}$	-	average flow time (batch) for the base case
$I_i$	$\frac{\rho^{\sqrt{2(m+1)}}}{(1-\rho)} \times \frac{c_i^2 + c_p^2}{2}$	average queue length
$WIP_k$	$T \times R_k$	total WIP for product $k$
$\Delta T$	$\frac{T}{T_{Base Case}}$	flow time difference

Demand for the multi-product case is defined as a function of price, where  $\mathbf{a} = (a_1, \dots, a_n)$  is the vector of coefficients;  $\mathbf{B} = [b_{ij}]$  is the matrix of price sensitivity (Talluri and Van Ryzin, 2005, p. 323):

$$D = a + Bp \quad (3.1)$$

Arrival rate for product  $k$  (Bolch *et al.*, 2006, p. 242):

$$R_k = \frac{D}{T_{pp}} \quad (3.2)$$

Production rate (or service rate; Bolch *et al.*, 2006, p. 242):

$$R_p = \frac{1}{\left(\frac{St_b}{b} + r_t + \frac{WLt_b}{b}\right)} \quad (3.3)$$

Utilization (Bolch *et al.*, 2006, p. 244):

$$\rho = \frac{R_k}{R_p \times m} = \frac{D}{R_p \times m \times T_{pp}} \quad (3.4)$$

Average processing time (batch) (Poiger *et al.*, 2010; Bolch *et al.*, 2006, p. 245):

$$T_p = St_b + (r_t \times b) + WLt_b \quad (3.5)$$

Average waiting time (batch) (Poiger *et al.*, 2010; Bolch *et al.*, 2006, pp. 247 and 270):

$$T_i = T_p \times \frac{\rho^{\sqrt{2(m+1)}-1}}{m(1-\rho)} \times \frac{c_i^2 + c_p^2}{2} \quad (3.6)$$

Average flow time (batch) (Bolch *et al.*, 2006, p. 245):

$$T = T_i + T_p \quad (3.7)$$

Average queue length (Bolch *et al.*, 2006, pp. 250-251):

$$I_i = \frac{\rho^{\sqrt{2(m+1)}}}{(1-\rho)} \times \frac{c_i^2 + c_p^2}{2} \quad (3.8)$$

Total WIP inventory for product  $k$  (Bolch *et al.*, 2006, p. 245; Little, 1961):

$$WIP_k = T \times R_k \quad (3.9)$$

Using the condition of stability ( $\rho < 1$ ) and the fact: ‘On average the number of jobs that arrive in a unit of time must be less than the number of jobs that can be process:  $R_k < R_p$ ’ (Bolch *et al.*, 2006, p. 244) the demand upper bound ( $D_{UB}$ ) is calculated as follows:

$$\rho = \frac{R_k}{R_p \times m} < 1 \quad (3.10)$$

$$\rho = \frac{R_k \times T_p}{b \times m} < 1, \text{ where } R_p = \frac{b}{T_p} \quad (3.11)$$

By replacing equation (3.2) with  $(R_k)$  and equation (3.5) with  $(T_p)$  in equation (3.11) we can get the following inequality:

$$\rho = \frac{\frac{D}{r_{pp}} \times [st_b + (rt \times b) + WLt_b]}{m \times b} < 1, \text{ and this leads to } D < \frac{T_{pp} \times m \times b}{st_b + (rt \times b) + WLt_b} \quad (3.12)$$

### 3.2.2 Customer-oriented performance measurement development

The second most important dimension is the customer-oriented performance. One fundamental market performance related metric is customer satisfaction. Satisfaction emerges as a result of a positive experience with a service or product (Lambin, 2000). What is of interest is the market related performance in terms of providing satisfaction and meeting customers' expectations. The model development is based on the connection between satisfaction, operational and financial performance.

#### I – Relation with operational performance

Market-oriented performance is connected to time-based measures. For instance, customer satisfaction is related to changes in waiting and lead times (Kalló and Koltai, 2010). Market shares can be very sensitive to the relative waiting times, especially in service-oriented industries. An example could be from the fast food industry highlights this fact: *'Seven seconds of waiting time reduction yields an average of one to twenty percent market share increase and fifteen percent improvement in sales,'* (Allon *et al.*, 2011). Therefore, delays and increased waiting times can have a negative impact on customer satisfaction, which also affects customer loyalty and sales (Pruyn and Smidts, 1998; Taylor, 1994; Bielen and Demoulin, 2007).

Customer satisfaction and productivity are connected. However, there are conflicting viewpoints on the dynamics of this relationship, whether customer satisfaction and productivity are compatible or conflicting (Anderson *et al.*, 1997, pp. 129-131). According to one school of thought, customer satisfaction and productivity are compatible and positively correlated. The operations research and production management perspective favors the positive relationship. Improving customer satisfaction improves productivity in terms of reduced extra time, resources and efforts (rework, corrective actions, aftersales services and the handling of customer complaints, etc.). Furthermore, there are cost based savings (diminished return rates, reduced repair costs, reduced penalty costs, less handling costs for customer complaints and the reduced cost of attracting new customers due to positive word-of-mouth). On the other hand, from an

economic and marketing perspective, customer satisfaction and productivity are generally viewed to have a negative relationship (Anderson *et al.*, 1997, p. 131); as increasing customer satisfaction also increases expectations, which necessitates the dedication of extra effort, time and money for providing higher levels of service quality (see Figure 1, p. 132, Anderson *et al.*, 1997). The direction of customer satisfaction – productivity trade-off is not always clear and depends on the type of product/service provided. According to Anderson *et al.* (1997, p. 129), ‘both customer satisfaction and productivity are positively associated with ROI for goods and services, the interaction between customer satisfaction and productivity is positive for goods but negative for services’. As the authors highlighted, the conflicting relations is more dominant where customer satisfaction is dependent on customization or when providing customization is relatively difficult or costly. This is especially the case for the service industry or for production companies where product attributes are important and customization is preferred by customers (private banking, private insurance; high-end fashion products or luxury goods, etc.). However, customization and productivity are more compatible (positively correlated) for industries where customer satisfaction is highly dependent upon the standardization of quality. Thereby, products are more likely to inherit these characteristics when compared to services (Fornell, 1992; Anderson *et al.*, 1997, pp. 129-142) (see Figure 3.1 shown below):

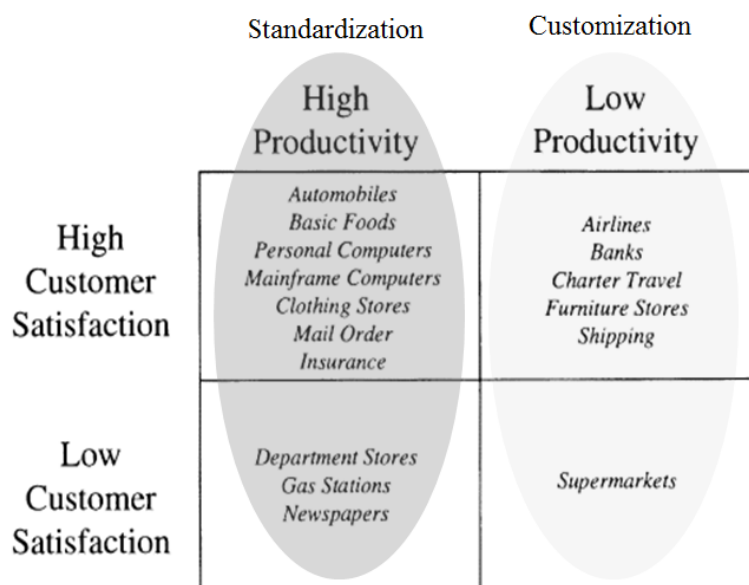


Figure 3.1: Customer satisfaction - Productivity trade-off based on earning of average ROI for different industries (Source: Anderson *et al.*, 1997, Figure 2, p. 140).

Customer satisfaction is also connected to other market-oriented performance measures:

- Improving satisfaction also improves customer loyalty (Szymanski and Henard, 2001; Oliver, 1997; Söderlung, 2006; and for an extended reference, see Anderson *et al.*, 1997, p. 130).

- Increased loyalties lead to higher levels of customer retention (Vanhamme and Lindgreen, 2001; Goderis, 1998).
- According to Rust and Zahorik (1993), customer satisfaction and customer loyalties are linked to market shares (Rust and Zahorik, 1993, p. 198).
- The level of satisfaction affects the buying behavior of customers (Anderson and Sullivan, 1993; Patterson and Spreng, 1997; Szymanski and Henard, 2001; Mittal and Kamakura, 2001; Olsen, 2002).
- According to Lambin (2000), there is direct relationship between customer satisfaction and repeated purchasing rate, as lower repurchase rates indicate lower satisfaction. Seider *et al.* (2005) proved that satisfaction is positively correlated to repurchase intention and moderated by customer and market characteristics (i.e. repeated repurchasing behavior, number of visits and money spent, etc., Seider *et al.* 2005, p. 27). Reinartz and Kumar (2003) and Gupta and Zeithaml (2006, p. 718) also highlighted this same fact.

In this regard, customer satisfaction and customer loyalty is highly related to the purchaser's motivation in terms of repeated purchasing behavior, which has a direct impact on sales, revenue and revenue growth (Rust *et al.*, 1993; Hellier *et al.*, 2003; Gupta and Zeithaml, 2006, p. 718). As Ittner and Larcker (1999, p. 32) expressed: '*... customer satisfaction measures are leading indicators of customer purchase behavior (retention, revenue, and revenue growth), growth in the number of customers, and accounting performance (business-unit revenues, profit margins, and return on sales).*'

However, the empirical link between customer satisfaction, buying behavior and customer demand has not yet been introduced (White and Yanamandram, 2007; Jammerneegg and Kischka, 2005; Hellier *et al.*, 2003; Mittal and Kamakura, 2001; Olsen, 2002).

Some authors (Yang and Geunes, 2007) considered models where demand is influenced by the lead time. However, these studies are missing the dynamic aspects. Reiner (2005) demonstrated the impact process improvements on customer satisfaction, customer loyalty and financial indicators. On the other hand, the long-term impact of lead time reduction and the improvement of customer satisfaction on demand are open to further discussion.

## **II – The relationships with financial performance**

Improving customer satisfaction also has financial impacts (Heskett and Sasser, 2010; Mukherjee *et al.*, 2003; Rust *et al.*, 1995; Kamakura *et al.*, 2002; Silvestro, 2002; Keiningram *et al.*, 2006);

as customer satisfaction is significantly and positively correlated with financial performance (Anderson *et al.*, 1994; Fornell, 1992).

As noted by Neely (1999), improving customer satisfaction increases the average net income, as customer satisfaction is associated with return on investment (Neely, 1999, p. 209; Ittner and Larcker, 1998, pp. 3-4; Anderson *et al.*, 1994, p. 129).

Anderson *et al.* (1994) illustrated the impact of customer satisfaction on profitability, which is based on the data from Business Week 1000 firms: ‘... an annual one-point increase in the average firm’s satisfaction index would be worth \$94 million or 11.4 percent of current ROI,’ (Neely, 1999, p. 209).

According to Anderson *et al.* (1997, p. 130) and Rust *et al.* (1994 and 1995), higher levels of satisfaction and customer loyalty improves future revenue while reducing related costs. Improving satisfaction reduces the future costs of handling returns, customer complaints and penalty costs. Furthermore, marketing/advertising costs reduce due to improved customer loyalty (i.e. the positive word-of-mouth effect) since fewer efforts are required to attract customers.

Anderson *et al.* (1997), Reinartz and Kumar (2000 and 2003), Reichheld (2006) and Sulek *et al.* (1995) all highlighted the customer satisfaction and profitability link.

Rust *et al.* (1995) displayed the statistical relationship between customer satisfaction, customer retention, market share and profitability through a model (see Figure 3.2 shown below):

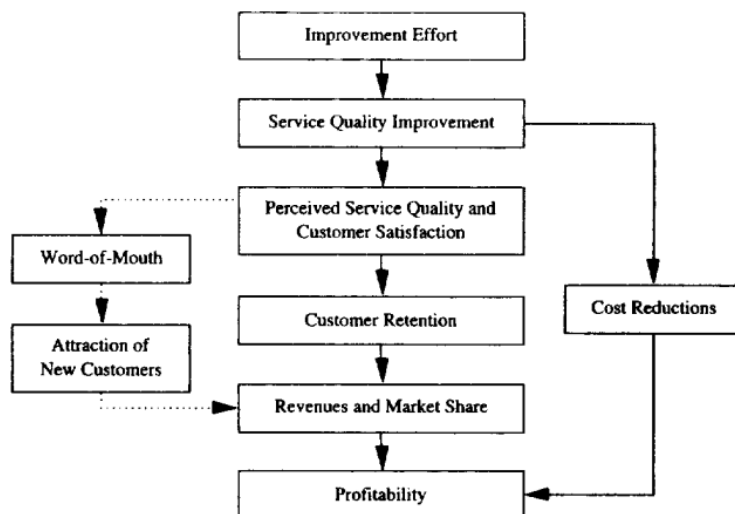


Figure 3.2: Model of Rust *et al.* (1995) on service quality improvement and profitability (Source: Rust *et al.*, 1995, Figure 1, p. 60).

Fornell (1992, p. 7) also highlighted the positive correlation between customer satisfaction and market shares. Mukherjee *et al.* (2003) and Gupta and Zeithaml (2006) emphasized the customer satisfaction – retention/loyalty – firm profitability connection (see Table 1, p. 725, Gupta and Zeithaml, 2006).

Edvardsson *et al.* (2000) analyzed the effects of satisfaction and loyalty on profits and the revenue growth of product and service firms (see Edvardsson *et al.*, 2000, Figure 1, p. 921 and Figure 2, p. 923).

Rust *et al.* (2002) analyzed the impact of cost and revenue emphasis on customer satisfaction and organizational performance. While cost emphasis initiates low effectiveness, low satisfaction and performance distortions; revenue emphasis initiates improved efficiency and greater satisfaction. According to Rust *et al.* (2002) significant financial gains are possible by focusing on revenue emphasis and market oriented initiatives such as customer satisfaction and customer retention (see Figure 3.3 shown below):

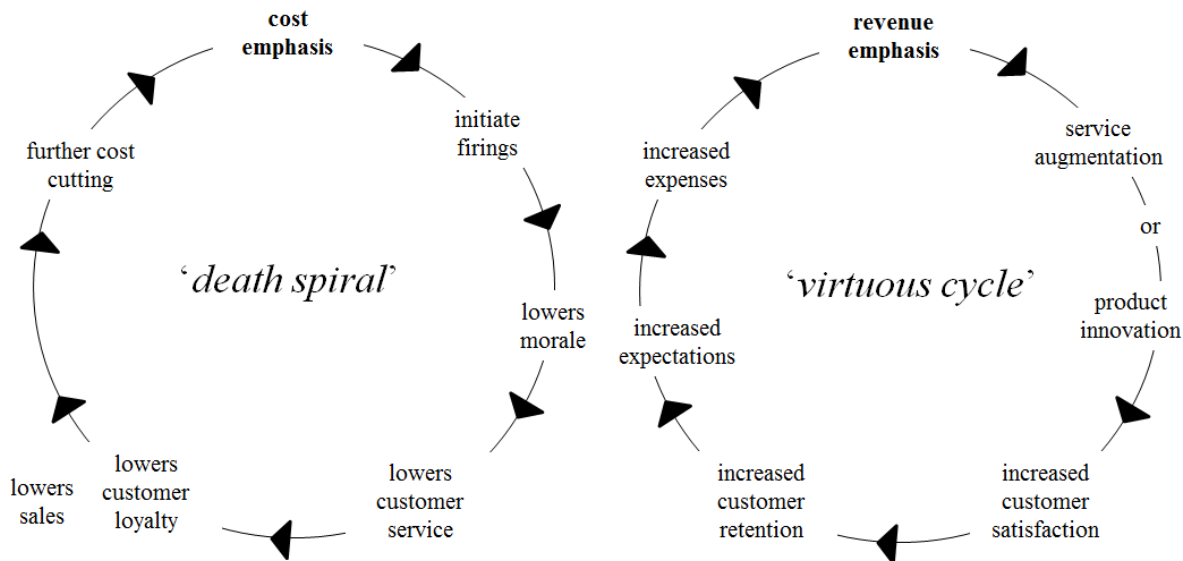


Figure 3.3: Cost (reduction) emphasis versus revenue (expansion) emphasis  
(Based on Rust *et al.*, 2002, Table 1, p. 8).

There have been further studies, which highlight the impact of nonfinancial measures on financial performance (Ittner and Larcker, 1996 and 1998; Gupta and Zeithaml, 2006; Ittner *et al.*, 2003).

According to Banker *et al.* (2000, p. 65): “Non-financial measures are better predictors of long-term financial performance than current financial measures; since customer-satisfaction measures are significantly and positively related to future financial performance, revenues and operating profit.”

Ittner *et al.* (2003) discussed non-financial – financial performance interaction from a global perspective. The authors analyzed the link between soft factors such as quality, innovation, risk, people and financial performance (*see Ittner et al., 2003, Figure 1, p. 733*).

Therefore, market related performance interactions motivate model development. Customer oriented measures of the model development here are provided in Table 3.3 (*shown below*):

Table 3.3: Customer oriented measures

Parameter	Formulation	Explanation
$S_0$	$-AT_0^Y e^{-rT_0}$	initial satisfaction
$S_1$	$-AT_0^Y e^{-rT_0} r$	variable satisfaction
$CS_t$	$S_0 + S_1 t = -AT_0^Y e^{-rT_0} - AT_0^Y e^{-rT_0} r t$	customer satisfaction
$CR_t$	$0.75 + 0.58 \times (CS_t - 0.67)$	customer retention
$NLC_t$	$\frac{NC_{t-\Delta t}}{\lambda} \times CR_{t-\Delta t}$	the number of loyal customers
$CN_t$	$\alpha(MP - NC_{t-\Delta t})$	new customers acquired
$CL_t$	$\frac{NC_{t-\Delta t}}{\lambda}$	number of lost customers
$NC_t$	$NC_{t-\Delta t} + (NLC_t + CN_t - CL_t)\Delta t$	number of customers

Both customer waiting and related impact on satisfaction can be expressed in different ways. In a recent study, Kalló and Koltai (2010) approximated customer satisfaction using a utility transformation of waiting time. According to Kalló and Koltai (2010, p. 114), *‘Utility related objective function may support queuing system changes even if the average waiting time does not improve.’* In this regard, the authors defined an average utility function (average satisfaction) of  $E(U)$  to represent the ‘waiting time – customer satisfaction’ relationship. Utility ( $U(W, T_0)$ ) is defined as a function of actual waiting time ( $W$ ), which is a stochastic variable and expected waiting time ( $T_0$ ). Thus, the expected utility is calculated by using the following equation:

$$E[U(W, T_0)] = -AT_0^Y e^{-rT_0} E[e^{rW}] \quad (3.13)$$

Kalló and Koltai (2010, pp. 114-115) used an exponential function ( $e^{rw}$ ) and an exponential transformation of waiting time to calculate the average satisfaction level. Therefore, the average customer satisfaction is formulated as a function of waiting time:

$$E[U(W, T_0)] = S_0 + S_1 t = -AT_0^Y e^{-rT_0} - AT_0^Y e^{-rT_0} r t \quad (3.14)$$

Where  $A$  represents the expected worth of customers' time;  $\gamma$  reflects the direct effect of the expected waiting time on satisfaction;  $T_0$  denotes the target waiting time;  $r$  is the extent of customers' risk averseness in terms of time and  $t$  represents the actual waiting time.

According to this formula, customer satisfaction is defined in two parts. The first part is the initial satisfaction level ( $S_0$ ) which is independent of the waiting time and reflects the expectations of customers. The second part ( $S_I$ ) is variable and dependent on waiting time.

Customer satisfaction has a direct impact on customer retention. In addition, the customers' repurchasing behavior and the company's financial results are affected by the level of satisfaction. According Anderson and Sullivan (1993) and Reiner (2005), the linear relationship between customer retention and customer satisfaction can be expressed as follows:

$$CR_t = 0.75 + 0.58 \times (CS_t - 0.67) \quad \text{for } t \geq 1 \quad (3.15)$$

The number of loyal customers (from period  $t-\Delta t$  to  $t$ ) is affected by three factors: The number of customers in period  $t-\Delta t$ ; the customer retention in period  $t-\Delta t$  and the average repurchase cycle ( $\lambda$ ) (Reiner and Natter, 2007):

$$NLC_t = \frac{NC_{t-\Delta t}}{\lambda} \times CR_{t-\Delta t} \quad \text{for } t \geq 1 \quad (3.16)$$

Similarly, the number of lost customers (from period  $t-\Delta t$  to  $t$ ) can be defined as the ratio of the number of customers in period  $t-\Delta t$  to average product lifecycle ( $\lambda$ ) (Reiner and Natter, 2007):

$$CL_t = \frac{NC_{t-\Delta t}}{\lambda} \quad \text{for } t \geq 1 \quad (3.17)$$

The acquisition of new customers (from period  $t-\Delta t$  to  $t$ ) is affected by the market potential ( $MP$ ), the number of customers in a time period  $t-\Delta t$  and the marketing effectiveness index ( $a$ ) (Reiner and Natter, 2007):

$$CN_t = a(MP - NC_{t-\Delta t}) \quad \text{for } t \geq 1 \quad (3.18)$$

According to the Bass-Model (Bass, 1969; Bass, 2004) there is a non-linear relationship between marketing effectiveness ( $a$ ), customer retention ( $CR$ ) and the average repurchase cycle ( $\lambda$ ):

$$\lambda^* = -\frac{1}{a + CR} \ln\left(\frac{a}{CR}\right) \quad (3.19)$$

Knowing the values of customer retention and average repurchase cycle, marketing effectiveness can be calculated as follows (Mahajan *et al.*, 1990, pp. 2-6; Mahajan *et al.*, 1993, p. 354):

$$a = e^{-\lambda^*(a+RT)\ln(RT)} \quad (3.20)$$

The main idea is based on the analysis of the cumulative number of customers and purchasing behavior over time. As indicated by Sultan *et al.* (1990, p. 70) and Mahajan *et al.* (1990):

$$\frac{dN(t)}{dt} = g(t)[N^* - N(t)] \quad (3.21)$$

Where  $\frac{dN(t)}{dt}$  is defined as the rate of diffusion at time  $t$ ; and  $N(t)$  is the cumulative number of customers at time  $t$ ; where  $N^*$  is the total number of customers and finally,  $g(t)$  is the rate of adaptation (Sultan *et al.*, 1990, p.70; Mahajan *et al.*, 1990, pp. 2-6).

There are three models of rate of adaptation: (i)  $g(t) = a$  is called the ‘*coefficient of innovation*,’ which represents an external influence; (ii)  $g(t) = RT \times F(t)$  is called the ‘*coefficient of imitation*,’ which represents an internal influence; and  $g(t) = a + RT[F(t)]$  is called the ‘*mix influence*,’ where the diffusion is driven by both innovation and imitation effects. In fact, the third model is the most suitable to define market growth (Sultan *et al.*, 1990, p.70; Mahajan *et al.*, 1990, p. 2). Based on this fact, Sultan *et al.* (1990) provided a meta-analysis involving two hundred and thirteen parameters from fifteen articles covering years from the 1950s until the 1980s. According to this study, the values of coefficient of innovation ( $a$ ) and the coefficient of imitation ( $RT$ ) vary within a broad range as shown in Table 3.4 (*shown below*):

Table 3.4: Reported ranges of coefficient of innovation and the coefficient of imitation <sup>(\*)</sup>

	Coefficient of innovation ( $a$ )	Coefficient of imitation ( $RT$ )
average	0.03	0.38
range	[0.000021, 0.03297]	[0.2013, 1.6726]
minimum observed value for $\lambda^* = 80$ years	0.00002	0.00003
maximum observed value for $\lambda^* = 1$ year	0.23	0.99

<sup>(\*)</sup> Source: Sultan *et al.* (1990) and Easingwood *et al.* (1987).

Based on Sultan *et al.*'s (1990) findings and using the *Bass Diffusion Model* (Bass, 1969; Bass, 2004; Sterman, 2000, p. 332) the number of customers (from period  $t-\Delta t$  to  $t$ ) is calculated as follows (Reiner 2005):

$$NC_t = NC_{t-\Delta t} + (NLC_t + CN_t - CL_t)\Delta t \quad \text{for } t \geq 1 \quad (3.22)$$

As a result, the acquisition of customers from period  $t-\Delta t$  to  $t$  is influenced by the number of customers in period  $t-\Delta t$  ( $NC_{t-\Delta t}$ ), the average repurchase cycle ( $\lambda$ ), market potential ( $MP$ ) and marketing effectiveness ( $a$ ):

$$NC_t = NC_{t-\Delta t} \times [0.75 + 0.58(CS_{t-\Delta t} - 0.67)] + a(MP - NC_{t-\Delta t}) - \frac{NC_{t-\Delta t}}{\lambda} \quad \text{for } t \geq 1 \quad (3.23)$$

The change in the number of customers from period  $t-\Delta t$  affects the demand of the next period  $t$ . Thus, the demand is expressed as a function of the number of loyal and new customers. This is motivated by the assumption of linear relationship between customers' repurchase likelihood and customer satisfaction (Auh and Johnson, 1997; Reiner, 2005).

Therefore, the increasing satisfaction level is expected to positively influence demand via increasing customer loyalty, increasing repurchasing rate and future sales (Reiner and Natter, 2007; Lambin, 2000). In this way, by connecting customer-oriented measures and external demand, the performance management framework forms a closed-continuous loop.

### 3.2.3 Financial performance measure development

The third dimension is the financial dimension. The connection between operational performance measures and financial measures is related to lead time principles. In this instance, emphasis is placed particularly on the impact of lead time reduction on work-in-process inventories (Little's Law: Little, 1961) and related inventory holding costs and penalty costs as well as other financial indicators such as profitability, capital turnover and return-on-investment (Hopp and Spearman, 2006).

Due to increased uncertainty, long lead times lead to increased inventory levels as well as increased cash-to-cash cycle times (Hammel *et al.*, 2002). By reducing variability and the average lead time, it is possible to reduce safety stocks and stock keeping costs while minimizing penalty costs without reducing the customer service level. In this regard, it is critical to integrate these dependencies into accounting processes. Since traditional cost accounting and reward systems fail to provide detailed insight by ignoring lead time related operational effects (Maskell and Kennedy, 2007; Suri, 1998). Furthermore, empirical studies highlight the connection between non-financial measures and future financial performance (Banker *et al.*, 2000; Ittner and Larcker, 1996 and 1998).

Market-oriented performance measures such as customer satisfaction and customer loyalties have an impact on a company's financial performance in terms of penalty costs, customer retention

costs and marketing costs. Acquiring new customers can be substantially costly compared to the cost of retaining and maintaining an existing customer (Mittal and Kamakura, 2001). There are also long-term effects of consumer satisfaction on revenues in terms of sales. Therefore, financial performance measures should be a starting point for the development of extended performance measurement models in conjunction with customer-oriented performance (Ghalayini and Noble 1996; Kaplan and Norton, 1997; Beamon, 1999; Neely, 1999; Li *et al.*, 2007).

Compared to previous studies where the benefits of lead time reduction are only shown through a few cost measures, the approach developed here provides a more detailed perspective by considering cost components that are directly and indirectly affected by the reduction of lead time. Financial measures of our model are given in Table 3.5 (*shown below*):

Table 3.5: Financial measures

Parameter	Formulation	Explanation
$C_t^{setup}$	$\sum_k \sum_m N_{k_{t-\Delta t}} \times c_{km}$	total setup cost
$C_t^{WIP}$	$\sum_k WIP_k \times h_k \times T_{pp}$	total WIP inventory cost
$C_t^I$	$\sum_k Inv_k \times h_k \times T_{pp}$	total finished goods inventory cost
$C_t^{inventory}$	$C_t^{WIP} + C_t^I$	total inventory cost
$C_t^{labor}$	$\sum_l LC_l \times T_{pp}$	total labor cost
$C_t^{machine}$	$\sum_m (\rho_m \times c_{run} + (1 - \rho_m) \times c_{idle}) \times T_{pp}$	total machine cost
$C_t^{penalty}$	$B_{t-\Delta t} \times c_t^{penalty}$	penalty cost
$C_t^{retention}$	$c_t^{retention} \times (5CN_t + NLC_t)$	customer retention cost
$C_t^{total}$	$C_t^{setup} + C_t^{inventory} + C_t^{labor} + C_t^{machine} + C_t^{penalty} + C_t^{retention}$	overall cost
$IN$	$P(D_t) \times ir$	process improvement investment
$R_t(D_{t-\Delta t})$	$D_{t-\Delta t} \times p(D_{t-\Delta t})$	revenue (Talluri and Van Ryzin, 2005)
$P(D_t)$	$R(D_t) - C_t^{total}$	profit (Talluri and Van Ryzin, 2005)

The cost system is composed of following components (based on Gläßer *et al.*, 2010a):

Total setup cost in period  $t$  for  $m$  machines and  $k$  products:

$$C_t^{setup} = \sum_k \sum_m N_{k_{t-\Delta t}} \times c_{km} \quad (3.24)$$

Total WIP inventory cost for period  $t$  for  $k$  products:

$$C_t^{WIP} = \sum_k WIP_k \times h_k \times T_{pp} \quad (3.25)$$

Total finished goods inventory cost for period  $t$  for  $k$  products:

$$C_t^I = \sum_k Inv_k \times h_k \times T_{pp} \quad (3.26)$$

Total inventory cost for period  $t$ :

$$C_t^{inventory} = C_t^{WIP} + C_t^I \quad (3.27)$$

Total labor cost for period  $t$ :

$$C_t^{labor} = \sum_l LC_l \times T_{pp} \quad (3.28)$$

Total machine cost for period  $t$ :

$$C_t^{machine} = \sum_m (\rho_m \times c_{run} + (1 - \rho_m) \times c_{idle}) \times T_{pp} \quad (3.29)$$

Penalty cost for period  $t$  is expressed by the number of backlogs for  $t - \Delta t$  and cost per backlog:

$$C_t^{penalty} = B_{t-\Delta t} \times c_t^{penalty} \quad (3.30)$$

Acquiring new customers is more costly than retaining an existing customer (Mittal and Kamakura, 2001; Reichheld, 1996). According to Rust *et al.* (1994) and Reiner (2005) the cost of acquiring a new customer is five times higher than cost of retaining an existing customer. Thus, companies can decrease marketing costs by improving their satisfaction and loyalty concept (customer retention costs versus the cost of acquiring new customers or marketing costs) (*see Reiner, 2005; Reiner et al., 2007; Bielen et al., 2007 for further details*).

In this direction, we define customer retention cost as follows:

Customer retention cost for period  $t$ :

$$C_t^{retention} = c_t^{retention} \times (5CN_t + NLC_t) \quad \text{for } t \geq 1 \quad (3.31)$$

Total cost for period  $t$ :

$$C_t^{total} = C_t^{setup} + C_t^{inventory} + C_t^{labor} + C_t^{machine} + C_t^{penalty} + C_t^{retention} \quad (3.32)$$

Process improvement investment is a function of profit and investment ratio where the value of investment ratio is determined by the company as seventeen percent:

$$IN = P(D_t) \times ir \quad (3.33)$$

In the model developed here, investment positively impacts capacity in terms of equipment reliability (Greenwood *et al.*, 1988). Investment has direct effects on operational efficiency and indirect effects on profitability and future investments opportunities (Lambin, 2000).

The revenue of a period  $t$  is defined as a function of price  $p(D_{t-\Delta t})$  and the demand ( $D_{t-\Delta t}$ ) of a previous period  $t-\Delta t$  (Talluri and Van Ryzin, 2005, p. 315):

$$R_t(D_{t-\Delta t}) = D_{t-\Delta t} \times p(D_{t-\Delta t}) \quad (3.34)$$

Several profit functions have been defined within literature. Among these functions the gross profit function was used (gross profit = net sales revenue – COGS, Talluri and Van Ryzin, 2005):

$$P(D_t) = R(D_t) - C_t^{total} \quad (3.35)$$

In Figure 3.4 (*shown on page 70*), dynamic impact of lead time reduction on non-financial and financial facets of performance is illustrated based on the make-to-stock manufacturing strategy. Make-to-stock strategy was selected due to its wide use and as it is a well-established manufacturing strategy for several companies (Hofmann and Reiner, 2006).

On the operational side, the framework focuses particularly on lead time related factor interactions. Lead time and work-in-progress inventories are linked based on Little's Law (Little; 1961). Particularly in a make-to-stock environment, customer service levels are highly dependent on lead time and inventory levels (*see Equation 2.3 and 2.4 on page 19*). Reducing (replenishment) lead times reduces the safety inventory level and tied capital (finished goods inventory) while reducing inventory and penalty costs. On the market side, reduced lead time improves customer service levels while positively influencing customer satisfaction and loyalty. Thereby, reducing marketing and overall costs. In the long term, future sales, and thereby demand is affected while leading to improved financial performance in terms of profitability and revenue.

This framework covers the major metrics interactions for each performance dimension. However, it should not be accepted as a panacea, which will be an answer to all performance measurement related problems. Development of this framework is the first step towards a comprehensive evaluation. For each performance dimension, essential metrics are covered in order to illustrate the usefulness and criticality of dynamic interactions.

In particular, covering a set of interactions between time-based, non-time-based and financial performance metrics provides a detailed picture of trade-off characteristics and the effects of lead time improvements over time, based on a *closed-loop dynamic performance evaluation approach*. The vast majority of modern lead time reduction models do not consider long-term effects and the dynamics of lead time reduction on demand.

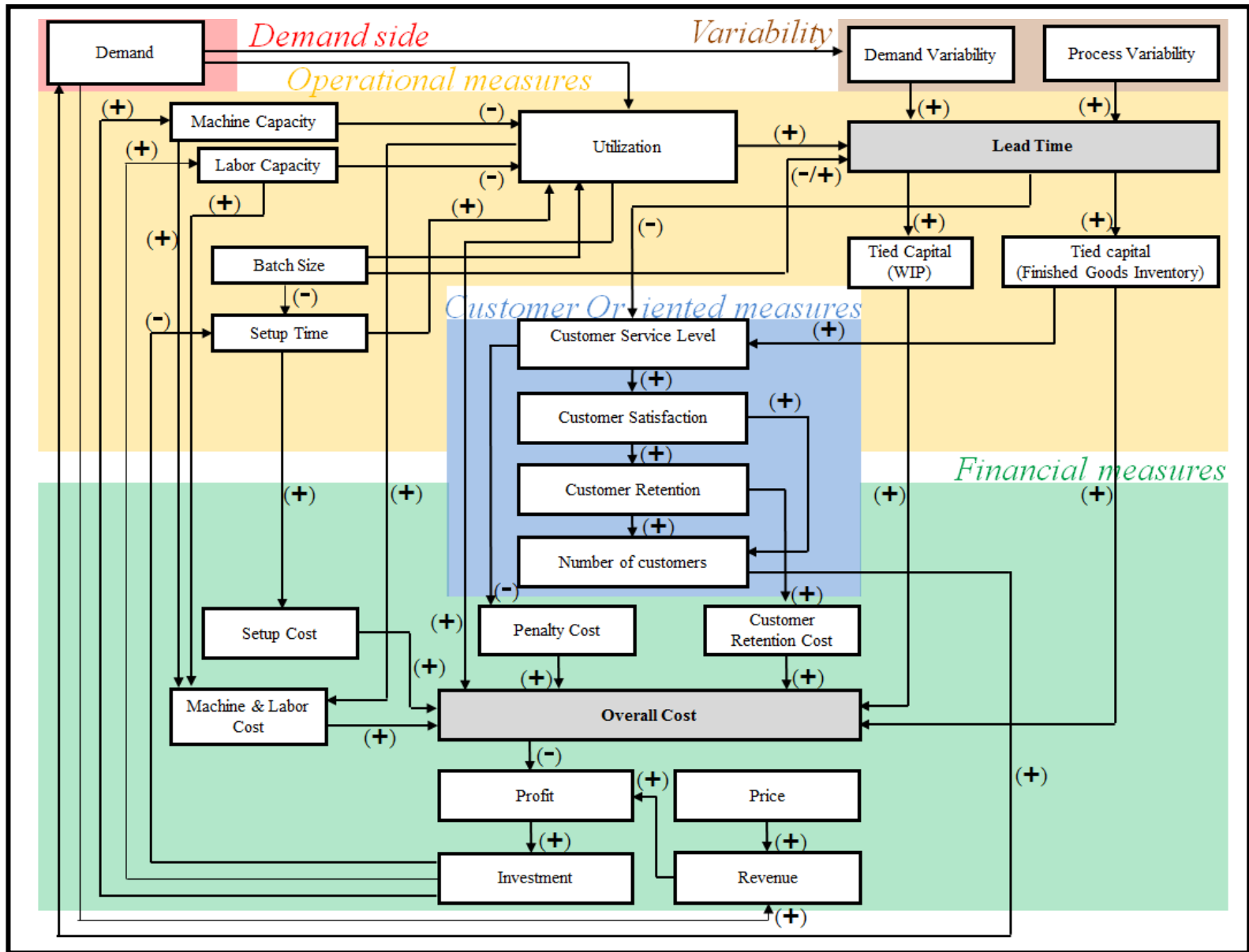


Figure 3.4: The dynamic performance evaluation framework for a make-to-stock manufacturing strategy.

## Chapter 4

# Methodology and Research Design

### 4.1 Ontology, epistemology and strategy of the research

The design of scientific research is primarily governed by the philosophy of science, numerous hidden assumptions surrounding the truth, reality, knowledge, objectivity, values and other key elements (Crotty, 1998). Our way of understanding, interpreting and discussion of knowledge influences the way research is done and our decisions regarding the choice of research method. In other words, the design of a scientific study is related to the philosophical perspective of questioning what and how we know; what is the real-world and how can we know what exists in the world? A particular paradigm, which researchers adopt towards the nature of knowledge, influences the entire research process, particularly the selection of a theoretical perspective (i.e. positivism or interpretivism). The theoretical perspective influences the nature of research questions while governing the choice of research methodology (Guba and Lincoln, 1988). Thus, the researcher's choice of philosophical assumptions influences the choice of research strategies and tools.

A scientific research paradigm can be characterized by using 'ontological, epistemological, methodological and method (research technique)' related dimensions (Crotty, 1998; Grubic and Fan, 2010, p. 779). Meredith *et al.* (1989) provide a detailed discussion on alternative research paradigms and various research approaches in operations management.

**Ontology** originates from the domain of philosophy (Grubic and Fan, 2010, pp. 776-778) and is defined as the metaphysical science/study of being (Etymology Dictionary, 2014). Ontology

deals with the order and structure of reality, the nature of truth in this world (Grubic and Fan, 2010). Principally, the concepts of being, existence and the nature of reality are questioned through a philosophical perspective, while studying the existence and essence of objects or events.

There are two extreme poles of ontology: The objectivist and subjectivist ontology. Whilst the objectivist perspective postulates objective analysis of reality through more scientific laws, causal relations and facts, the subjectivist perspective postulates constructed reality and facts which are based subjectively on the observer’s interpretation and concept of those facts (Grubic and Fan, 2010; Meredith *et al.*, 1989) (see Figure 4.1 below):

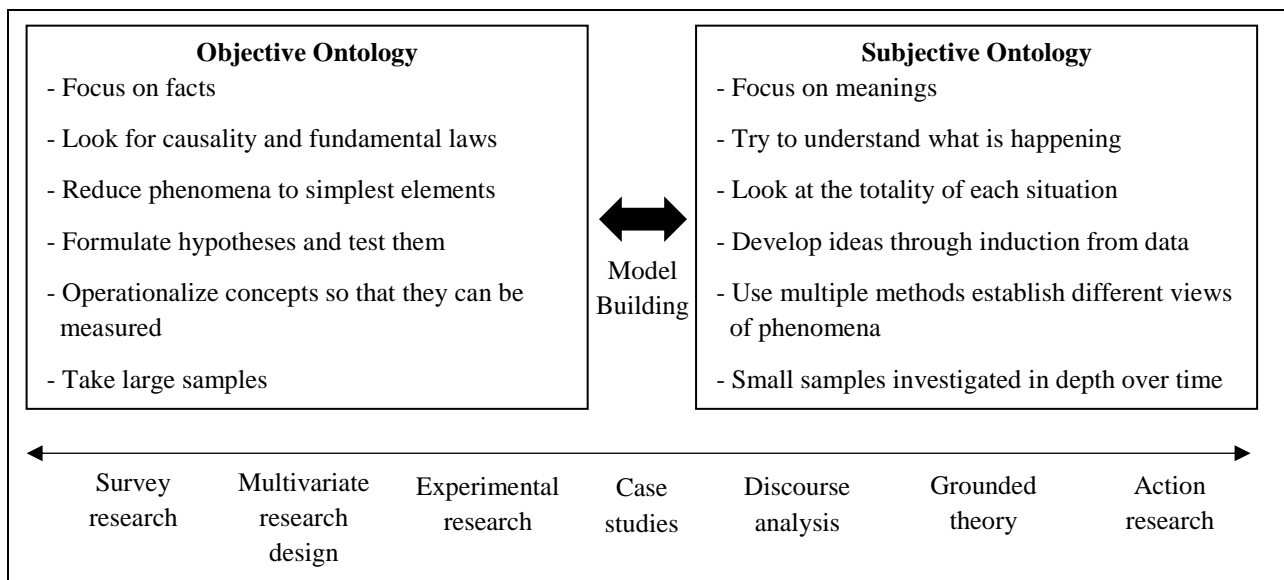


Figure 4.1: Choice of research methods related to ontology  
(Source: Beech, 2005).

**Epistemology** is the philosophical study of knowledge: ‘How we know and what we know’ (Crotty, 1998, p. 8), which is also known as the ‘theory of knowledge’. Epistemology concerns philosophical aspects, such as nature, grounds, scope and methods of knowledge; in particular, ‘The relationship between the knower and what can be known’ (Guba and Lincoln, 1998, p. 201). The main focus is, ‘The knowledge about reality and what can be considered as valid knowledge of that reality’ (Grubic and Fan, 2010, p. 779). In epistemology, generally, the connection of knowledge with truth, belief and justification, as well as the limit and validity of knowledge, is discussed through a philosophical perspective (G & C Merriam, 1913; Oxford, 2014).

The theoretical perspective of research comes from a selection of particular research paradigms (Crotty, 1998). A paradigm is defined by a set of certain axioms and is defined as ‘The entire constellation of beliefs’ (Kuhn, 1970, p. 146), and ‘A basic set of beliefs that guide action’ (Guba, 1992, p. 17). Thus, a paradigm forms the theoretical framework of research (Beech, 2005).

Crotty (1998, p. 10) differentiated epistemology and ontology as follows: “*To talk about the construction of meaning (epistemology) is to talk of the construction of a meaningful reality (ontology)*”. Aram and Salipente (2003, p. 193) underscored ontological and epistemological perspectives as critically important in terms of ‘creation and conceptualizations of management knowledge’.

Among different epistemological perspectives of social sciences (i.e. positivism, relativism, interpretivism, etc., Meredith *et al.*, 1989), Klein and Hirschheim (1987) and Grubic and Fan (2010, p. 779) characterize the two epistemological poles of a scientific paradigm by *positivism* and *interpretivism* (see Table 4.1 below):

Table 4.1: Axiomatic contrasts of research paradigms (\*)

	Positivism	Constructivism (Interpretivism)
Ontology	The reality exists independently of the observer. A singular reality is favored (Realism).	The reality is subjective construction; relativist. Multiple, holistic, competing realities are constructed by individuals (Nominalism).
Epistemology	Primary concern is the identification of causal relationships. Postulates the independency of the knower and the known. Objectivist.	Primary concern is the observer’s pre-understands of a domain/ phenomenon. Postulates the independency of the researcher and subject. Subjectivist. Interactive.
Methodology	Experimental study based on controlled and systematic procedures. Verification and falsification.	Hermeneutics. The research study is based on interpretation. There is an empathetic interaction between researcher and subject. Interpretation and interaction.
Research outcomes	Generalizations are context and time independent. Results lead to immutable laws or predictions.	Outcomes, hypotheses are context and time dependent. Results lead to understanding.

(\*) based on Grubic and Fan (2010) and Pickard and Dixon (2004), Figure 2.

Positivism and constructivism represent the two extreme poles of the methodological dualism. As Meredith *et al.* (1989) and Klein and Hirschheim (1987) stated, these are two important dimensions regarding the understanding of reality and the philosophical aspects of modeling in Operations Management (Grubic and Fan, 2010, p. 779). Positivism represents rational

dimensions where there is singular reality whereas constructivism represents the relativist dimension where the reality is subjectively constructed. Therefore, the epistemological and ontological stance of the *constructivist research paradigm* differs from realist ontology and the objectivist epistemology of the *positivist research paradigm* (Lincoln and Guba, 1985; Crotty, 1998; Grubic and Fan, 2010; Pickard and Dixon, 2004).

Ontologically, the positivism paradigm postulates *realism* where there is a single and tangible reality. According to realism, reality exists independently of the observer. Contrarily to the constructivist paradigm, which postulates *nominalism*; i.e. subjective construction of multiple realities. Thus, questioning the knowledge surrounding this reality, the validity of the knowledge is the primary concern.

Epistemologically, positivism is more objectivist and postulates independency of the knower of the known. A positivist epistemology is value-free where the choice of subject and method are objective, being independent from the beliefs and interests of what is being observed. The identification of causal relationships is important in terms of explaining an observable phenomenon. This may require the researcher to deal with large samples of data and mental constructs, etc. (Beech, 2005). Contrarily, in the constructive epistemological approach, the primary concern is the observer's pre-understanding of a domain or phenomenon. Thus, constructivism postulates subjectivity and knowing an unknown phenomenon is only possible through the researcher's individual belief system. This requires further interaction of the researcher and related research phenomenon (Grubic and Fan, 2010, p. 779), and the researcher's focus and in-depth understanding of data, data analysis, observations, interviewing and a deeper understanding of an organization (Beech, 2005).

Constructivism is defined as a form of research within the boundaries of interpretivism, where knowledge of the real-world is constructed by individuals and is based on their pre-understanding of a phenomenon. This form of research, i.e. constructivist inquiry, provides a rich picture of individual realities. However, the main challenge is the applicability of research findings to other contexts. As mentioned by Lincoln (1992, p. 73), the main question is, "*How can multiple, holistic, competing, conflictual realities of multiple research participants be applied to any situation other than the situation in which the research was grounded?*"

The applicability of these individual realities, namely the generalizability and transferability of related findings, are based on the credibility and external validity of the research (Pickard and Dixon, 2004). As a result, verification and validation of results is critical in terms of comparing

the accuracy of outcomes with the modelled reality (Patton, 1988). According to Pickard and Dixon (2004), it is critical to develop criteria to evaluate the methodological and analytical soundness of constructivist research. Furthermore, highlighted by Smith (1993, p. 150): *“The task for interpretivists is to elaborate what lies beyond epistemology and beyond the idea that there are special, abstract criteria for judging the quality of research”*. Guba (1992) defined such criteria as the ‘*criteria of trustworthiness*’, which is defined as a combination of sub-criteria such as *credibility, transferability, dependability and conformability*.

*Credibility* refers to the approval of the findings of a constructivist study where multiple realities were studied. *Transferability* ensures the transfer of the findings from the researcher to the reader. Therefore, the reader can regenerate those findings and apply them to a context of his or her research interest. *Dependability* is about the examination and assessment of a research process, as well as the quality of the research data by an external auditor or referee. *Conformability* refers to limiting the bias of the researcher in order to ensure that the research outcome is not influenced by the biased, prejudgment of the researcher (Pickard and Dixon, 2004).

**Methodology:** A sub-dimension under epistemological and ontological stances is the selection of the research methodology. Methodology is defined as the ‘*strategy, plan or action, process or design lying behind the choice and use of particular research methods*’ (Crotty, 1998, p. 3). A methodology can be quantitative or qualitative. Gorman and Clayton (1997, pp. 24-28) defined the difference between qualitative and quantitative methodologies as follows: *“Quantitative research postulates the objective reality of social facts”* whereas *“qualitative research postulates social constructions of reality”*.

The selection of an appropriate research methodology is important as it ensures a certain research quality. A research methodology may imply an individual method, which is accustomed to and associated with the chosen methodology, or a set of individual research methods or techniques. Typically, by deciding on a certain research paradigm, researchers often follow methods and techniques, which are generally accustomed to that particular epistemology.

**A research method** is the overall approach used to manage the data that is related to the research focus and questions. Crotty (1998, p. 3) defined a research method as *“The techniques or procedures used to gather or analyze data related to some research question or hypothesis.”* A research method may imply the use of very specific or particular research tool(s), technique(s) and data collection approach(es). In this direction, related research techniques may necessitate the

use of particular research instruments, tools, software packages, which are compatible with the chosen research method(s) and techniques(s) (Pickard and Dixon, 2004). Some of well-known research methods/techniques are stated by Beech (2005) as follows: *statistical testing, experimental studies, secondary data analysis, case studies, observations, interviews* and *participation* (see Figure 4.1 on page 72).

**Research Design Hierarchy:**

A particular research paradigm shapes the theoretical perspective of research (Crotty, 1998) and also forms the theoretical framework (Beech, 2005). The selection of a paradigm, the decision of ontology and epistemology, structures how the research is perceived and implies a choice of methodology, which guides the research process. For instance, a positivist paradigm generally postulates deductive methodology, whereas a constructivist paradigm postulates a generally inductive methodology (Meredith *et al.*, 1989). Typically, the selection of a particular methodology leads the researcher to choose and adopt methods, techniques and research instruments that are characteristically associated with the chosen methodology.

The building blocks of a research methodology and the map of a research design are illustrated by Beech (2005) as follows (see Figure 4.2 below):

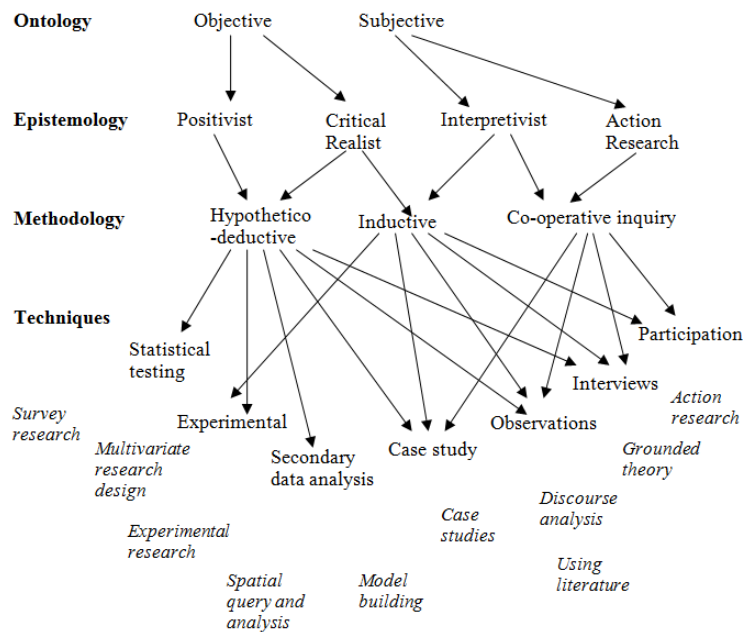


Figure 4.2: Research design map (Source: Beech, 2005).

In the following part, the specific methodological details of this research will be provided.

## 4.2 Empirical quantitative modeling

The research design map and strategy of this research is based on the discussion provided on the ontology and epistemology at the beginning of the methodology section. However, before providing a particular philosophical discussion on the research design map and strategy of this research, a brief discussion of Operations Management research methodologies will be provided as background information. An overview of quantitative model-based research will be discussed. In particular, the differences between *empirical* and *axiomatic* research, and between *descriptive* and *normative* research will be justified in order to better map the research design of this thesis.

In this thesis, a quantitative model-based empirical research methodology is followed. As mentioned by Bertrand and Fransoo (2002, p. 241) ‘The quantitative modeling has been the basis of most of the research in operations and management consulting and this research type was oriented towards solving real-life problems in operations management’. According to Meredith *et al.*, (1998, p. 71) and Bertrand and Fransoo (2002, p. 241, 249 and 251), quantitative model-based research is as a rational, objective and scientific approach, and objective models can be built using quantitative model-based research. These models can be used to explain a part of the behavior of real-life operational processes or capture a part of certain decision-making problem faced by managers.

Quantitative model-based research is defined as “*the research where models of casual relationships between control variables and performance variables are developed, analyzed or tested*” (Bertrand and Fransoo, 2002, pp. 241-242).

In this regard, Bertrand and Fransoo (2002) distinguished quantitative model-based research in Operations Management (OM) from other research in OM as follows:

*“Quantitative models are based on a set of variables that vary over a specific domain, while quantitative and causal relationships have been defined between these variables.”*

Bertrand and Fransoo (2002, p. 242)

Quantitative model-based research focuses on the development, analysis and testing of models through introducing ‘*causal*’ and ‘*quantitative*’ relationships amongst control and performance variables. The performance variables can be either physical variables (i.e. inventory, utilization rate, etc.) or financial variables (i.e. profits, costs, revenues, etc.).

'Causal' defines a relationship where the change of value of one variable leads to a change in the value of another variable. 'Quantitative' defines to which extent the change in the value of a dependent variable can be expressed quantitatively as the change in the value of the independent variable. According to Bertrand and Fransoo (2002), related claims and analysis properties of quantitative modeling are 'unambiguous' and 'verifiable', which makes quantitative model based research a rational, objective and scientific approach. In fact, quantitative research is used to develop rational solutions for many problems encountered in empirical research.

Quantitative model-based research in Operations Management is defined under two distinct classes: *empirical quantitative modeling research* and *axiomatic quantitative modeling research* (Bertrand and Fransoo, 2002, p. 242 and 249).

*Axiomatic model based research* is primarily driven by idealized models, theorems and logical proofs (Meredith *et al.*, 1998). As explained by Bertrand and Fransoo (2002, p. 249) 'axiomatic research generates knowledge about the behavior of certain variables of a model based on the assumptions about the behavior of other variables'. The researcher can focus on 'obtaining a solution within a defined model' or 'providing insights into the structure of a problem which is defined through this model'. The models studied in this research class are generally determined by mathematical, statistical or computer science techniques where the researcher studies related operational processes or decision problems through mathematical models, decision theory, dynamic programming, etc.

Axiomatic model based research can be further classified in two classes: *normative axiomatic research* and *descriptive axiomatic research*. The main focus of normative axiomatic research is on either improvement of an existing problem or related findings in literature by developing policies, strategies, actions; or providing an optimal solution for a new problem (Bertrand and Fransoo, 2002). For instance, as the authors mentioned, the majority of operations research studies are normative research. On the other hand, in descriptive axiomatic research the primary interest is on analyzing and understanding certain characteristics of a model. For instance, research in the area of queuing theory and game theory is stated to fall in this research category.

The main focus of *empirical quantitative model based research* is on the implementation of theoretical research findings in real-life operational processes (Bertrand and Fransoo, 2002). Being different than axiomatic research, empirical research is driven by empirical evidence (direct observations or measurements). Using quantitative model based empirical research, the predictions of a specific event or the future state of a quantitative model can be tested with a

suitable experiment that reflects reality. In this sense, the primary concern is on maintaining a fit among observations in real-life and the model that reflects this reality.

There are two types, i.e., *descriptive empirical quantitative research* and *normative empirical quantitative research* (Bertrand and Fransoo, 2002, p. 250). Descriptive empirical quantitative research focuses on creating models to describe the causal relationships of a process, which exist in reality. This helps to improve the understanding of the dynamics of the process. A well-known example of this research type is the industrial dynamics research of Forrester (1961). In descriptive empirical research, primary interest is on analyzing and understanding the characteristics of a process. On the other hand, normative empirical quantitative research focuses more on the development of policies, strategies and actions with the goal of improving the current status or situation. A simple differentiation between these two methods is defined by the authors: “*Studying a process is stated as descriptive research, whereas studying a problem is normative research*” (Bertrand and Fransoo, 2002, p. 254).

The classification of quantitative model-based OM research is illustrated below (Table 4.2):

Table 4.2: Classification of quantitative (model-based) OM research types <sup>(\*)</sup>

	Descriptive	Normative
Empirical	ED	EN
Axiomatic	AD	AN

<sup>(\*)</sup> Source: Bertrand and Fransoo (2002), Table I, p. 251

Quantitative model-based empirical research has been subject to certain criticism regarding the application and performance of theoretical problem solutions in real-life operational processes. As mentioned by Bertrand and Fransoo (2002, p. 257) ‘*quantitative model-based empirical research is still in its infancy*’ and some researchers may have less consensus about quantitative empirical research than quantitative axiomatic research.

This is related to the nature of quantitative empirical research. Characteristics of complex real-life problems cause certain difficulties, modeling and methodological challenges. In complex real-life systems there are hundreds of variables, countless factor interactions. This requires complete understanding of critical factor interactions, stationary and dynamic behavior of the systems (Hopp and Spearman, 1996; Serman, 2000 and 2001). As discussed by Bertrand and Fransoo (2002, p. 244 and 246) most classical Operations Research (OR) models are inadequate to explain or predict the behavior of real-life operational problems. Since, these models focus on certain aspects of operational processes; and less attention is paid to describe the statics and dynamics of the processes. This is not enough to understand system behavior. Usually casual

relationships are ignored, which does not provide a sufficient basis for the development of ‘explanatory and predictive models’ of operational processes.

The major problem is the lack of *objective, situation independent, generally accepted procedure* for the observation of a specific operational process: “*Operation management still lacks a well-defined, shared methodological framework for identifying and measuring the relevant characteristics of real-life operational processes.*” Bertrand and Fransoo (2002, p. 251).

In empirical quantitative model-based research ‘there is no objective, situation independent and generally accepted procedure’ for observing a specific operational process. Operational processes are all different and each real-life situation is unique. Each situation has specific sources of problems. Thus, each real-life application is done in a ‘situation-dependent way’. This type of research requires the researcher’s knowledge about relevant characteristics of the operational process under study (i.e. the processing times of operations, capacity of resources, arrival rates of customer orders, etc.). Therefore, situation dependent analytic techniques and systematic methods are applied to operational processes (Bertrand and Fransoo, 2002, p. 251).

However, as mentioned by the authors, it is possible to develop an objective and rational way, given the fact that the quantitative model-based research is a rational, objective, scientific approach (Meredith *et al.*, 1998, p. 71; Bertrand and Fransoo, 2002, pp. 249 and 251). Bertrand and Fransoo (2002) provided an extensive, explicit discussion and fine examples of such research from literature (see Inman, 1999 and DeHoratius and Raman, 2000).

Meredith *et al.* (1989) present a generic framework for the classification of research methods based on the source and kind of information used in research, and a knowledge generation approach. Meredith *et al.*’s (1989) generic framework is useful to aid an understanding of where this research design can be mapped among the dimensions of philosophical paradigms (*see Table 4.3 on page 81*).

Table 4.3: A generic framework for classifying research methods <sup>(\*)</sup>

		SOURCE AND KIND OF INFORMATION USED IN THE RESEARCH		
		NATURAL		ARTIFICIAL
KNOWLEDGE GENERATION APPROACH		<b>Direct observation of object reality</b>	<b>People's perceptions of object reality</b>	<b>Artificial reconstruction of object reality</b>
	RATIONAL	<b>Axiomatic</b>		Reason/logic theorems Normative/descriptive modeling
		<b>Logical positivistic/empirical</b>	Field studies Field experiments	Structured interviews Survey research
				Prototyping Physical modeling Laboratory experimentation Simulation
EXISTENTIAL	<b>Interpretive</b>	Action research Case studies	Historical analysis Depth/expert panel Intensive interviewing Introspective reflection	Conceptual modeling

<sup>(\*)</sup> Source: Meredith *et al.* (1998), p. 71; Karlsson (2009).

Due to certain characteristics of quantitative model-based empirical research methodology, it is difficult to position our research approach on a certain research design map. Based on the ontological and epistemological discussion provided, we can say this research is between positivism and constructivism. On one hand, the research paradigm is close to positivism. We take existing knowledge; we use logical rules to verify the theory. Furthermore, we have experimental studies, and these experimental studies are based on controlled, systematic procedures supported by verification and validation procedures. On the other hand, our research is constructivist, since our research is context specific and subjective, given the fact that quantitative model-based empirical research is subjective (as explained by Bertrand and Fransoo, 2002). Regarding research outcomes, our results lead to better understanding of lead time reduction and related factor interactions. This is stated to be one of the conditions of constructivist research (*see Table 4.1 on page 73*).

We use positivistic research to verify theory. Industrial cases are used to confirm that the general rules can apply in reality but the research method is not pure classical case study research. Since we do not develop theories; but we test the theories and we do experiments. This is explained by Voss *et al.* (2002).

According to Voss *et al.* (2002, p. 205): “*Case research in operations management differs from case research in the wider social science in that researchers are interested in analyzing the manufacturing and service processes and systems of the plant. Thus research design in operations management should pay attention to what processes and systems are to be studied, the methods for studying them, and the operating data to be collected from them...case research protocols need piloting either in a pilot case or in initial interviews within an organization*”. Based on Voss *et al.*'s (2002, p. 205) statement, we can say the use of industrial cases in this thesis and classical case study research, is different.

Based on Meredith *et al.*'s (1989) framework, our methodological approach uses the artificial reconstruction of reality (conceptualization and dynamic modeling of reality), which is a more interpretive approach, rather than being axiomatic. As a result, simulation and System Dynamics based modeling have been used to conceptualize lead time related factor interactions. As mentioned before, this research is between positivism and constructivism (interpretivism). In a similar way, we observe that, in Meredith *et al.*'s (1989) framework, empirical research is located between the border of interpretive and axiomatic research dimensions (*see Table 4.3 on page 81*).

Another differentiation between descriptive and normative empirical research is based on Mitroff *et al.*'s (1974) research model, in which the authors define a research approach as a sum of four phases: *Conceptualization, modeling, model solving* and *implementation* (*see Figure 4.3 on page 83*). The first phase starts with developing the conceptual model of the problem/system being studied. At this stage, the scope of the model, model objective and model variables should be addressed. The next phase is the actual model-building phase, where causal relationships among the variables are defined. This phase is followed by the model-solving phase. The final step is the implementation phase, where the results are integrated with the practice. Mitroff *et al.*'s (1974) model is a useful reference guide to identify the methodological path of a certain research activity.

Mitroff *et al.*'s (1974) definitions have been referred to in order to highlight the differences among descriptive and normative empirical research using a differing perspectives. Empirical descriptive research focuses more on ‘*conceptualization – modeling – validation*’ contrarily to empirical normative research, which focuses on ‘*conceptualization – modeling – model solving – implementation*’ phases. Regarding this perspective, this research design is more descriptive empirical research.

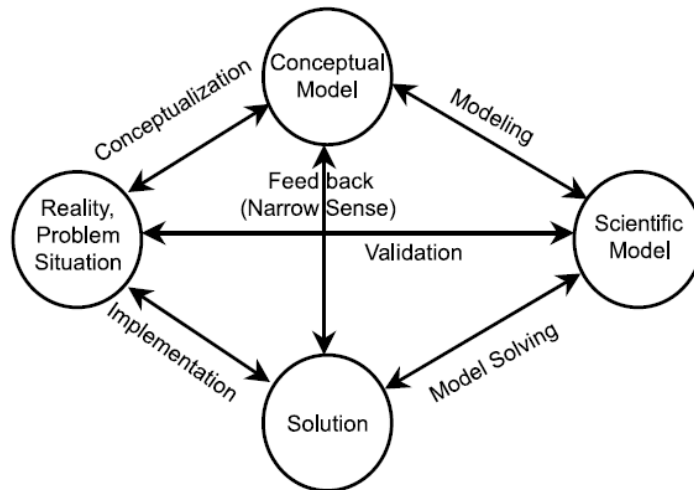


Figure 4.3: Mitroff *et al.*'s (1974) research model.

During the model-building phase, focus was extensively placed on analyzing the causal relationships between control and performance variables. This necessitates: (i) analysis of dependencies among the performance dimensions; (ii) analysis of delayed effects over time; (iii) enhancement of understanding regarding interconnected business processes and their dynamic behavior. For this purpose, an integrated model of two distinct methods has been used: *Queuing Theory Based Modeling* (Open Queuing Network Model) and *System Dynamics Modeling*. In the following sections the motivation behind the method selection shall be explained and how these two methods are integrated.

#### 4.2.1 Queuing Theory Based Modeling

Queuing Theory Based Modeling is used to understand the stochastic behavior and performance of a complicated manufacturing system or a service process (Suri *et al.*, 1993; Govil and Fu, 1999; Bolch *et al.*, 2006; Shanthikumar *et al.* 2007). The modeling capabilities provide a basis to analyze impact of certain factors (machine-labor interactions, setup time, lot size, waiting in queues or service, etc.) on operational performance (Bertrand and Fransoo, 2002; Suri, 1998).

For relatively basic models (i.e. M/M/1) or simplified versions of real-life problems where only a few variables/system components interact, it is possible to have an exact solution. On the other hand, characteristics of complex real-life systems cause certain difficulties, modeling and methodological challenges. In complex real-life systems there are hundreds of variables and countless factors interact. It is not easy to obtain exact solutions; therefore, certain simplifications and restrictive assumptions have to be made. In Queuing Theory Based Modeling, the performance of a system is predicted using certain queuing theory based assumptions and

approximations. The analysis methodology is based on decomposition methods where several steps of aggregation are used to handle the complexities of manufacturing or service systems. Each product follows the production process according to a predefined route; for a service process there is a specific sequence of servicing events. Input measures such as arrival rates, service rates and coefficients of variations are used to estimate performance measures like mean queue length, mean waiting time, mean flow time, level of resource utilizations, amount of finished goods, WIP inventories and scrap, etc. (Bolch *et al.*, 2006).

The history of Queuing Theory Based Modeling dates back to Jackson's study (Jackson, 1957 and 1963). Jackson used Queuing Networks Theory to obtain product form solutions under certain conditions. Later, Baskett *et al.* (1975) and Kelly (1975) extended Jackson's findings to cover certain cases where there are multiple networks of queues (open, closed and mixed) with multiple jobs and different service disciplines. Other researchers (Kuehn, 1979; Whitt, 1983a and 1983b; Pujolle and Wu, 1986; Gelenbe and Pujolle, 1987) generalized product form solutions and proposed decomposition methods for general type networks (i.e. open G/G/m queuing networks). Additionally, different approaches such as '*diffusion approximations*' (Reiser and Kobayashi, 1974) and '*Brownian approximations*' (Dai and Harrison, 1993; Harrison and Nguyen, 1990; Dai, 2002) were proposed to solve some performance problems encountered (high variability and heavy traffic).

Today, the Queuing Theory is a well-known and well-established method for analyzing the stochastic behavior (i.e. variability occurred due to stochastic inter-arrival times and service durations) and performance of manufacturing systems.

There are several articles, which explain the use of queuing theory based analytical models in manufacturing applications: Suri *et al.* (1993), Govil and Fu (1999), Bolch *et al.* (2006) and Shanthikumar *et al.* (2007) are the authors of some of these well-known studies (Rabta *et al.*, 2009).

Queuing Theory Based Modeling became very popular due to its rough-cut calculation capabilities. The complexity and size of real-life problems can be reduced to relatively simple yet complex enough models (Bertrand and Fransoo, 2002; Vokurka *et al.*, 1996). Compared to simulation, modeling results reflect key insights, but are not as detailed to provide a complete and in-depth understanding of the system. Yet, it is sufficient enough for real-world applications (Suri *et al.*, 1995; De Treville *et al.*, 2006). Indeed, due to the challenges of complex mathematical or simulation models (e.g. requirement for in-depth mathematical/statistical background, difficulties

in maintaining a certain level of understanding on theories), managers and executives prefer relatively simple and quick solutions for quick decisions and initial systems analysis. As De Treville and Ackere (2006, p. 173) stated, '*Despite certain challenges, queuing-theory-based modeling is likely to yield a better competitiveness in lead time reduction.*'

Real-life problems impose soft factors that are difficult to quantify (Vokurka *et al.*, 1996). Queuing theory based software packages such as Rapid Modeler (Rapid Modeler, 2009), MPX, Q-LOTS (Karmarkar *et al.*, 1985) and MANUPLAN (Suri *et al.*, 1986), Operations Planner (Jackman and Johnson, 1993) is especially designed for manufacturing applications to make model development simple and automatic. Their core algorithms use queuing network decomposition methods. Multiple-servers and queue situations are described by a G/G/m queuing system. Users can make relatively easy analytical insights without having any queuing or stochastic theory background (De Treville *et al.*, 2006; Rabta *et al.*, 2009). The ease of rough-cut calculations provides the user with more scenarios and possibilities, helping evaluate the effects of alternative managerial/operational decisions along with *what if questioning* and *sensitivity analysis* capabilities. These tools are also useful to analyze the impact of manufacturing parameters (i.e. labor-equipment integration, lot sizes, waiting time, setup time and repair times, etc.); and uncover the negative effects of variability on system performance (Rabta *et al.*, 2009; Hopp and Spearman, 2006; Enns, 2000 and 1996). Today, a considerable number of professionals are using Queuing theory-based software, from industrial managers to educators. Actual status and recent developments are provided by Rabta *et al.* (2013).

Queuing theory-based software packages are quite efficient tools for teaching mathematical principles of lead time reduction and Factory Physics (De Treville *et al.*, 2006). Modeling aid and low requirements for queuing theory knowledge made these tools especially suitable tools for managers and industrial application.

Further review on Queuing Theory Based Modeling and software packages is provided in '*Queuing Networks Modeling Software for Manufacturing*' (Rabta *et al.*, 2009).

In this thesis, the queuing networks software, Rapid Modeler (Rapid Modeler, 2009), and MPX software ([www.networkdyn.com](http://www.networkdyn.com)), are used to analyze complex manufacturing processes and identify the bottlenecks in the system and discover lead time reduction oriented improvement opportunities. The software provides estimations for operational performance (i.e. lead time, resource utilization, WIP, etc.), which serves as a basis for System Dynamics Modeling. The Rapid Modeler has been used in various manufacturing and service applications (Reiner, 2009 and 2010).

## 4.2.2 System Dynamics Based Modeling

The second method is the System Dynamics methodology. The development of System Dynamics is based on the *Industrial Dynamics* of Jay W. Forrester (1961). During the early 1960s, Forrester started to apply the *systems thinking methodology* and *industrial dynamics models* to managerial issues; and strategic and operational problems.

System Thinking is, “*The ability to see the world as a complex system... as a holistic worldview where everything is connected to everything else,*” (Sterman, 2001, p. 9). System Thinking provides a better understanding of *dynamic complexity* or *combinatorial complexity* through enhancing learning about the internal mechanisms of a complex system. The general methodology of modeling dynamic systems is known as the *System Dynamics* (Sterman, 2000).

*“System Dynamics is an interdisciplinary approach grounded in theory of nonlinear dynamics, differential equations, feedback control mechanisms; and an effective tool, a mathematically model used in various disciplines social disciplines on behavior of human, economics, fundamental science, technical systems and engineering; operations management as well as operations research.”* (Sterman, 2001, p. 10)

System Dynamics models are accepted as scientific theoretical models that can explain and predict the dynamic behavior and performance of the processes, which can be empirically validated (Bertrand and Fransoo, 2002).

System Dynamics can be used to represent and analyze the causal relationships; as it provides a continuous perspective/insight on complex system mechanics/inter-organizational dynamics changing over time (Forrester, 1961).

In particular, System Thinking handles a managerial problem or an organization as a system composed of interacting variables, changing patterns of behavior, certain events and their causes. *Behavioral patterns* usually represent changing performance (i.e. efficiency, effectiveness, certain financials and market metrics, etc.) through time. *Variables* may represent various types of business entities, such as lead time, throughput, inventories, costs, demand, customers and so forth (Kirkwood, 1998).

Models of System Dynamics have strong explanatory powers, used to characterize the structure underneath a system and provide a continuous perspective on nonlinear behavior of complex operational processes using causal loop diagrams (cause and effect relations); feedback loops,

stock/flow diagrams (accumulation of flows into stocks) and time delays (Forrester, 1961; Sterman, 2000; Größler *et al.*, 2008). As explained by Größler *et al.* (2008):

*“...system dynamics postulates the dynamic processes in social systems function in feedback loops and that the history of systems accumulates in state variables. In addition, the accumulated history influences the future development of a system - a process that is often affected by time delays.”* (Größler *et al.*, 2008, p. 374)

System Dynamics models are content-wise a representation of a real-world system. Each *variable* of the model is the representation of an entity in reality and each *link* between variables corresponds to a hypothesized positive or negative interaction in the real world. In this regard, System Dynamics is more suitable to obtain a continuous perspective on system behavior and the interactions of system entities (*‘macro behavior’*) whereas; it has limited capability in providing an insight into the characteristics of individual entities (*‘micro behavior’*) or simulation of discrete events (this terminology is defined by Größler *et al.*, 2008).

This capability is suitable to explain inter-organizational dynamics and interactions among the parts of a system. This potentially makes System Dynamics suitable for strategic issues where understanding the overall behavior and aggregated relationships is important. The explanatory power and strength of System Dynamics models is due to certain characteristics: (i) representation of nonlinearities, causal links and interacting feedback loops, (ii) time delays and (iii) accumulation processes.

**Feedback** is, *“The results of our actions define the situation we face in the future; and indeed the new situation alters our assessment of the problem and the decisions we take tomorrow,”* as defined by Sterman (2001, p. 12). Generally, feedback leads to learning and a repeated corrective action or improvement initiatives in a closed-loop manner.

**Feedback loops** emerge as a result of mutual interactions among variables, which are related with one another by causal links (Sterman, 1989 and 2000). The direction of causality is indicated with *causal links* and polarity symbols (Kirkwood, 1998, p.7):

- Positive denotation (+) is used to define a positive correlation that any increase in independent variables leads to an increase in dependent variables. Namely, a change in independent variables produces a change in independent variables in the *same* direction.

- Negative denotation (-) is used to define a negative correlation that any increase in independent variables leads to a decrease in dependent variables. Namely, a change in independent variables produces a change in independent variables in the *opposite* direction.

As a result of positive and negative interactions, a sequence of causal relationships forms a *causal loop diagram* and the system is indirectly influenced by itself through a *feedback loop*: “A *feedback loop* is a closed sequence of causes and effects, that is, a closed path of action and information,” (Richardson and Pugh, 1981; mentioned by Kirkwood, 1998, p. 5).

Two types of feedback loops are defined: (i) positive feedback loops (‘*self-reinforcing*’) and (ii) negative feedback loops (‘*self-correcting*,’ ‘*regulating*’ or ‘*balancing*’) (Sterman, 2001; Sterman *et al.*, 1997; Keating *et al.*, 1999).

A positive feedback loop is also referred to as a ‘*reinforcing loop*,’ where any change in the value of system entities leads to an ever-increasing and reinforcing growth pattern. This growth pattern can grow at an exponential rate where, at the initial stages of growth, certain effects might be ignored (*see Figure 4.4 shown below*). However, at later stages, depending on the direction of growth, considerably larger effects (the snowball effect) might be inevitable (Chapter 1: Kirkwood, 1998).

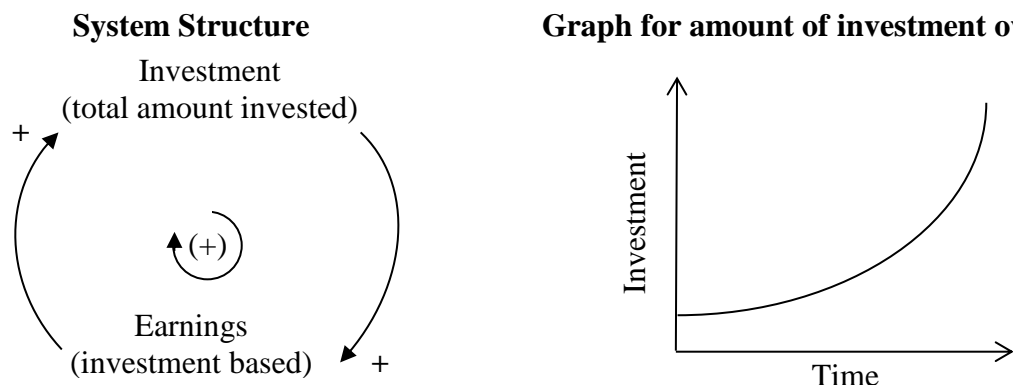


Figure 4.4: Positive (reinforcing) feedback loop: *Growth of investment*  
(Modified based on Figure 1.5, Chapter 1: Kirkwood, 1998, p. 9).

Negative loops work to counteract the growth initiated by positive loops in a self-correcting manner (Sterman, 2001). A negative feedback loop is also referred to as a ‘*goal seeking loop*’ since the loop structure regulates and balances itself by comparing the value of the independent variable and the goal of the loop. Depending on the direction of the gap between value and goal, this regulation can be an action to increase or to decrease the value of the variable. Typically, negative feedback loops serve to maintain stability. In Figure 4.5 (*shown on page 89*) a negative

feedback loop is shown to regulate the water level of a swimming pool (Chapter 1: Kirkwood, 1998):

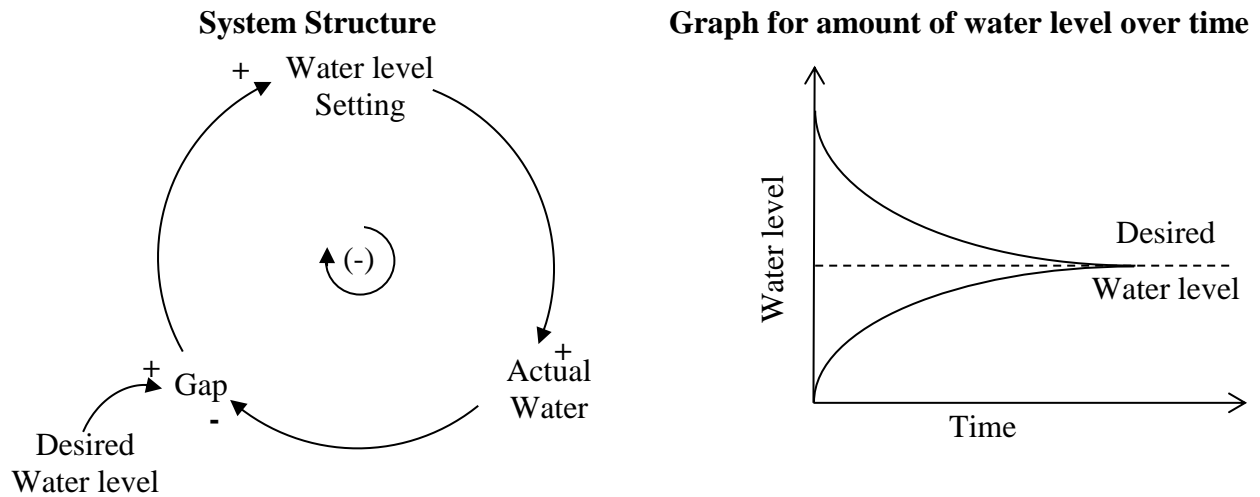


Figure 4.5: Negative (balancing) feedback loop: *Swimming pool water level* (Modified based on Figure 1.6, Chapter 1: Kirkwood, 1998, p. 10).

**Time delays** represent the duration of time that has passed between any actions (i.e. a decision to increase/decrease the value of an independent variable) and the related effect that changes the state of the dependent variable. Certain effects do not happen instantaneously and a certain amount of time passes until the system reaches a state of equilibrium (Sterman, 2001). During a delay, any instabilities and increased oscillations in the state of the system are highly likely to be observed. For instance, when delays are inherent in negative feedback loops, oscillations are observable in value of decision variables. As mentioned by Kirkwood (1998) and Sterman (2001), depending on the characteristics of a loop and the system of interest, the value of a variable may continue to oscillate indefinitely or decrease until the variable value reaches the desired target goal. In Figure 4.6 (*shown on page 90*) a simple negative feedback loop with a delay is illustrated for an online order service.

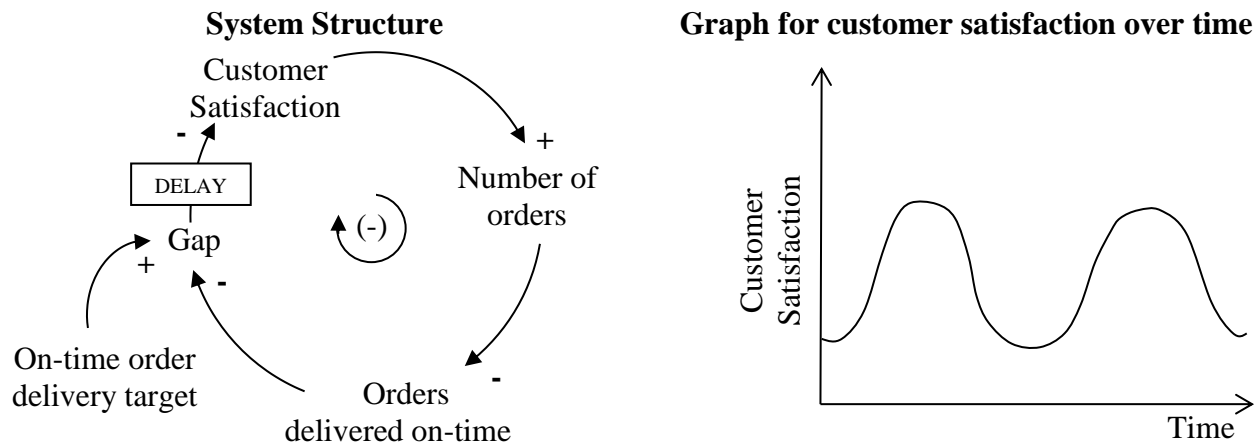


Figure 4.6: Negative (balancing) feedback loop with delay concept: *Customer satisfaction* (Modified based on Figure 1.7, Chapter 1: Kirkwood, 1998, p. 11).

The impact of delays essentially needs to be considered by the decision makers. Delays cause instabilities, which lead to underestimations on long-term performance and poor decision-making dynamics. Usually, the effects of time delays are either ignored or underestimated. For complex systems, interconnected with several positive and negative feedback loops, delays can display a complex behavior, which is difficult to predict. Particularly with premature indicators of system performance (a short-term performance increase, which is followed by long-term performance deterioration) may lead most decision makers to make premature decisions, use short-term solutions and enter a vicious loop that worsens system performance in the long-term. This phenomenon is known as the *'better-before-worse' phenomenon* (Keating *et al.*, 1999; Repenning and Sterman, 2001) (see Figure 4.7 shown below).

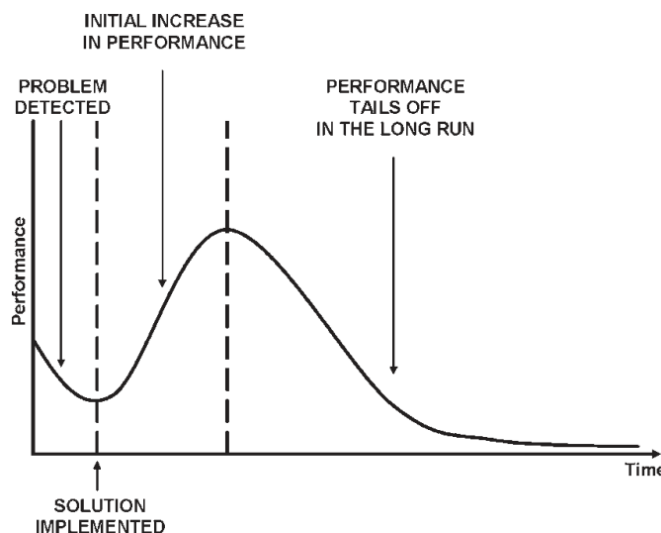


Figure 4.7: The *'better-before-worse'* phenomenon (Source: Maani and Li, 2010, Figure 2, p. 569).

According to Sterman (1989a and 1989b), “Delays in the feedback loops create instability and increase the tendency of systems to oscillate. As a result, creating damaging fluctuations, overshoot and instability” (Sterman, 2001, p. 13; mentioned by Maani and Li, 2010).

The dynamics of a simple loop are easy to understand; however, when a considerable amount of positive and negative loops interact with multiple delays and feedbacks, highly complex dynamics emerge. Thus, it may be difficult to understand and estimate the long-term behavior of complete system performance. In order to illustrate the complexity of positive and negative loop interactions with the delay concept; an example shall be considered, a simplified version of a manufacturing improvement program. Repenning and Sterman (2001) analyzed the reason why several improvement programs fail by studying the internal dynamics of an improvement. A simplified part of this model will be used to explain the mechanics of feedback loops and the delay concept. Positive and negative loop interactions are illustrated in detail in Figure 4.8 (shown below).

In Figure 4.8 (shown below), the desired throughput acts as an external factor, which represents customer demand. Throughput represents the actual production capacity. There is a natural gap between the desired and actual throughput, which leads to throughput pressure. Increasing customer demand amplifies this pressure. An increase in throughput may help to reduce the gap.

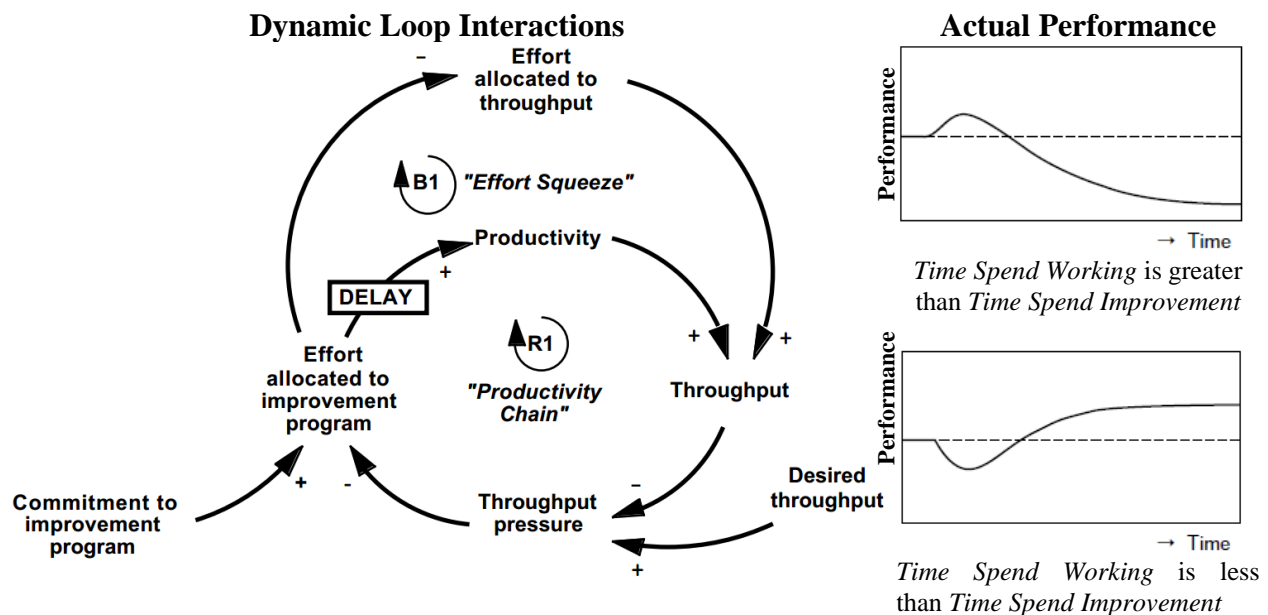


Figure 4.8: Combination of positive and negative loops: *The improvement paradox* (Source: Keating *et al.*, 1999, Figure 1, p. 4; Repenning and Sterman, 2001, Figure 6, p. 74).

One way to increase throughput is by improving productivity. Investing in improvement implementations raises the productivity level whilst at the same time creating even more time for further improvements. This is illustrated in Figure 4.8 (shown on page 91) as the ‘*productivity chain*,’ which is a positive self-reinforcing feedback process (R1 loop). On the other hand, there are negative influences, which may limit the productivity chain. Improvements are timely efforts and it takes time to reach the desired throughput increases and productivity gains. Thus, in the short-term, any improvement effort may not rapidly provide the desired throughput increases, but may cause an instantaneous temporary performance fall. This may unintentionally give a false impression that time and efforts dedicated to improvement are useless. Many managers facing daily pressures may make a premature decision by cutting down the improvement investments/efforts in order to dedicate time to work harder. This is illustrated in Figure 4.8 (shown on page 91) as the ‘*effort squeeze*’ loop, which is a balancing (negative) feedback process (B1 loop). While in the short-term this may yield a throughput increase, in the long-term, system performance distorts, throughput pressure increases and the system enters a vicious cycle (‘*better-before-worse*’ situation, Sterman, 2001; Repenning and Sterman, 2001, Figure 6, p. 74).

**Accumulation processes (Stocks and Flows):** The Stock and Flow diagrams are used to represent potential changes of variables over time. ‘*Stock variables or accumulation*’ conserve the state of the system, physical entities (i.e. money, number of customers, inventory and raw materials, etc.), which accumulate through time. A stock variable is an accumulation process that starts from an initial value and reaches a final value. ‘*Flow variables*’ or ‘*rate*’ denote the changing mechanics of stock variables or flow process (i.e. transfers of money and flow of unfinished products between stations) between any two stock variables (Größler *et al.*, 2008; Kirkwood, 1998). According to Kirkwood (1998, p. 18), “*For an on-going process, at any time, if the value of a quantity is nonzero, then that quantity is defined as a stock; and in case where the quantity is uncountable, then it is defined as a flow.*”

In Figure 4.9 (shown below) a stock and flow diagram for a simple production model is shown.

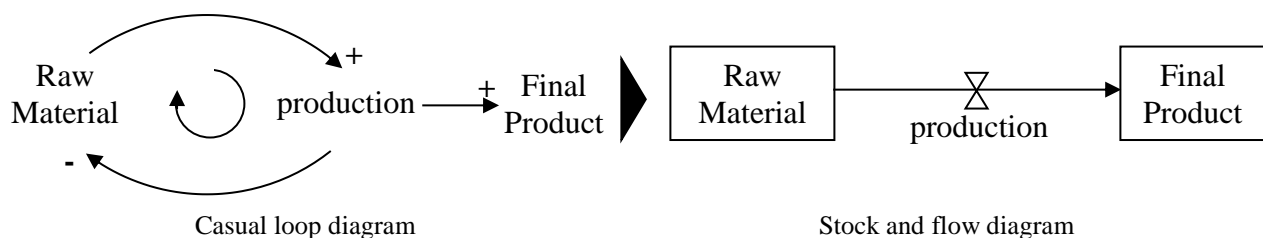


Figure 4.9: Stock and flow diagram: *Production example*  
 (Modified based on Figure 2.1, Chapter 2: Kirkwood, 1998, p. 16).

In Figure 4.9 (*shown on page 92*), raw materials are turned into products via the production process. Raw materials and production is connected through a negative feedback loop in which the loop has the goal of finishing the raw material inventory. As long as there is a raw material inventory, production continues (a positive relationship); and increasing production decreases raw materials (a negative relationship) since raw materials are processed into final products. In case of scarce resources, the production process halts. The amount of variables, raw material and products (*stocks*), change over time as the production processes (*flow or production rate*). In Figure 4.9 (*shown on page 92*) stocks are illustrated as rectangles and the flow is indicated by an arrow and a collate symbol ( $\otimes$ ) (Chapter 2: Kirkwood, 1998).

Cause and effect diagrams, feedback loops, accumulation, flow processes and delays and all such capabilities strengthen the explanatory power of System Dynamics. Thus, System Dynamics is not only useful to gain theoretical insight, but is an effective managerial tool for better decision-making and performance management (Ren *et al.*, 2006). According to Sterman (2000) and Größler *et al.* (2008) realistic insights of System Dynamics modeling contributes to the goal of improving the actual performance of real-life systems.

Today, several organizations have had significant success using System Dynamics models (Santos *et al.*, 2002). Several System Dynamics business applications have been produced by Sterman (2001).

There is further discussion to be had regarding System Dynamics and related theories. For the further theories surrounding the subject of System Dynamics and related theory, reference shall be made to Größler *et al.* (2008) where the link between System Dynamics structural theory and Operations Management is conceptualized. In another study, Größler and Milling (2007) discussed the characteristics and distinct properties of inductive and deductive System Dynamics modeling. Größler (2007) provided insights on the implementation issues of failed System Dynamics projects. Repenning (2003) highlighted the errors and lessons learned by System Dynamics. For further theoretical developments and a detailed literature survey reference is made to Sterman (2000 and 2001) and Kirkwood (1998).

In this thesis, System Dynamics, the software, Forio Business Simulations (<http://forio.com>), is used in combination with Microsoft (MS) Excel. Equations are altered with MS Excel tools; and the Forio tool is used to visualize related causalities and sketch causal diagrams using a graphical user interface. Simulation runs are taken in combination. As mentioned by Santos *et al.* (2002), measuring and managing the performance of a full scale, real-life system is complex and difficult. The combined use of the System Dynamics tools helps in dealing with the dynamic

complexity of the real-life manufacturing system. This provided a risk-free environment, which could analyze the relevant cause-and-effect relationships and test several alternative what-if scenarios.

### **4.2.3 A hybrid usage of Queuing Theory Based Modeling and System Dynamics Based Modeling**

The final discussion here will be on why and how these two methods are integrated. The integration concept is motivated by the potential synergy derived through the hybrid use of Rapid Modeling and System Dynamics modeling tools. As Bertrand and Fransoo (2002, p. 246) highlighted: “*System Dynamics provides a theoretical framework for understanding the dynamic or non-stationary behavior and feedback characteristics of the system; whereas Queuing Theory provides a theoretical framework to understanding the steady-state or stationary behavior of the system under variability of orders and resources*”.

Queuing-theory-based modeling and System Dynamics modeling are distinct, but complementary methods in a way that while one method provides insights on dynamic behavior, the other one provides insights on stationary behavior. For this purpose, methods are integrated using a stepwise approach. The Rapid Modeler is used in combination with System Dynamics modeling software. Rapid Modeler provides a base to quantify how lead time reduction related decisions impact related operational measures (i.e. utilization, setup utilization, total work-in-process inventory and average flow time). In the next stage the System Dynamics model uses these measures and some other input variables to quantify how customer-related and financial measures are affected. Consequently, using this stepwise procedure, shows how lead time reduction related decisions influence future performance and demand. By spreading the analysis over a long time horizon it is easier to analyze the impact of external factors (i.e. changing market conditions and situational factors) on the overall system.

The integrated use of these two approaches provides a synergy, a better way of exploring the dynamic complexity of the system thereby, enhancing complete understanding of the mechanics of lead time reduction and complexity issues raised by multiple use performance dimensions. Some studies in the literature also indicated the potential synergy that can be derived from integrated use of System Dynamics modeling with other quantitative methods/tools (i.e. integrated use of System Dynamics and Multi-criteria Decision Analysis, Santos *et al.*, 2002; integrated use of optimization methods and System Dynamics modeling, Coyle, 1985).

In Figure 4.10 (*shown on page 96*) the integrated use of Rapid Modeler with System Dynamics modeling is illustrated from a global perspective, covering lead time reduction – performance interactions and the impacts of internal and external factors.

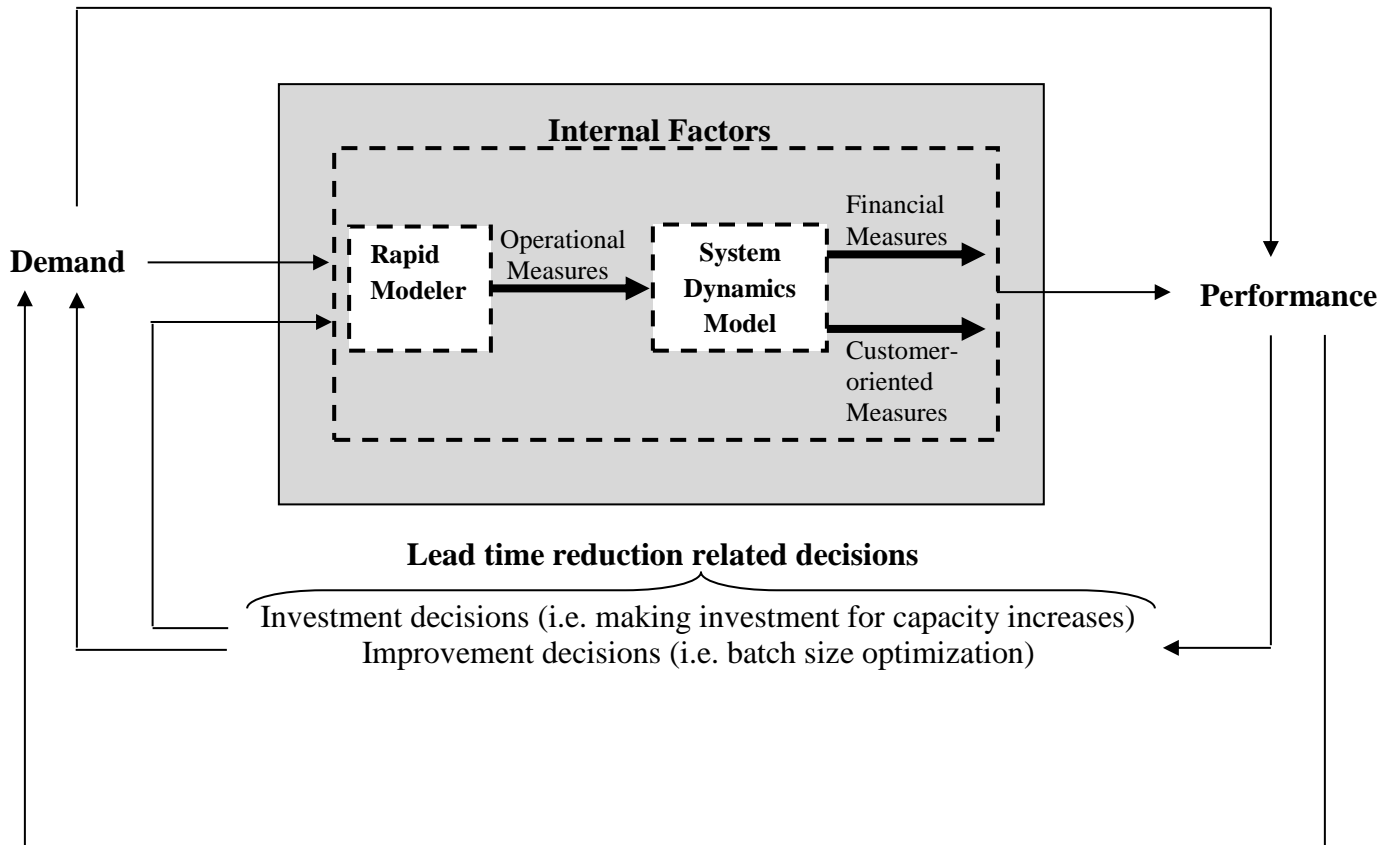


Figure 4.10: Global perspective of the integrated performance evaluation framework.

## **Chapter 5**

# **Lead time reduction strategies in the glass industry: Integrated analysis of buffer configuration and loading policies**

This chapter focuses on the integrated analysis of lead time reduction strategies (locating bottleneck capacity buffers, eliminating sources of waiting and reducing variability) on system performance. This study is motivated by certain characteristics of the glass manufacturing industry. In particular, focus has been on analyzing how buffer configurations, bottleneck station loading policies and related dependencies affect the operational performance of a real-life glass manufacturing system. The study shows that increased throughputs and reduced lead times are possible without the need for extra capacity increases in bottleneck resources.

### **5.1 Introduction**

Selection of optimal buffer configuration and management of related inventories have always been a major concern in Operations Management. The determination of the appropriate buffer configuration is critical due to the direct impact on production efficiency, costs and customer service level (Altiok and Stidham, 1983; Mohsen and Shanthikumar, 1989; Yamashita and Altiok, 1998). However, it is somewhat challenging to uncover the appropriate buffer sizes. Inventory levels should be sufficient enough to hedge uncertainties, avoid any stock outs and penalty costs, but extra inventory levels should also be avoided so as not to increase inventory carrying costs and lead times. Therefore, determination of the optimal buffer inventory level is necessary to reach the desired operational efficiency and financial performance.

In a typical production line, units move continuously through a sequence of stations and buffers, which are located between serially or parallel connected workstations. The production process starts with the raw materials and materials follow the production line until they are converted into finished products. In an ideal system where there are no variations in the arrival of production orders or in the production process, buffer inventories should be zero. However, in real-life, there are variations in the demand process (i.e. varying order times) and in the production process (i.e. varying setup and process times). Furthermore, unexpected events, such as machine failures and temporary machine stoppages may occur. This causes problems along the material flow. The stoppage of machine and material flow causes station *blockages* and *starvations*. A station is blocked when the succeeding station is not idle and the buffer corresponding to that station is full. A station starves when related buffers are empty and there is no material transfer from the previous stations due to a malfunction or busy machine. Stoppages and starvations have negative impacts on the efficiency of the production line (Yamashita and Altioik, 1998). Thus, extra buffer inventories are put in place to provide material to stations when there is a material shortage. In this way, buffer inventories maintain the continuity of the production process while absorbing the negative effects of variability. As a result, the correct determination of buffer capacity is important in terms of reducing the effects of variability, improving operational performance (i.e. waiting and lead times) (Gershwin and Schor, 2000) and reducing costs (waiting or blocking related costs and excess inventory costs) (Hopp *et al.*, 1990).

Optimal buffer size allocation is a complex design issue. In order to determine the buffer size there has to be a tradeoff between the buffer size, necessary amount of inventory (stock safety level), inventory carrying costs and increased production efficiency. On the one hand, very small buffer inventories cause increased waiting and lead times. On the other hand, carrying an excessive amount buffer inventory requires additional capital investment for the floor space allocated for the buffers. Thus, buffer (size) allocation is a critical design issue and this interesting problem has attracted the attention of several researchers. There is a significant amount of literature on buffer (size) allocation problems. Table 5.1 (*shown on page 99*) provides a brief overview of some of these studies.

Table 5.1: Brief overview of buffer (size) allocation literature <sup>(\*)</sup>

Reference	Target buffer (size) determination objective
Yamashita and Altiok (1998)	Minimization of total buffer space for a desired output rate
Altiok and Stidham (1983), Smith and Daskalaki (1988)	Maximization of profit
Ho <i>et al.</i> (1979), Soyster <i>et al.</i> (1979), Yamashita and Suzuki (1988), Jafari and Shanthikumar (1989), Shi and Men (2003)	Maximization of throughput rate
Anderson and Moodie (1969), Min and Leon (1989), Kut (1997)	Minimization of cost for a given buffer capacity
So (1997), Yamashita and Altiok (1998), Gershwin and Schor (2000)	Minimization of the buffer space subject to a target system performance measure

<sup>(\*)</sup> Source: Reiner *et al.* (2010).

Buffer (size) allocation literature is centered on two types of approaches: *Exact models* and *Approximation models*. The exact models focus on the analysis of the steady-state performance of systems. These models are based on Markov chains and steady-state probability distributions of the jobs (Liu and Lin, 1994; Yamashita and Altiok, 1998). Approximation models are used to decompose complex systems (large queuing networks) into a smaller set of systems (two-node systems) where the steady-state performance of each sub-system is studied separately (e.g. Dallery and Frein, 1993). An iterative procedure aggregates sub-results and produces an overall performance approximation for the complete system.

Finding the optimal buffer allocation/buffer size is a difficult stochastic, integer and nonlinear programming problem (Smith and Cruz, 2005). There are no closed-form expressions of the buffer allocation problem (neither for the objective function nor for the problem constraints). Therefore, meta-heuristics based solutions (Bulgak *et al.*, 1995; Sabuncuoglu *et al.*, 2006; Spinellis and Papadopoulos, 2000; Vitanov and Harrison, 2009) and simulation based solutions (Gershwin and Schor, 2000) are proposed for this problem. In Table 5.2 (*shown below*) some of the solution methodologies proposed in literature are classified:

Table 5.2: Solutions methodologies proposed for the buffer (size) allocation problem <sup>(\*)</sup>

Reference	Proposed methodology
Smith and Cruz (2005)	Closed-form expressions of the M/M/1/K and M/G/1/K systems
Bulgak <i>et al.</i> (1995), Shi and Men, 2003; Sabuncuoglu <i>et al.</i> (2006), Spinellis and Papadopoulos (2000), Vitanov and Harrison (2009)	Meta-heuristics based
Gershwin and Schor (2000)	Simulation based
Reiner <i>et al.</i> (2010)	Rapid Modeling & simulation based

<sup>(\*)</sup> Source: Reiner *et al.* (2010).

The literature is limited in terms of studies analyzing buffer allocation issues in a stochastic and real-life manufacturing system (Koo *et al.*, 2007). The majority of the research has missed out buffer capacity related dynamics and the integrated effects on system performance. As a result, an analysis framework for the buffer (size) allocation problem motivated by the specifications and particular needs of the glass production industry is proposed. A simulation based analysis of buffer configuration/platform loading policies is suggested. Two types of simulation approaches were used. A *discrete-events simulation model* is used to analyze the dynamic dependencies of platform loading policies and related buffer allocation scenarios. *Rapid Modeling* is used to analyze the dynamic effects of buffer based decisions on operational performance, in terms of machine and labor utilizations, throughput, WIP and lead time. The current actual system performance is used as the benchmark point.

In Section 5.2 (*see below*), the theoretical background of the buffer configuration and platform loading problem will be provided. In Section 5.3 (*on page 101*), the problem details and a real-life example of a glass industry will be discussed. In Section 5.4 (*on page 103*), alternative scenarios and a solution proposal will be provided. Within Section 5.5 (*on page 107*), the experimental study will be explained. And finally, in Section 5.6 (*on page 114*), concluding remarks will be provided.

## **5.2 Theoretical background and analytical framework**

Optimal buffer allocation problems are generally defined as finding the optimal buffer allocation or optimal buffer size (Smith and Cruz, 2005). However, within framework of this particular study, an investigation is undertaken by loading a bottleneck machine with glasses of different sizes in combination with different buffer characteristics. For this purpose, proposals were made to integrate a solution for two related problems and therefore, analysis was carried out to uncover the dynamic impact of alternate buffer scenarios and platform loading policies on operational performance.

The primary target is to improve the capacity of the bottleneck platform by optimizing the loading performance of the rectangular platform surface facilitated by multiple buffers. For the purposes of this, there are two optimization objectives (Reiner *et al.*, 2010):

- i) *Optimization of 'glass buffer combinations' to load the platform*: For this, the classification of pieces is based upon their size and allocation to related buffers, which are located in front of the bottleneck station;

ii) *Optimization of 'orientation of glass sheets' to maximize the loading on the platform:* For this, a definition for a set of glass orientation rules is needed to maximize the areal usage and a simulation of alternative scenarios is undertaken to find the best possible orientation.

Due to the complexity of the problem, the existing buffer allocation/size optimization approaches were not applicable to this problem setting. For the glass industry, the adoption of a customized approach is necessary, which is derived from a well-known '*two-dimensional cutting stock optimization problem*.' This particular issue has been extensively studied in literature (Christofides and Whitlock, 1977; Israni and Sanders, 1982; Buzacott and Yao, 1986; Cheng *et al.*, 1994; Lai and Chan, 1997; Soke and Bingul, 2006).

The cutting-stock problem refers to finding an optimal arrangement of the multiple items in a single or multi-dimensional space, whilst at the same time, minimizing material wastage and costs or maximizing the allocation/arrangement of items efficiently. The precise nature of certain physical constraints (i.e. area, length, width and production quantity, etc.) can lead to different mathematical characteristics and increased complexities. Exact solutions and heuristics based solutions are proposed for the two-dimensional cutting stock problem (genetic algorithm based: Gonçalves, 1997; Soke and Bingul, 2006; Beasley, 2004; Lodi *et al.*, 2002; tabu search and simulated annealing based: Bulgak *et al.*, 1995; Lai *et al.*, 1997; Alvarez *et al.*, 2007; Leung *et al.*, 2001).

Cutting-stock problems can be classified in various ways, depending on the problem dimensions (i.e. *one-dimensional*: Cutting of water pipes, steel bars, electric wires; the *two-dimensional*: Cutting of wood sheets, clothes, glass and *three-dimensional*: Packing and container allocation). The types of problems and constraints may vary from industry to industry (i.e. wood, paper, clothing, film, metal or automotive industries). However, the approach used here can be generalized to serve and fit various industries with similar bottleneck station characteristics (Reiner *et al.*, 2010).

### **5.3 Empirical problem illustration**

This study was undertaken with the cooperation of an industrial partner from the glass manufacturing industry. The current glass market is highly competitive. Due to the increasing variety of products and higher specifications, there is a rise in customer expectations as well as the number of customer orders. This situation seriously effects production, which is very sensitive to the needs of the market (i.e. customer-order-driven). Managers are facing capacity

problems, which forces them to find efficient solutions to increase current throughput and reduce current lead times, preferably without having any need for extra financial investment (i.e. buying new machines). Thus, the goal here is to maximize the throughput and increase the bottleneck platform loading efficiency with respect to buffer space limitations and technical constraints. A related production process flow chart is given in Figure 5.1 (*shown below*):

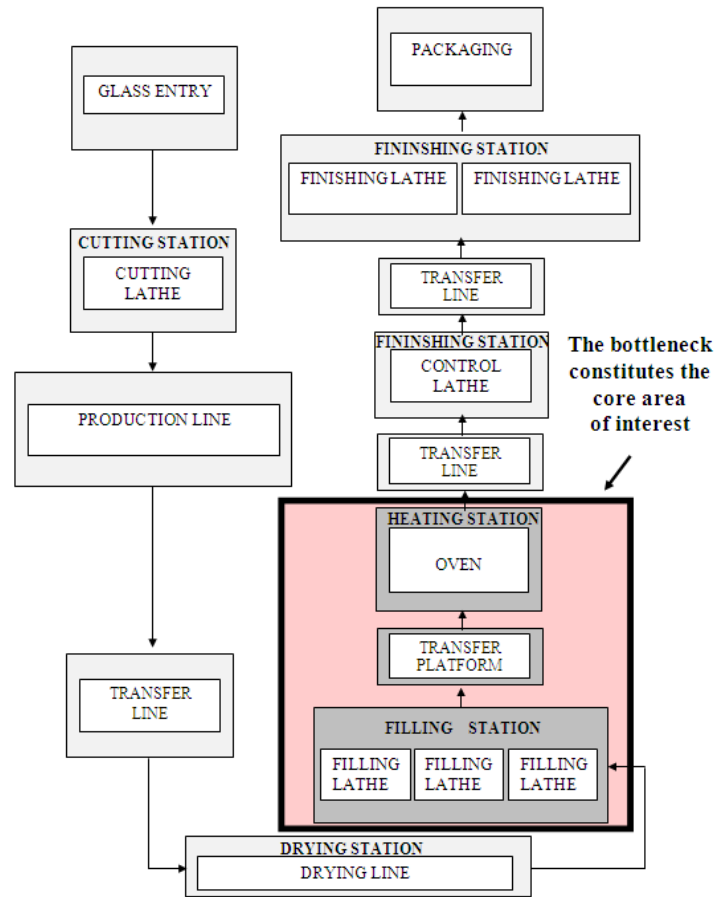


Figure 5.1: Current glass production process flow chart (Source: Reiner *et al.*, 2010).

According to an initial analysis of the system, the oven is the bottleneck, followed by the filling station, with the second highest utilization. These two stations have the lowest performance in terms of least throughput rate and longest station processing time. Platforms are not efficiently loaded. Each platform has a relatively low number of glass pieces and there is a considerably large space between the pieces. System throughput rate and total flow times are directly affected by the capacity of these stations. As a result, the priority of management is to increase the bottleneck station capacity. To this end, it is highly critical to improve the oven platform usage through introducing an intelligent glass loading/orientation strategy. Thus, any capacity increase at this station will improve overall production capacity and reduce processing lead time.

Filling and heating stations have simple process mechanics. Semi-finished products have to pass through the filling station where single or multiple glass chambers are filled with a protective material. The stability of glass-material integration is obtained through a heating process. For this, glass chambers have to be placed on oven platforms where they are heated for a certain amount of time. The number of glass sheets per platform may change depending on the platform capacity (available platform surface) and the size of the glass (width and length), which are available in the buffer. For technical reasons, one glass should not wait too long in the buffer; the first item in the buffer should be used first. Thus, buffers are managed with a First-In-First-Out (FIFO) policy. However, the FIFO policy is an obstacle that requires the improvement of the oven platform usage. The number of pieces to be placed on a single oven platform is limited with this strategy. Thereby, current oven platform usage is relatively low.

## 5.4 Proposed solution

The proposed solution began at the filling station; since any filling procedure related improvement impact the performance of the platform space usage. A complete change in buffer configuration is suggested, along with a new filling policy to maximize the platform load through maximum possible surface usage.

There are two major physical constraints: (i) each platform is bound with a usable surface area of  $3000mm \times 2000mm$ ; (ii) each platform is separated in the middle by a reference line. This reference line is the key to the loading operation. Glass loading should start from the bottom edge of the platform since the positioning of glass on the reference line can be feasible only if no glasses have crossed this line (*see Figure 5.2, shown below*):

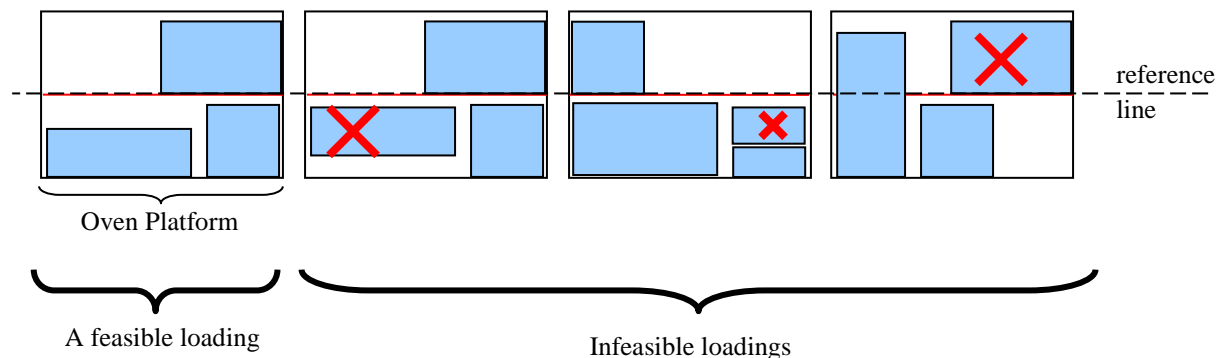


Figure 5.2: Illustration of feasible and infeasible loadings  
(Source: Reiner *et al.*, 2010).

The platform surface maximization problem for a given set of available glasses is defined as follows (Reiner *et al.*, 2010):

Let  $w_j, h_j$  be respectively the width and the height of glass  $j$  (expressed in *mm*) and consider the following decision variables (the width designates the smallest value);

$$O_j = \begin{cases} 0 & \text{if glass } j \text{ is oriented as portrait} \\ 1 & \text{if glass } j \text{ is oriented as landscape} \end{cases}$$

$$B_j = \begin{cases} 1 & \text{if the glass } j \text{ is positioned in the bottom area of the platform (below the reference line)} \\ 0 & \text{if the glass } j \text{ is positioned in the top area of the platform (above the reference line)} \end{cases}$$

$$T_j = \begin{cases} 1 & \text{if the glass } j \text{ is positioned in the top area of the platform (above the reference line)} \\ 0 & \text{if the glass } j \text{ is positioned in the bottom area of the platform (below the reference line)} \end{cases}$$

$$\text{Objective function: } \max z = \sum_i (B_i + T_i)w_i h_i$$

*Constraints:*

$$\text{C1: } B_j + T_j \leq 1, \forall j$$

$$\text{C2: } \sum_i B_i (O_i w_i + (1 - O_i) h_i) \leq 3000$$

$$\text{C3: } \sum_i T_i (O_i w_i + (1 - O_i) h_i) \leq 3000$$

$$\text{C4: } B_j (O_j h_j + (1 - O_j) w_j) \leq 2000, \forall j$$

$$\text{C5: } \left( \sum_i T_i \right) [B_j (O_j h_j + (1 - O_j) w_j) - 1000] \leq 0, \forall j$$

$$\text{C6: } T_j (O_j h_j + (1 - O_j) w_j) \leq 1000, \forall j$$

*Explanation:*

C1: insures that the glass is positioned either on the bottom part of the platform or on the top part  
(The glass is not loaded if the  $B_j + T_j = 0$ )

C2: insures that the glasses on the bottom part fit horizontally on the platform

C3: insures that the glasses on the top part fit horizontally on the platform

C4: insures that the glasses on the bottom part fit vertically on the platform

C5: insures that, if at least one glass crosses the reference line then no glass must be put on the top part of platform (all  $T_i$  must be 0)

C6: insures that the glasses on the top part fit vertically on the platform

An additional constraint can be added to ensure a certain glass  $j$  can be only used if glass  $i$  is used (e.g. FIFO). Thus:

$$C7: T_j + B_j \leq T_i + B_i, \forall i, j$$

Solving this problem is highly complex. For this reason, a meta-heuristics and a simulation based approach is used to find near-optimal solutions. However, within the glass industry, specific constraints pose extra difficulties and it would be infeasible to implement near-optimal solutions in reality. Workers are not trained to perform complex 2-D glass arrangements and complex allocations on platforms. Furthermore, time limitations do not provide workers any time flexibility for the selection of suitable glass sizes out of multiple buffers. Therefore, a problem specific, simple, efficient heuristic approach is proposed:

- buffers are redefined and reclassified by considering glass dimensions;
- workers are provided wider glass selection/combination alternatives in order to maximize platform surface usage;
- each buffer is defined as a cluster and for each cluster an orientation (portrait, landscape) rule is suggested to minimize surface loss.

The following constraints are taken into consideration during the heuristic development:

- The solution should target the minimization of buffers;
- The filling policy should be simple enough to implement and it should be efficient enough to solve the problem;
- The glasses having the *width/length* < 1/2 ratio (*1:2 rule*) should only be positioned in landscape orientation to warrant the technical specifications.

Based on these constraints, only a set of glass class definitions is identified as feasible. Therefore, only for these particular glass classes are orientation rules defined. These orientation rules are given in Table 5.3 (*shown on page 106*):

Table 5.3: Class definitions and orientation possibilities (W: width, L: length) (\*)

Class definition	Orientation Possibility	Orientation Rule
AA1 - width: 0-1000, length: 0-1000	2 Orientation	Max (W, L) ≤ 1000 and 1:2 rule
AA3 - width: 0-1000, length: 2000-3000	1 Orientation	Max (W, L) > 2000 and Min (W, L) ≤ 1000 and 1:2 rule
BB1 - width: 1000-2000, length: 0-1000	2 Orientation	1000 ≤ Max (W, L) ≤ 2000 and Min (W, L) ≤ 1000 and 1:2 rule
BB2 - width: 1000-2000, length: 1000-2000	2 Orientation	Max (W, L) ≤ 2000 and Min (W, L) > 1000 and 1:2 rule
BB3 - width: 1000-2000, length: 2000-3000	1 Orientation	Max (W, L) > 2000 and Min (W, L) > 1000 and 1:2 rule

(\*) Source: Reiner et al. (2010).

Depending on the orientation rule, glass classes AA3 and BB3 are limited to one possible orientation, whereas classes AA1, BB1 and BB2 have two possible orientations. Reference line constraints are a determining factor for the feasibility of glass class definitions (*related boundary mechanics are illustrated in Figure 5.2, shown on page 103*). For instance, any landscape or portrait oriented glass sheet in class AA1 does not cross the reference line. This leaves room for another glass sheet to be placed on the top halve of the platform. On the other hand, any glass in class BB2 (due to its dimensions), either landscape or portrait, crosses the reference line, leaving no room for any other glass sheet to be positioned on the top half of the platform. For classes AA1 and BB2, the portrait orientation is selected; and the sheets of glass, having *width/length* < 1/2 ratio, are positioned in landscape orientation (due to '1:2 rule' and for technical reasons). The only critical class is the BB1 in terms of a landscape/portrait orientation decision. Only in this category, a special orientation rule is defined, which is based on a 'regret/lost function.' This additional rule is defined in Table 5.4 (*shown below*):

Table 5.4: Regret/lost function defined for glass class BB1 (\*)

Position	Name	Lost function
vertical orientation	'Orientation 1'	$Lost\ 1 = (2000 - \text{MAX}(W, L)) * \text{MIN}(W, L)$
horizontal orientation	'Orientation 0'	$Lost\ 0 = (1000 - \text{MIN}(W, L)) * \text{MAX}(W, L)$

(\*) Source: Reiner et al. (2010).

The final orientation decision is made by comparing the difference between the value of lost functions and making a comparison with the difference with the area of the glass, which is under consideration ( $(Lost\ 0 - Lost\ 1) / (Glass\ Area)$ ). If this value is lower than a certain threshold

percentage, then *Orientation 0* is selected; otherwise, *Orientation 1* is selected. This decision criterion is summarized as follows:

- decide for *Orientation 0* IF  $((Lost\ 0 - Lost\ 1) / (Glass\ Area)) < threshold\ \%$  ;
- decide for *Orientation 1* IF  $((Lost\ 0 - Lost\ 1) / (Glass\ Area)) \geq threshold\ \%$  .

The threshold value is determined by the company managers. The orientation of the glass may change based on this value. Furthermore, the total number of glass sheets that fall into the categories of *Orientation 1* or *Orientation 2* is also determined by this factor.

During the experimental phase of this research, the chosen threshold value was thirty percent, which indicates the areal loss between two orientations (*Lost0 – Lost1*) is thirty percent of the total area. The smaller the threshold, the more glass sheets are likely to be positioned in portrait orientation; therefore, the more glass sheets are likely to cross the reference line. However, this is not a desirable situation for the company. On the other hand, increasing the value of threshold would cause more areal losses. For example, an illustration would be the percentage of glass sheets falling into each class definition based on yearly production data (*see Table 5.5, shown below*):

Table 5.5: Class definitions and percentages of glasses respectively <sup>(\*)</sup>

Class definition	Percentage of glasses in this class	
AA1- width: 0-1000, length: 0-1000	<b>27.10 %</b>	
AA3 - width: 0-1000, length: 2000-3000	<b>12.51 %</b>	
BB2 - width: 1000-2000, length: 1000-2000	<b>7.25 %</b>	
BB3 - width: 1000-2000, length: 2000-3000	<b>3.48 %</b>	
BB1 - width: 1000-2000, length: 0-1000	<i>Orientation 0</i>	<i>Orientation 1</i>
	<b>30.80 %</b>	<b>18.86 %</b>

<sup>(\*)</sup> Source: Reiner et al. (2010).

## 5.5 Experiment and results

The experiments were conducted on a set of feasible scenarios and the performance of each scenario is compared to the actual system performance. Three consecutive scenarios (I to III) were defined by considering various input rates and demand settings. Each scenario is divided into five sub-scenarios (1 to 5) where different orientation and priority rules (service discipline) were used, along with various values for the number of buffers and number of filling stations. These scenarios are shown in Table 5.6 (*shown on page 108*):

Table 5.6: Simulation scenarios and sub-scenarios (\*)

Scenario		Explanation		
<b>I</b>		<b>Without increase</b> - the input factor of 1.00		
<b>II</b>		<b>Increasing the input</b> by factor of 1.25		
<b>III</b>		<b>Increasing the input</b> by factor of 1.50		
Sub-scenario (SUcn)	Buffer Number	Service Discipline	Number of Filling Stations	Orientation
1	1 (common)	FIFO	3	landscape
2	1 (common)	FIFO	3	defined (1:2 rule)
3	6	Buffer heuristic	3	defined (1:2 rule)
4	1 (common)	FIFO	4	defined (1:2 rule)
5	6	Buffer heuristic	4	defined (1:2 rule)

(\*) Source: Reiner *et al.* (2010).

Scenario I is in combination with *Sub-scenario 1* reflects the actual situation. The actual scenario is a single buffer system (based on the FIFO service discipline) with three filling stations (*see Figure 5.3 below*). A single (common) buffer case is compared to a multi-buffer case where each buffer corresponds to a single cluster as shown in Figure 5.4 (*shown below*):

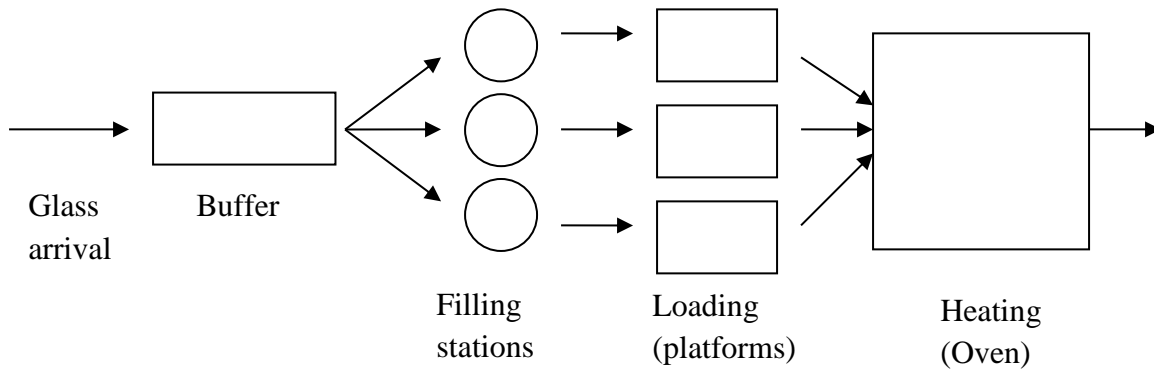


Figure 5.3: Single buffer system (actual) (Source: Reiner *et al.*, 2010).

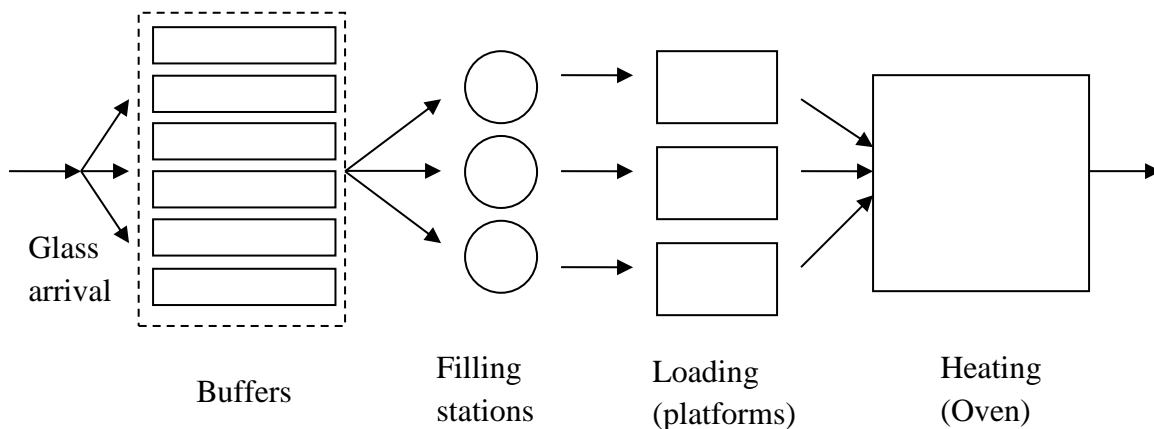


Figure 5.4: Multiple buffer system (proposed) (Source: Reiner *et al.*, 2010).

*Sub-scenario 3* and *Sub-scenario 5* analyze the effects of the multi-buffer system. Two service disciplines, FIFO and the glass loading strategy are compared. *Sub-scenario 4* and *Sub-scenario 5* analyze the effects of the addition of one more filling station to the system.

The simulation results are based on a simulation run of ~170 working days (3 shifts par day and 8 hours per shift). The simulation length (of each replication) is about *14688000 seconds*. Interarrival times and variability are estimated based on a yearly production data of ~85000 articles. Interarrival time statistics are provided in Table 5.7 (*shown below*). Unit processing times are estimated based on observations of unit processing times for ~250 glasses pieces with varying dimensions. Processing time statistics are provided in Table 5.8 (*shown below*).

A regression model is built to estimate the components of processing time. The regression model is of the form:  $Y = a + b X$  where  $a$  is the fixed time representing opening, closing and handling operations;  $b$  is the variable time proportional to the dimensions of the glass;  $X$  is the filled volume of the glass (*Width x Length x constant thickness*) and  $Y$  is the processing time,  $Y = 126.80987 + 0.0002 X$ . The estimated value for the squared coefficient of variation of the service time is approximately  $F.SCV = 0.3$  (Reiner *et al.*, 2010).

Table 5.7: Interarrival Time Statistics (in seconds) (\*)

Class definition	Mean ( $\mu$ )	Coefficient of variation
AA1	<b>841.97</b>	<b>3.82</b>
AA3	<b>11163.41</b>	<b>1.92</b>
BB1	<b>934.48</b>	<b>5.29</b>
BB2	<b>3867.19</b>	<b>2.57</b>
BB3	<b>12092.75</b>	<b>1.78</b>

Table 5.8: Processing Time Statistics (in seconds) (\*)

Class definition	Mean ( $\mu$ )	Coefficient of variation
AA1	<b>279.77</b>	<b>0.46</b>
AA3	<b>352.73</b>	<b>0.33</b>
BB1	<b>487.48</b>	<b>0.78</b>
BB2	<b>415.00</b>	<b>0.64</b>
BB3	<b>501.45</b>	<b>0.32</b>

(\*) Source: Reiner *et al.* (2010).

### 5.5.1 Results of Scenario I

The following performance measures are used to compare different sub-scenarios (see Table 5.9):

Table 5.9: Performance measures used to compare the scenarios<sup>(\*)</sup>

<i>platform utilization:</i>	the ratio of ‘ <i>surface of all glasses produced per period</i> ’ to ‘ <i>number of platforms per period x theoretical surface of the platform</i> ’
<i>mean pcs/Platform:</i>	the average number of glass pieces located per platform
<i>mean buffer length:</i>	the average number of glass pieces that can be stored at a buffer space
<i>mean labor utilization:</i>	the proportion of time that a labor is used by the filling station (expressed as an average)
<i>total labor utilization:</i>	the sum of average proportion of time the labor is busy (mean labor busy) and the average proportion of time the labor is blocked by the system (mean labor blocked)

<sup>(\*)</sup> Source: Reiner et al. (2010).

The multi-buffer scenarios of *Sub-Scenario 1* to *Sub-Scenario 3*, and *Sub-Scenario 5* performed better than a single common buffer case in terms of increased mean pieces per platform and decreased mean buffer inventories. The capacity of the oven is improved in combination with the filling station. In *Sub-Scenario 5*, the mean labor utilization of the filling station is decreased due to the increased number of filling stations. Based on the results, it was observed that multiple buffers provide a throughput increase based on the increased capacity. However, this leads to the question of the limits of this capacity expansion: *How much more input can be handled?* Through Scenarios II and III, the feasibility of the system was tested using a 25% and 50% input increase. One of the benchmark performances is the current platform utilization (Scenario I), which is 25.49%. Simulation results are provided in Table 5.10 (shown below):

Table 5.10: Simulation results of Scenario I (F.SCV=0.3)<sup>(\*)</sup>

	<b>Mean pcs/Platform</b>	<b>Mean buffer length</b>	<b>Mean labor utilization</b>	<b>Mean labor busy</b>	<b>Mean labor blocked</b>
<i>Sub-Scenario 1</i>	<b>1.91</b>	3.41	64.64	58.33	6.31
<i>Sub-Scenario 2</i>	<b>1.94</b>	2.64	62.74	58.14	4.59
<i>Sub-Scenario 3</i>	<b>1.95</b>	2.15	62.14	58.24	3.9
<i>Sub-Scenario 4</i>	<b>2</b>	0.84	50.25	43.71	6.54
<i>Sub-Scenario 5</i>	<b>2</b>	0.68	49.69	43.5	6.19

<sup>(\*)</sup> Source: Reiner et al. (2010).

### 5.5.2 Results of Scenario II

The system feasibility was not affected from the 25% input increase; especially *Sub-Scenario 3* and *Sub-Scenario 5*, which were critical in terms of handling input increase. However, new orientation rules and the use of multi-buffers did not have any negative effects on performance and the system is still able to handle the 25% input increase.

Additionally, there is a significant decrease in mean buffer inventories when compared to the initial sub-scenario (*Sub-Scenario 1*). Among those multiple buffers scenarios, the addition of the fourth filling table (*Sub-Scenario 4* and *Sub-Scenario 5*) leads to improved performance in terms of the least mean buffer inventory and mean labor utilization (see Table 5.11, shown below). There is a slight increase in platform utilization 31.93% compared to Scenario I.

Table 5.11: Simulation results of Scenario II (F.SCV=0.3) (\*)

	Mean pcs/Platform	Mean buffer length	Mean labor utilization	Mean labor busy	Mean labor blocked
<i>Sub-Scenario 1</i>	2.07	30.54	83.13	72.84	10.3
<i>Sub-Scenario 2</i>	2.12	18.47	80.39	72.84	7.56
<i>Sub-Scenario 3</i>	2.14	13.61	78.88	72.88	6
<i>Sub-Scenario 4</i>	2.21	4.31	66.25	54.72	11.53
<i>Sub-Scenario 5</i>	2.23	3.04	64.62	54.65	9.98

(\*) Source: Reiner et al. (2010).

### 5.5.3 Results of Scenario III

In Scenario III, system feasibility is affected as the process configuration and system resources are not able to handle the 50% input increase. A high input increase leads to increased work in the process for *Sub-Scenario 1*, *Sub-Scenario 2* and *Sub-Scenario 3*. Only for *Sub-Scenario 4* and *Sub-Scenario 5*, the system stability is at acceptable levels. This is achieved through the addition of a filling table. There is also a significant difference among the platform utilizations, because of this additional filling table. Simulation results are shown in Table 5.12 (shown below):

Table 5.12: Simulation results of Scenario III (F.SCV=0.3) (\*)

	Platform utilization	Mean pcs/Platform	Mean buffer length	Mean labor utilization	Mean labor busy	Mean labor blocked
<i>Sub-Scenario 1</i>	37.49	2.14	831.64	98.43	85.46	12.97
<i>Sub-Scenario 2</i>	37.91	2.2	369.28	96.26	86.43	9.83
<i>Sub-Scenario 3</i>	38.12	2.25	279.02	95.02	87.06	7.96
<i>Sub-Scenario 4</i>	38.4	2.4	32.68	83.36	65.83	17.53
<i>Sub-Scenario 5</i>	38.4	2.45	16.65	79.8	65.72	14.08

(\*) Source: Reiner et al. (2010).

### 5.5.4 Effects of variability on system performance

In addition to quantitative insights provided on operational factor interactions, operational effects of variability on system performance (i.e. buffer length, labor utilization, platform loading, etc.) were analyzed and quantified. System performance is negatively affected by increasing variability in terms of an increase in processing times, lengthy delays and more waiting and increased lead times (Hopp and Sperman, 2006). High levels of utilization in combination with

high variability will increase the waiting times exponentially. However, acceptable levels of deterioration in system performance can be achieved by reducing variability up to tolerable limits. This is illustrated in Figure 5.5 (*shown below*) (Poiger *et al.*, 2010, based on Figure 2, p. 287):

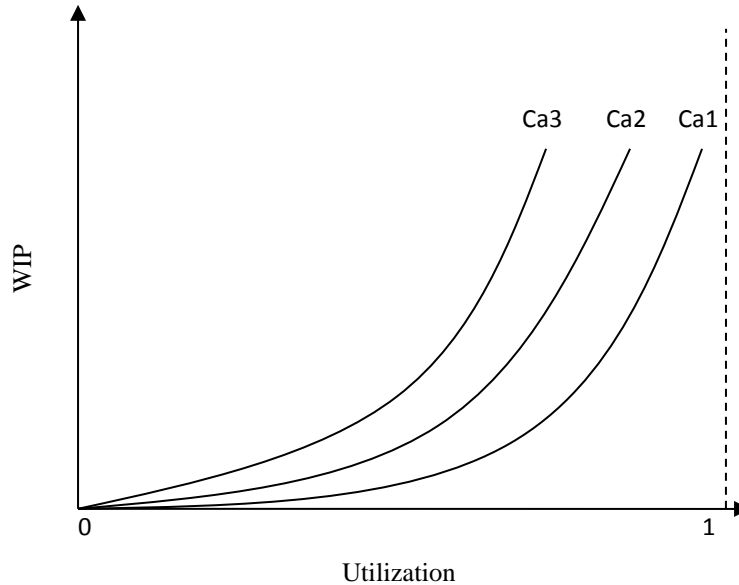


Figure 5.5: Evolution of WIP with respect to utilization regarding variability settings of a typical queuing system: Coefficients of variability  $Ca1 < Ca2 < Ca3$  (Source: Reiner *et al.*, 2010).

The impact of variability (process variability) is tested using three alternate values of the coefficient of variation (F.SCV) of labor service time:

- F.SCV = 0, which states the ideal case where there is no variation;
- F.SCV = 0.3, which states the moderate variation case;
- F.SCV = 1, which states the worst case where there is a high variation.

The effects of changing process variability on system performance is shown in terms of *mean pieces per platform*, *mean buffer length*, *mean labor utilization* and *mean labor blocked* (see Table 5.13 shown on page 113).

Scenario I is considered as a basis for variability analysis; since Scenarios II and III are performing worse when compared to Scenario I (i.e. in terms of platform utilization, pieces per platform and labor utilizations) (see Tables 5.10, 5.11 and 5.12 shown on pages 110 and 111). The higher the effects of variation, thus, the greater the number of distortions in system performance are expected under Scenarios II and III with respect to the same F.SCVs. The experimental results are provided in Table 5.13 (*shown on page 113*):

Table 5.13: Effects of variation on system performance measures (\*)

Performance measure		F.SCV=0.0	F.SCV=0.3	F.SCV=1.0
<i>Mean pcs /Platform</i>	<i>Sub-Scenario I-1</i>	1.91	1.91	1.95
	<i>Sub-Scenario I-2</i>	1.94	1.94	2.00
	<i>Sub-Scenario I-3</i>	1.95	1.95	2.01
	<i>Sub-Scenario I-4</i>	2.00	2.00	2.03
	<i>Sub-Scenario I-5</i>	2.00	2.00	2.03
<i>Mean buffer length</i>	<i>Sub-Scenario I-1</i>	2.26	3.41	6.08
	<i>Sub-Scenario I-2</i>	1.64	2.64	4.61
	<i>Sub-Scenario I-3</i>	1.46	2.15	3.78
	<i>Sub-Scenario I-4</i>	0.56	0.84	1.44
	<i>Sub-Scenario I-5</i>	0.46	0.68	1.22
<i>Mean labor utilization</i>	<i>Sub-Scenario I-1</i>	61.96	64.64	69.08
	<i>Sub-Scenario I-2</i>	60.49	62.74	66.84
	<i>Sub-Scenario I-3</i>	60.04	62.14	65.81
	<i>Sub-Scenario I-4</i>	48.5	50.25	53.28
	<i>Sub-Scenario I-5</i>	48.21	49.69	52.93
<i>Mean labor blocked</i>	<i>Sub-Scenario I-1</i>	3.72	6.31	10.9
	<i>Sub-Scenario I-2</i>	2.24	4.59	8.66
	<i>Sub-Scenario I-3</i>	1.79	3.9	7.76
	<i>Sub-Scenario I-4</i>	4.81	6.54	9.7
	<i>Sub-Scenario I-5</i>	4.52	6.19	9.11

(\*) Source: Reiner et al. (2010).

Based on the results obtained, it was observed that increasing variability has a significant impact on buffer length; as more buffers are required when variability increases. This situation is much more visible for *Sub-scenario 2* and *Sub-scenario 3* where the difference in terms of mean buffer length is increased with increasing variability. Increasing variability also impacts other performance metrics; such as average number of pieces per platform is slightly increased due to the effect of variability on the platform loading utilization. More labor and resources are needed to hedge the negative effects of variability. This has less critical effects on labor utilization, but the variability effect can be observed more clearly on the average proportion of time labor is blocked by the system. The labor blockage drastically increases under increasing uncertainties (Reiner et al., 2010).

## 5.6 Conclusion

In this chapter an industrial example of a buffer allocation problem is provided. In particular, an analysis was undertaken of the impact of different buffer characteristics and loading policies on operational performance specifically for the glass industry.

In the light of the quantitative results, it is shown that a customized glass orientation rule and the deployment of a multi-buffer policy provides better performance (compared to a single buffer case with the FIFO policy), even if variability is increasing. Lead time reduction oriented performance improvement is possible with no need for significant investments (i.e. increasing resources for the bottleneck or buying a new oven with a larger capacity). Based on the glass orientation/loading strategy and the use of multiple buffers, input increases of up to twenty-five percent can be handled. For further input increases current system analyses highlight the infeasibility of the system configuration.

The combined use of Rapid Modeler and discrete event system simulation provided a higher level of detail and the possibility of testing different complex filling policies compared to other approaches (analytical, numerical). Furthermore, the approach developed for this study provided a feasible and intuitive strategy, which is implementable in the real system. The results obtained with other approaches are approximations where various system interactions are neglected. Such solutions may lead to infeasible applications in a real-life setting.

This study can be extended with further analysis and process improvements. The overall system should be analyzed in order to identify further bottlenecks. The current filling policy could be improved or further filling policies could be defined. The heuristics used for platform loading is open to possible extension. Non-technical constraints, such as the bounding conditions of suppliers, can be integrated into the solution process.

To a certain extent, it is possible to apply this approach to other industries with similar buffer configuration characteristics and platform loading policies (Reiner *et al*, 2010).

This industrial case has contributed by enriching our understanding on the mechanics of operational performance factor interactions, which were critical for the development of the dynamic performance measurement framework.

Through this case, the reader witnesses the implications of the mathematical laws of Factory Physics (Hopp and Spearman, 2006; Sterman, 2000 and 2001). This case illustrates how lead time can be reduced effectively by understanding factors that determine the lead time.

In particular, this case shows the reader how resource interactions and dynamic dependencies, between bottleneck buffer configuration and station loading policies, considerably impact operational performance. The reader observes the effective implications of lead time reduction strategies, such as locating bottleneck capacity buffers, eliminating sources of waiting, setup times and reducing variability lead to operational performance improvement.

A common conception is to target the station with the lowest throughput capacity (bottleneck station) as the starting point for performance improvement (Koo *et al.*, 2007) (*see Section 2.2, on page 14*). However, this case shows that not only the bottleneck station should be targeted, but that a non-bottleneck station can also be critical in terms of performance improvement. It has been shown that increasing the capacity of a non-bottleneck station (filling station) contributes to increasing system capacity and throughput as well as having a positive impact on the capacity of the bottleneck station (oven). Moreover, this case provides evidence for a significant increase in capacity without needing to increase resources for the bottleneck or purchase a new oven with a larger capacity.

Another point is about the effects of variability on system performance (Hopp and Spearman, 2006; Cattani and Schmidt, 2005; De Treville *et al.*, 2004; Suri, 1998). This case successfully illustrates to the reader the negative effects of variability on buffer length, labor utilization, platform loading performance. The reader observes the high levels of utilization in combination with high variability lead to exponential increase in waiting times. The analysis of this case demonstrates that throughput increase, reduction of lead time and resource utilization are possible while considering various levels of demand variability. Furthermore, the reader is able to observe that better performance is achievable via the application of a particular station loading strategy and the usage of multiple buffers when variability increases.

The last point to mention surrounds the contribution of this case. According to Beech (2005), '*contribution to knowledge*' and '*contribution to practice*' are two of the key criteria to ensure the quality of research work. One way to contribute to existing knowledge is via the '*confirmation of existing theories.*'

In this regard, the application of lead time reduction principles and Factory Physics (Hopp and Spearman, 2006), provides the reader an illustration of mathematical relationships, principles and rules that determine the lead time in a real-life manufacturing application. Secondly, this case also contributes to practice. As stated by Beech (2005), a contribution to practice is relevant if the research is in the applied research domain and if research implications and conclusions help practitioners and decision makers by acknowledging and supporting them in business related decision making. The results of this case do provide support in real-life decision-making since the suggestions of this study were implemented by the company.

*Note:* The fundamentals of this study were first introduced and presented in the study: '*Simulation Based Analysis of Buffer Configuration and Loading Policies: An Example from the Glass Industry*' (Reiner *et al.*, 2010).

## **Chapter 6**

# **Dynamic evaluation of lead time reduction improvements: Empirical illustration through a real-life industrial case and a theoretical study**

This chapter focuses on analyzing the dynamic impacts of lead time reduction approaches on customer-oriented and financial performance based on a real-life industrial case. In particular, the effects of batch size optimization, reallocation of system resources by pooling, setup time reduction and capacity investment (i.e. buying a new machine) on customer satisfaction and corresponding financials are analyzed. The industrial production process is successfully improved. Acceptable resource utilization levels are achieved without significant cost increases and time investments. Indeed, short and long-term system performance is remarkably improved. These results reveal the fact that companies can strengthen their strategic position and competitive advantage through reduced lead times, without large scale investments. Later on in the study, and motivated by this industrial application, the integrated performance measurement framework was used to extend the findings of a System Dynamics model, which provided additional insight into the dynamic behavior of the framework.

## 6.1 Industrial application

Application of the framework is conducted in joint cooperation with a European based international polymer processing company. The company was facing capacity problems and company managers were having difficulties in satisfying customer demand. Due to increased competition in the polymer market, companies in this sector require higher levels of customer service and shorter lead times. Products are relatively simple and can be satisfied by any producer. Thus, keeping market position and maintaining customer satisfaction is highly important. However, the company's lead times were unacceptably long and this negatively affects customer satisfaction.

The company's management has a primary goal to improve the performance of the production process by reducing lead time. In particular, the main focus is on achieving acceptable resource utilization levels without costly and time consuming investments. As a result, focus was placed on resource utilization, reallocation of system resources and the optimization of batch size, as these components significantly influence the overall lead time. The goal was to optimize total system performance by reducing the lead time and without changing the complete production design. We evaluate related effects on customer satisfaction and key cost figures, which were determined by evaluating the underlying cost accounting system.

### 6.1.1 Production process definition

Company has a make-to-stock manufacturing strategy. Current process bottleneck is the extruder. Extruders are large, complex, multi-task machines where several production steps can be handled consecutively. Mainly there are four complex extruders in the system. One generic extruder is illustrated in Figure 6.1 (*shown below*):

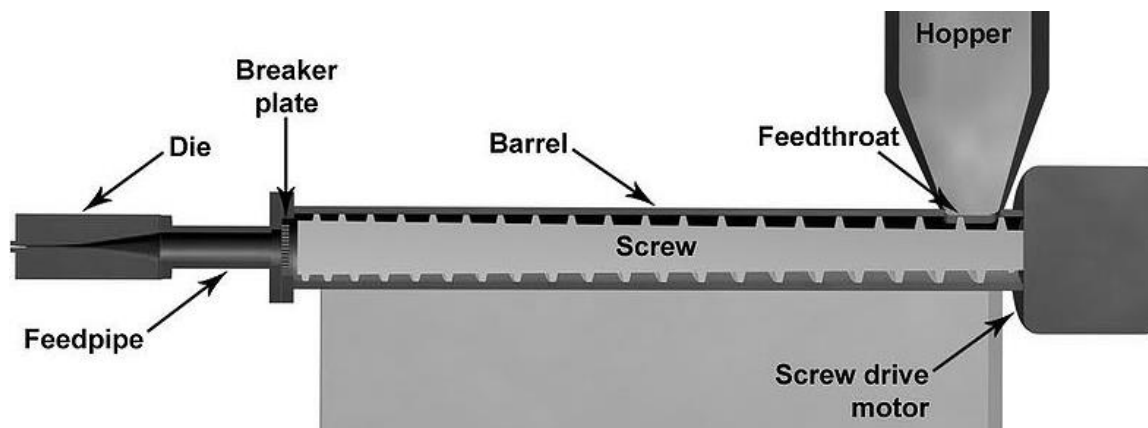


Figure 6.1: A general type of extruder  
(Due to confidentiality, a generic type of extruder is shown here; thereby this image is not linked to any company specific information; *Source*: Open source).

The extrusion is a continuous process of extrusion, painting, embossing and packaging phases. However, the process has to be discretized in order to allocate the correct labor force to the right manufacturing step. The production process starts with pre-work operations, where the operators handle the setup process, prepare the right tools and mix the right color for the extrusion. The quality of the final product is inspected by the operators. The packaging of the finished article is undertaken by the packaging operators (packers) and the transfer operators are responsible for transferring the finished products to the storage area. This process is shown in Figure 6.2 (*shown below*):

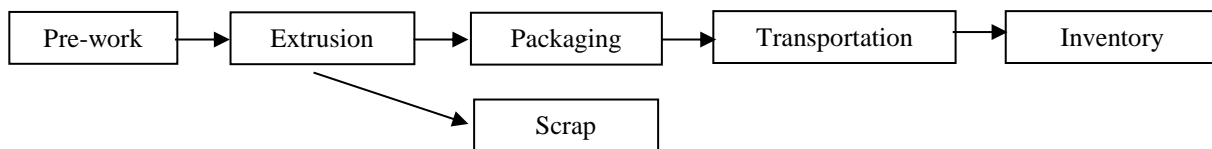


Figure 6.2: Production process in brief  
(Adopted from Figure 2, p. 21, Gläßer *et al.*, 2010a).

### 6.1.2 Empirical data and data collection

The development of the model was based on both quantitative data (i.e. demand data, production data and bill of materials, etc.) and qualitative data (i.e. logical data, process flow diagrams and manufacturing strategies, etc.).

The data collection approach used for this study is compatible with methods proposed in the literature. According to Sterman *et al.* (1997), developing and testing a model relies on primary and secondary data sources. Primary data can be collected by conducting interviews and via observational techniques (i.e. participant observation and fieldwork) or from written sources (company reports and internal data, etc.). Secondary sources refer to any published material such as journals or reputable material.

In this study, the primary data was collected through direct field observations, interview sessions with managers and related employees (i.e. supply chain manager, production manager and IT manager, etc.), historical data analysis (e.g. demand for certain products and previous company practices) and internal documents. The cost accounting system was studied in particular in order to determine the related key cost figures. Relevant scientific articles are used as a secondary source.

The accuracy of an empirical model is highly dependent on the quality of the input data. In order to validate the data, the data triangulation approach was chosen and different data types were

collected on the same phenomenon (Jick, 1979; Croom, 2009). Model assumptions are verified by comparing each cause and effect relationship with the relevant characteristics in reality.

### **6.1.3 Verification and validation of the model**

Model verification and validation is an important part of the development phase since the validity of results is critically dependent on the validity of the model, as stated by Barlas (1996, p. 183). Verifying and validating a model is more critical if models are supposed to support or be part of the decision-making process of a real-life application. As a model can be an accurate decision support tool if, and only if, it is an accurate representation of the system being modeled. Accuracy of the model can be tested via verification and validation. The verification and validation process can ensure a degree of statistical certainty that decisions made with the modeling tools are consistent with those that would be made in a real-life system.

Model validity and validation in System Dynamics methodology has critical importance, because System Dynamics models have always been subject to criticism for lacking validation or being heavily reliant on subjective and qualitative validation procedures as stated by Barlas (1996, p. 183), Reiner *et al.* (2009, p. 655) and Kleijnen (1995a). Barlas (1996, pp. 187-188) defined the model validity and validation activities in System Dynamics into two aspects: (i) philosophical aspects of model validity; and (ii) formal aspects of model validation. The philosophical aspects are related to the validity structure and the formal aspects are related to validity behavior. According to the authors, for the System Dynamics models and causal-descriptive models, generation of an accurate output is an insufficient condition to validate the credibility of the model (Barlas, 1996, p. 183). In fact, the model's structure should be 'good enough' to accurately represent the real system under study (Kleijnen, 1995b, p. 21). Therefore, the internal structure of the model should also be verified. This can be ensured by checking whether the model meets the specified requirements and whether it is an error-free implementation as intended. This step is also referred to as the '*internal structure validity*' or '*face validity*' (Reiner *et al.*, 2009, p. 655). According to Barlas (1996, p. 185), 'The validity of a System Dynamics model primarily means the validity of its internal structure'. As the second step, model validation is used to ensure that the model and real system outputs are the same (Kelton *et al.*, 1998; Law and Kelton, 1991). The model is checked to see whether it reproduces the expected behavior; namely behavioral accuracy. Thus, this step is also referred to as '*behavioral validation*' (Reiner *et al.*, 2009, p.655). The main goal of this step is to establish credibility and generate statistically accurate information about the real-life system being modeled.

Generally, the logical order for the validation procedure is to start by testing the structural validity and perceive the adequacy of the model structure, and then to proceed to formal validation activities (testing the behavior accuracy) (Barlas, 1996; Sterman, 2000). The detail of this logical sequence is illustrated by Barlas (*see Figure 1, Barlas, 1996, p. 189*).

For the internal structure validation, some methods, such as consistency checking, data flow analyses, expert reviews, inspections, walkthroughs, extreme-condition checks, behavior sensitivity tests and some others, are suggested (Kleijnen, 1995a; Balci, 1994). As part of direct structure testing, the validity of the model's internal structure is assessed by taking each causal relationship of the model and comparing the logical relationship (each individual mathematical equation) with existing knowledge about the real production system structure. For this purpose, the knowledge of experts from the company, actual performance measures provided by the company and quantitative information (i.e. annual production data of a hundred and three different articles, process flow diagrams and demand data) are used. As a secondary test, the equations of the model are also compared with generalized knowledge, which has been successfully used by previous studies in the literature (Reiner 2005; Reiner and Natter, 2007). This approach is suggested as a valid structure confirmation test by Forrester and Senge (1980). Integrating established knowledge and validated equations from previous studies into the framework development also ensures philosophical validation of this model (Reiner *et al.*, 2009, p. 655; Miser and Quade, 1988). In addition, the validity of the model's equations was evaluated under extreme conditions of some selected key variables (i.e. lead time and demand). Extreme values are assigned to these variables and related model equations are tested by comparing the model-generated behavior (the resulting value of the output variable) to the anticipated behavior of the real system under the same extreme condition. This procedure is called '*direct extreme-condition testing*' (Barlas, 1996, p. 189; Forrester and Senge, 1980). At this point, the analyses are based on the knowledge of experts from the company. During model development and coding phases, some semi-formal structure confirmation tests, such as '*walkthroughs*', '*reviews*' and '*data flow analysis*' are carried out against modeling flaws and faults (Barlas, 1996, p. 186; Baci, 1994).

As the second step, the model is evaluated to validate how accurately the major behavior patterns of the real-life system can be reproduced by the model (behavioral accuracy). In other words, the model is checked to see whether it reproduces the expected behavior (Kelton *et al.*, 1998; Law and Kelton, 1991). This is possible by measuring the degree of consistency between the outcomes of the model and reality (real-life dependencies) through a set of statistical testing procedures (Reiner *et al.*, 2009). Common statistical methods, such as Mean Absolute Percent Error

(MAPE), Theil's inequality statistics, Schruben-Turing and  $t$  tests, are proposed for this purpose (Oliva and Sterman 2001; Lin *et al.*, 2008; Reiner *et al.*, 2009; Kleijnen (1995a). In general, real-life dependencies can be generated based on empirical historical data. Real-life data can be obtained through a set of interviews or on-line/mail based surveys (Forza, 2002). However, as Reiner *et al.* (2009, p. 656) stated, historical data is not always available, depending on the system, complexity or related physical constraints. In this case, the researchers did not have access to historical data, and thus, it was not possible to perform the recommended statistical testing procedures. One of the methods proposed for evaluating the behavior accuracy is the use of graphical/visual measures of typical behavior features (*see Figure 3, p. 195, Barlas, 1996; Kleijnen, 1995a*). As a result, a comparison was made of the output figures of the System Dynamics simulations (the shape and behavior of the graphs) with the established figures from Repenning and Sterman (2001) and Sterman *et al.* (1997). Extreme-condition testing was also used at this stage, where extreme values were assigned to lead time and demand parameters, and model-generated long-term behavior (the shape of the graphs) was compared to the anticipated behavior of the real system under the same extreme condition (Balci, 1994; Barlas, 1999). Furthermore, the robustness of the results was tested by analyzing the variation of the outputs under the variation of the inputs. In addition, the behavior sensitivity of the model was tested under specific conditions where the model (and corresponding performance measures) were highly sensitive to changes with selected variables (or parameters) and the question was asked as to whether the real system would exhibit similar high sensitivity to the changes in corresponding variables or parameters (*'Behavior Sensitivity Test,' Barlas, 1996, p. 191*). For this purpose, two sets of tests were performed. First, the sensitivity of customer satisfaction and customer loyalty was analyzed against the changes in lead time. Second, the sensitivity of lead time, the WIP inventory and resource utilization was analyzed against changes in demand values. Later, as suggested by Kleijnen (1995a, p. 155), the model's behavior was checked to discover whether it was compatible with the experts judgments.

#### **6.1.4 Solution proposal**

Capacity based problems in the production line were causing long production lead times. Customer satisfaction ratings and company profit figures were not as high as expected. Management preference was to solve the capacity problem without making any investment in a new machine or hiring extra labor. As a result of this, the decision was taken to focus on the improvement of resource utilization through the reallocation of current resources and the optimization of batch sizes, since impact lead time performance and approaches do not require costly investments or large-scale changes in the system design. Thus, the following improvement alternatives were investigated to reduce lead time:

I) *Improvement of Resource Utilization*: According to Suri (1998), Anupindi *et al.* (1999) and Hopp and Spearman (1990 and 2006), increasing resource utilization and variability causes exponential increases in lead time and the WIP inventory. Thus, performance and productivity can be significantly improved by reducing resource utilization. This fact is illustrated in Figure 6.3 (shown below):

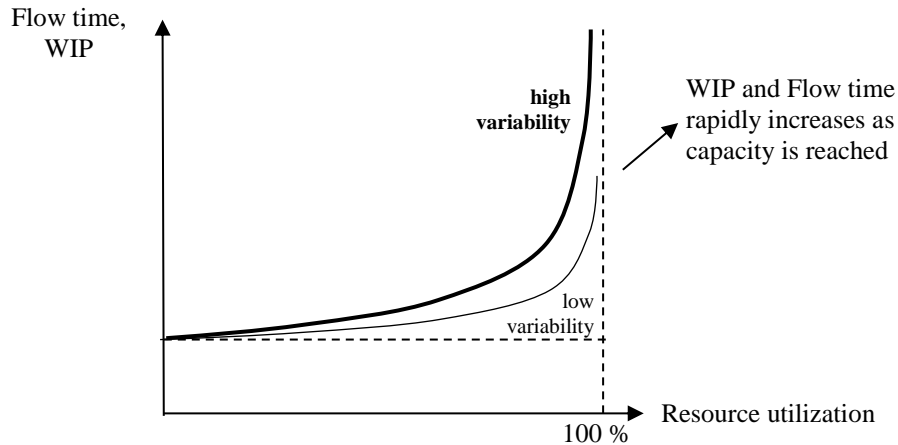


Figure 6.3: Resource utilization – lead time relation  
(Source: Anupindi *et al.*, 1999; Hopp and Serman, 2006).

As a result of the improvement, the following improvement targets were determined (Gläßer *et al.*, 2010a):

- a) *Minimization of excess labor force*: The main target of this strategy is to reduce the number of workers required for each station. However, labor minimization should be handled delicately to reduce the possibility of any excessive increase in labor utilization. The primary function of a worker is to perform setups and loading and unloading operations when the machine is idle. If a worker is busy (with another machine), the machine waits (*waiting-for-labor* situation) until the employee is once again idle in order to serve the machine. This situation is called *the operator-machine interference problem* (Stecke and Aronson, 1985). In order to reduce lead time, waiting-for-labor time should be minimalized through allocating machines with sufficient number of labors. In general, *waiting time* is one component of *total flow time* (Hopp and Spearman, 2006). However this component should not be confused with *waiting-in-queue*, as in this study, *waiting-for-labor* is considered to be one component of processing time. The processing time is assumed to be composed of *waiting-for-labor time*, *setup time*, *loading time*, *run time* and *unloading time*.

b) *Pooling of labor force:* In general, the ‘*Pooling Principle*’ is used for the pooling of customer demands or resources in order to achieve operational improvement. The main principle is the allocation of fewer, but a highly skilled workforce, for a group of tasks/stations. Aside from several advantages, as a general rule, the pooling of resources is expected (theoretically speaking) to decrease the waiting time in the queues. Pooling also allows better management of variability (Cattani and Schmidt, 2005). Particularly, in this case where the pooling principle is used to reduce the number of workers allocated to each task/station and reduce the workforce with fewer highly skilled employees who are capable of working on several tasks/stations. However, this level of specialization increases labor costs, since extra investment is required for high-skilled labor and training costs, etc. Thus, the cost of pooling the workforce should be compensated with lead time reduction based cost savings and profit increases.

Figure 6.4 (shown below) shows the pooling of labor for four extruders. Originally, an operator would have been allocated to an extruder (see Figure 6.4.1, shown below). In the pooling scenario, these less skilled operators are replaced with two highly skilled operators, where each is responsible for two extruders (see Figure 6.4.2, shown below):

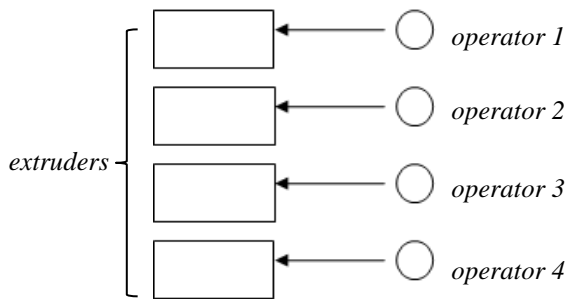


Figure 6.4.1: Original setting

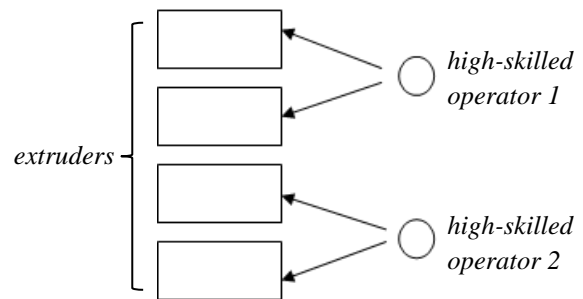


Figure 6.4.2: Pooling of labor resource

(Source: Figure 3 and Figure 4, p. 22, Gläßer *et al.*, 2010a).

*II) Batch Size Optimization:* Significant lead time improvements are achievable by optimizing the batch size (Mikati, 2010; Hopp and Spearman, 2006; Koo and Koh, 2007; Vaughan, 2004). Batching is used when multiple products are processed on the same machine. Batching can be particularly useful when switching from one product type to another, which is necessary for the setup operation. Batching reduces the number of setups and the setup time if proper batch sizes are selected. On the other hand, batching is a source of variability, which is an important and influential factor on the process flow time (Hopp and Spearman, 2006):

$$T_b = S_{tb} + (r_{tp} \times b) + w_t + w_{tb} \quad (6.1)$$

Batch flow time ( $T_b$ ) is the sum of setup time per batch ( $S_{tb}$ ), wait-in-queue time ( $w_t$ ), wait-in-batch time ( $w_{tb}$ ) and batch run time (run-time-per piece ( $r_{tp}$ )  $\times$  batch size ( $b$ )). Setup time ( $S_{tb}$ ) and unit run time ( $r_{tp}$ ) are independent of batch size ( $b$ ), whereas wait-in-queue time ( $w_t$ ) and wait-in-batch time ( $w_{tb}$ ) are batch size dependent since every piece in a batch has to wait until the last piece of the batch is processed (Hopp and Spearman, 2006; Poiger *et al.*, 2010). In the end, batch size selection is a critical decision. The selection of smaller or larger batch sizes (compared to optimal batch size,  $b^*$ ) increases the average flow time  $T_b$  (see Figure 6.5, shown below):

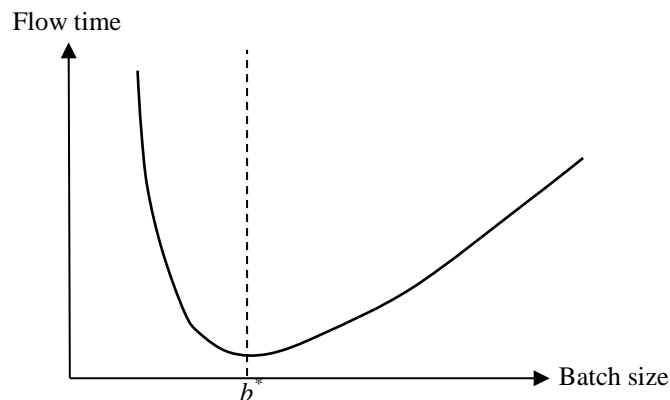


Figure 6.5: Batch size – flow time interaction  
(Based on Poiger *et al.*, 2010, Figure 6, p. 294 and Mikati, 2010, Figure 3, p. 7).

As explained by Poiger *et al.* (2010), wait-in-queue time ( $w_t$ ) (resource waiting time), at first, sharply decreases until the optimal batch size is reached. If the batch size is increased further, wait-in-queue time increases due to greater effect of process variability on relatively large batch sizes (see *batch size - coefficient of variation interaction*, Poiger *et al.*, 2010). The second factor, wait-in-batch time ( $w_{tb}$ ), has a linearly increasing characteristic when batch sizes are increased. As a result of the interaction of these two factors, flow time has a particular shape, as shown in Figure 6.5 (shown above) (Poiger *et al.*, 2010). In fact, the selection of optimal batch size is a trade-off between waiting times and setup times. Due to this challenging behavior, the *batch size optimization* problem has always been an interesting topic for researchers. For a detailed literature survey reference is made to Gläßer *et al.* (2010a).

### 6.1.5 Lead time reduction scenarios

Six scenarios were developed to test and evaluate the impact of resource reallocation, resource pooling and optimization of current batch size on operational, customer-oriented and financial performance.

The initial scenario (Scenario 0) represents the actual system settings. In this scenario, four extruders and four operators are responsible for the pre-work operations and handling of extruders. The packaging is undertaken by three packaging operators (packers), and three transfer operators are responsible for the transfer of finished products to the storage area (*see Figure 6.6.1 shown on page 128*).

In Scenario 1, only batch size optimization is applied to the actual settings. The initial average batch size (100%) is reduced by eighty percent to the final average optimal value (19.43%) (Due to confidentiality, the actual batch size values are linearized and substituted by percentages). Optimal batch sizes are obtained using the genetic algorithm based procedure of Rabta and Reiner (2010). According to the authors, the method uses queuing network decompositions to find near-optimal batch sizes within reasonable computation time, even for larger sized problems with hundreds of product families.

In Pooling Scenario 2, (constructed in Scenario 0) three packing and three transfer operators are pooled and replaced with four highly skilled operators. The four operators responsible for pre-work and extrusion processes are untouched (*see Figure 6.6.2 shown on page 128*). In terms of labor costs, packers and transfer operators are assumed to have the same unit labor cost, which is somewhat lower than the unit labor cost of an operator. Operators are highly skilled and costly in comparison to packers and transfer operators.

Scenario 2.1 is an extension of Scenario 2, where the same pooling principle is combined with the optimal batch sizes of Scenario 1.

In Pooling Scenario 3, (constructed in Scenario 0), four operators of the pre-work and extrusion processes and three operators of packaging are pooled and replaced with five highly skilled operators. Three transfer operators are untouched (*see Figure 6.6.3 shown on page 128*).

Scenario 3.1 is an extension of Scenario 3, where the same pooling principle is combined with the optimal batch sizes of Scenario 1.

Based on initial analysis and pilot runs, it was discovered that instead of pooling the labor force and reducing the number of operators by two (under Pooling Scenario 2 and 3), reducing operators by one yields better operational results and a further reduction in lead time.

On the one hand, shorter lead times provide further inventory and penalty cost advantages; on the other hand, the reduction of labor will result in added labor costs. At this point, the extension of Pooling Scenarios 2 and 3 provides a nice base for studying the trade-offs between the added value of the well-designed pooling principle and related labor costs.

As a result, in Pooling Scenario 4, five highly skilled transfer/packaging operators were used instead of four operators as in Scenario 2 (*see Figure 6.6.4 shown on page 128*).

Scenario 4.1 is an extension of Scenario 4, where the pooling principle is combined with the optimal batch sizes of Scenario 1.

In Pooling Scenario 5, six highly skilled operators were used (for pre-work, extrusion and packaging), instead of five, as in Scenario 3 (*see Figure 6.6.5 shown on page 128*).

Scenario 5.1 is an extension of Scenario 5, where the pooling principle was combined with the optimal batch sizes of Scenario 1.

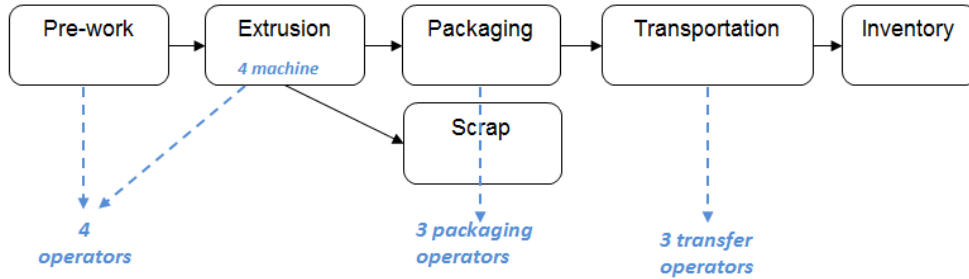


Figure 6.6.1: Original Setting (Scenario 1).

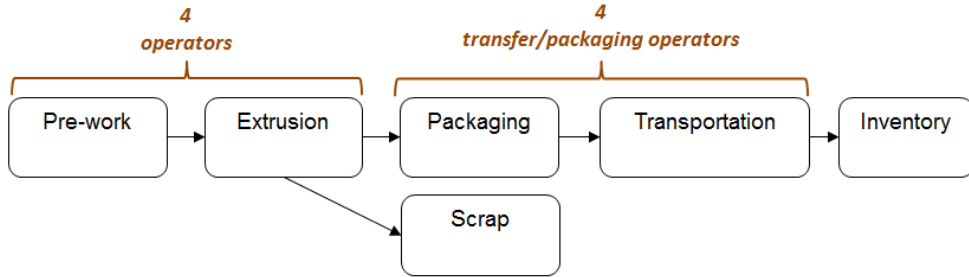


Figure 6.6.2: The Pooling Scenario 2.

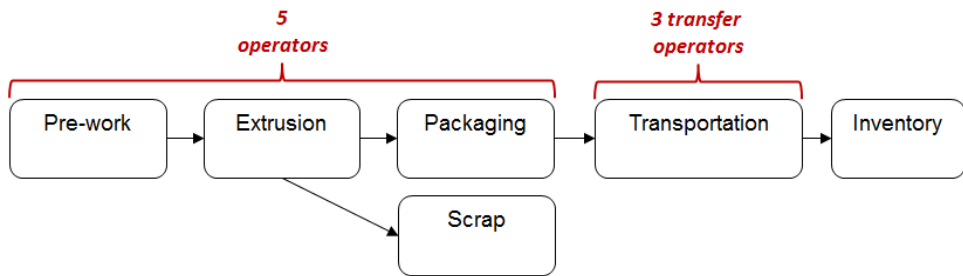


Figure 6.6.3: The Pooling Scenario 3.

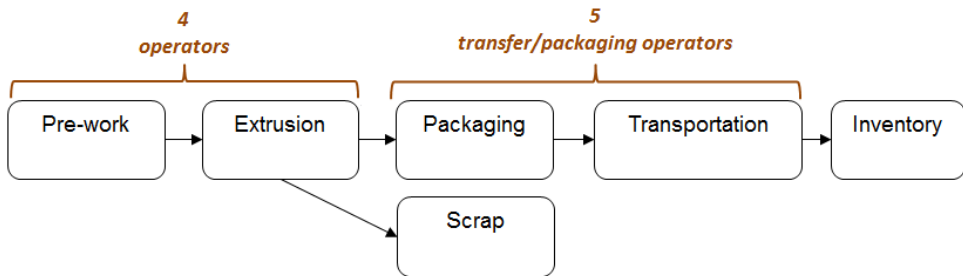


Figure 6.6.4: The Pooling Scenario 4.

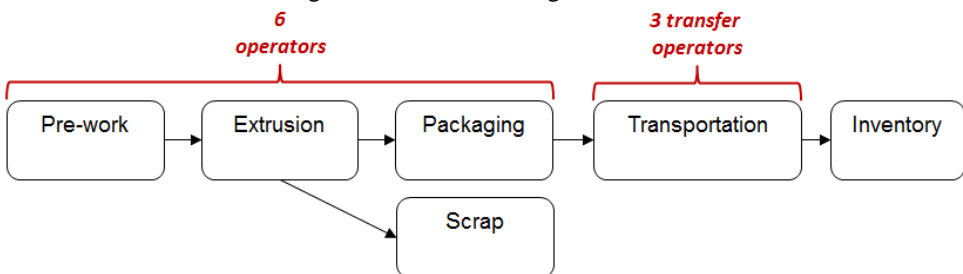


Figure 6.6.5: The Pooling Scenario 5  
(Modified based on Figure 2, p. 21, Gläßer *et al.* 2010a).

## 6.1.6 Results – I

Results of each scenario are generated by simulation of the production system for a production period of one year. Simulation runs are based on yearly production data of 103 different articles (*see Section 6.1.2 on page 119 for further details of data collection*). Computations are done using the Rapid Modeler (Rapid Modeler, 2009) and System Dynamics Modeling. The Rapid Modeler provides estimations for operational performance measures (i.e. lead time, setup utilization, run utilization, labor utilization, total work-in-process inventory, etc.), which serves as a basis for the System Dynamics model. In the next stage the System Dynamics model uses these measures and some other input variables to quantify how customer-related and financial measures are affected (*see Section 4.2.1 - 4.2.3 on pages 83 – 95 for further details*).

Detailed results are provided in Table 6.1 (*on page 131*) for each operational, financial and customer-oriented performance categories. Results are based on the initial production period,  $t_0$ .

The results of Scenario 0 are used as a benchmark for performance values (due to confidentiality, the actual financial performance results are presented as percentage values based on Scenario 0).

The lead time is reduced in almost all scenarios. It is possible to reach an 87.26% reduction in lead time and 99.34% customer satisfaction rate while fulfilling the company target.

The batch-size reduction approach (Scenario 1) provided an 85.63% reduction in lead time. In parallel, WIP, WIP costs and finished goods inventory costs are reduced almost by the same magnitude. The amount of lead time reduction led to a sharp increase (30%) in customer satisfaction and (85%) reduction in penalty costs. On the other hand, the reduction of batch sizes increased the frequency of setups (setup utilization is increased from 2.40% to 11.70%) and setup costs (487.50%). The setup costs are relatively sensitive to changes in batch size due to the cost structure of the extruder (variable costs). However, this dramatic increase in setup costs is compensated by the reduction in lead time based gains. In the end, the overall cost (99.66%) is not influenced by the increased setup cost. Furthermore, there is a slight increase of 6.28% in profits (from 100% to 106.28%).

The individual use of the pooling strategy (Scenarios 2 and 3) provided a slight increase in lead time (113.94% and 100.14%). Penalty and inventory costs also increased. A reduction in cost of almost ~40% is achieved due to the reduced setup utilization. The pooling scenario provided ~ a 15-20% reduction in labor costs (81.80% and 84.06%), which was expected. As a result, the

overall cost is reduced around ~10% and profits sharply increased ~2.5 times (286.49% and 271.35%).

Pooling scenario 2 provided slightly better results (based on final cost figures and utilization values) when compared to pooling scenarios 3. In scenario 3, the pooling of three processes, rework, extrusion and packaging with five operators increased wait-for-labor utilization (3.90%) compared to scenario 2, where wait-for-labor utilization was 2.5%.

Pooling and batch size reduction approaches in combination (Scenarios 2.1 and 3.1) produced significant reductions in lead time (14.33% and 13.37%). WIP inventories (14.40% and 13.46%), WIP inventory costs (14.40% and 13.46%) and finished goods inventory costs (14.33% and 13.37%) are reduced in the same direction. Batch size reduction and pooling, in combination, provided moderate setup cost increases (295.83%) compared to the setup cost increase (487.50%) in Scenario 1. This setup cost increase is compensated with the reduction in labor costs (81.80% and 84.06%). In the end, Scenarios 2.1 and 3.1 provided minimal overall costs (88.02% and 89.20%) and maximum increased profits (318.89% and 285.89%). This provides new investment possibilities. In this case, the investment volume is positively correlated with the profit increase. Thus, the success in lead time reduction led to the highest level of customer satisfaction (98.71% and 99.09%) and the highest level of customer retention (93.39% and 93.61%) rates.

The strategy of pooling with less labor (Pooling Scenarios 4 and 5) as opposed to pooling with more labor (Pooling Scenarios 3 and 4) provided promising operational and customer-oriented results, but less impressive financial results. The combined use of the new pooling strategy with batch-size reduction (Scenarios 4.1 and 5.1) provided the lowest lead time values (12.77% and 12.74%), highest customer satisfaction (99.32% and 99.34%) and highest customer retention (93.75% and 93.75%) values.

Labor cost is slightly reduced (90.90% and 95.41%) and customer retention costs have increased (113.33% and 113.33%). The overall costs have moderately reduced (93.18% and 95.68%), while profits increased (224.58% and 177.42%). These two scenarios provided complete customer satisfaction whilst at the same time fulfilling the company's targets. Due to relatively increased cost figures, compromises were given from profits.

Table 6.1: Results of scenarios based on Rapid Modeler and System Dynamics model (*results are based on the initial production period,  $t_0$* ).

		Initial scenario	Batch-size reduction	Pooling Scenario 2	Pooling Scenario 2 + Batch-size reduction	Pooling Scenario 3	Pooling Scenario 3 + Batch-size reduction	Pooling Scenario 4	Pooling Scenario 4 + Batch-size reduction	Pooling Scenario 5	Pooling Scenario 5 + Batch-size reduction
	Performance measure	Scn 0	Scn 1	Scn 2	Scn 2.1	Scn 3	Scn 3.1	Scn 4	Scn 4.1	Scn 5	Scn 5.1
Operational Performance	Idle utilization extruder	26.60%	15.70%	27.7%	21.10%	26.30%	19.00%	27.70%	21.10%	27.60%	21.10%
	Setup utilization extruder	2.40%	11.70%	1.50%	7.10%	1.50%	7.10%	1.50%	7.10%	1.50%	7.10%
	Run utilization extruder	67.40%	67.40%	67.40%	67.40%	67.40%	67.40%	67.40%	67.40%	67.40%	67.40%
	Wait-for-labor utilization extruder	2.60%	4.20%	2.50%	3.40%	3.90%	5.40%	2.50%	3.40%	2.60%	3.40%
	Repair utilization extruder	0.90%	1.10%	0.90%	1.00%	0.90%	1.00%	0.90%	1.00%	0.90%	1.00%
	Total utilization extruder	73.40%	84.30%	72.30%	78.90%	73.70%	81.00%	72.30%	78.90%	72.40%	78.90%
	Lead time	100%	14.37%	113.94%	14.33%	100.14%	13.37%	98.20%	12.77%	97.80%	12.74%
WIP inventory	100%	14.49%	113.71%	14.40%	100.14%	13.46%	98.22%	12.86%	97.76%	12.82%	
Financial Performance	Setup cost	100%	487.50%	62.50%	295.83%	62.50%	295.83%	62.50%	295.83%	62.50%	295.83%
	WIP inventory cost	100%	14.49%	113.71%	14.40%	100.14%	13.46%	98.22%	12.86%	97.76%	12.82%
	Finished goods inventory cost	100%	14.37%	113.94%	14.33%	100.14%	13.37%	98.20%	12.77%	97.80%	12.74%
	Total inventory cost	100%	14.42%	113.85%	14.36%	100.14%	13.41%	98.21%	12.81%	97.78%	12.77%
	Total labor cost	100%	100%	81.80%	81.80%	84.06%	84.06%	90.90%	90.90%	95.41%	95.41%
	Total machine cost	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Customer retention cost	100%	113.10%	99.04%	113.11%	100.99%	113.24%	101.27%	113.33%	101.32%	113.33%
	Penalty cost	100%	14.37%	113.94%	14.33%	100.14%	13.37%	98.20%	12.77%	97.80%	12.74%
	Overall cost	100%	99.66%	89.79%	88.02%	90.62%	89.20%	94.48%	93.18%	97.05%	95.68%
	Revenue	100%	100%	100%	100%	100%	100%	100.00%	100%	100%	100%
	Profit	100%	106.28%	286.49%	318.89%	271.35%	285.89%	200.86%	224.58%	153.92%	177.42%
Investment	100%	106.28%	286.49%	318.89%	271.35%	285.89%	200.86%	224.58%	153.92%	177.42%	
Market-oriented Performance	Customer satisfaction	65.01%	98.70%	59.52%	98.71%	64.95%	99.09%	65.72%	99.32%	65.87%	99.34%
	Customer retention	73.84%	93.38%	70.66%	93.39%	73.81%	93.61%	74.26%	93.75%	74.35%	93.75%
	Number of customers	100%	98.90%	98.90%	98.90%	98.90%	98.90%	98.90%	98.90%	98.90%	98.90%
	Expected demand for next period	99.38%	98.82%	98.82%	98.82%	98.82%	98.82%	98.82%	98.82%	98.82%	98.82%

## 6.1.7 Results – II

In order to demonstrate the long-term effects and dynamic dependencies of the underlying system, a second set of results were provided, which were based on System Dynamics. The long-term dynamic behavior of the model is simulated for twenty-year period and illustrated in Figures 6.7 to 6.9 (shown on pages 132, 133 and 134). The same data set is considered for the simulation. The results are based on the following selected scenarios:

- Scenario 0 is the initial scenario;
- Scenario 2.1 is the best performing scenario among all of the improvement scenarios;
- Scenario 4 shows the long-term effects of investing in capacity by purchasing a new machine.

Due to confidentiality, the results are provided as percentage values, which are normalized based on the performance of the base case. The dotted-line represents Scenario 0; the solid line represents Scenario 2.1 and the dashed line represents Scenario 4. The *x-axis* represents a twenty-year period, whereas the *y-axis* represents the related performance value in percentages:

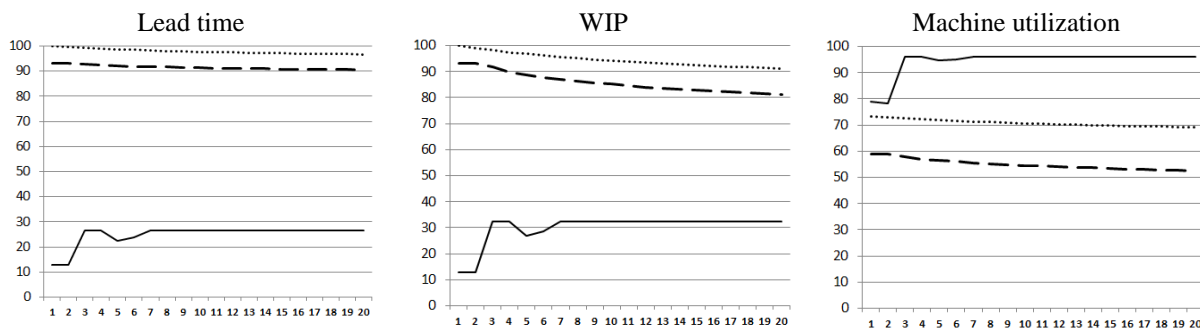


Figure 6.7: The comparison of operational performance: Scenario 0 (dotted line), Scenario 2.1 (solid line), Scenario 4 (dashed line).

Regarding the operational perspective, the initial scenario performed poorly in terms of long lead times and low levels of customer satisfaction. In the long-term, the company loses customers and demand follows a decreasing pattern. On the other hand, a considerable amount of improvement is achieved with the improved scenario, when compared to the initial scenario. In Scenario 2.1, lead time substantially reduces along with a reduction in the WIP inventory. In the long-term, lead time, WIP and machine utilization increases slightly. However, the magnitude of the increase is still within acceptable levels. In Scenario 2.1, the level of machine utilization is higher when compared to other scenarios. Nonetheless, this is compensated with shorter lead times and higher levels of customer satisfaction. Such an improvement is achieved without any costly or time-consuming investments.

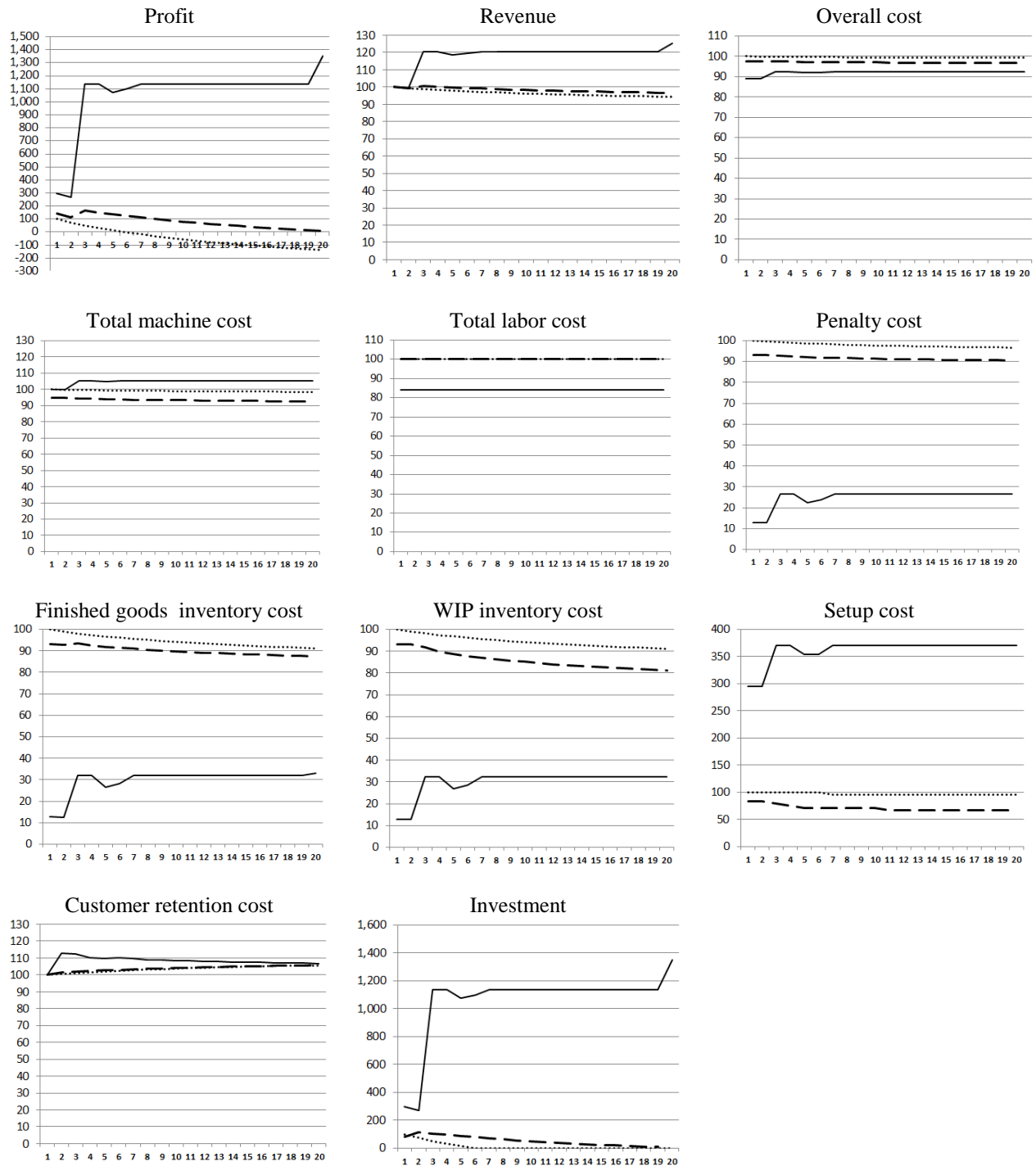


Figure 6.8: The comparison of financial performance:  
Scenario 0 (dotted line), Scenario 2.1 (solid line), Scenario 4 (dashed line).

Scenario 2.1 outperformed Scenario 0 with respect to financial performance. In Scenario 0 profits and revenue decreases and overall costs increases over time. The revenue distortion can be explained with lost demand and sales. Losses in demand are realistic due to the market oriented product characteristics. Major customers are extremely time sensitive. Extended lead times may

easily result is lost customers. In Scenario 2.1, the financial improvements are significant when compared to the base case (with the exception of setup and customer retention costs). Reducing the waiting and lead times led to reduced inventories and inventory costs. The slight increase in inventory costs is in parallel to the increase in demand. Lead time improvements provided a substantial penalty cost reduction. As an effect of the decreased machine setup and run utilization, slight decrease in machine costs was observed. Since the company does not wish to downsize, labor size and costs are fixed. The decrease in labor costs is achieved with pooling of the workforce; as the number of employees is reduced by using skilled workers.

The substantial increase in setup costs is related to the reduced batch sizes. The reduced batch size requires further setups, but this is compensated with lead time and cost based improvements. In this regard, the level of the setup costs increase is acceptable. Furthermore, the setup costs also decrease over time in parallel to the improvements in setup time. The slight increase in customer retention costs can be explained with the increasing number of new customers; since the attraction of new customers is costly compared to retaining existing customers.

The total overall cost is reduced by almost 10% compared to the base case. Revenue increases in parallel to sales increases. One of the most significant improvements is related to profits, where almost ten times growth in profit has been observed towards the end of the experimental period.

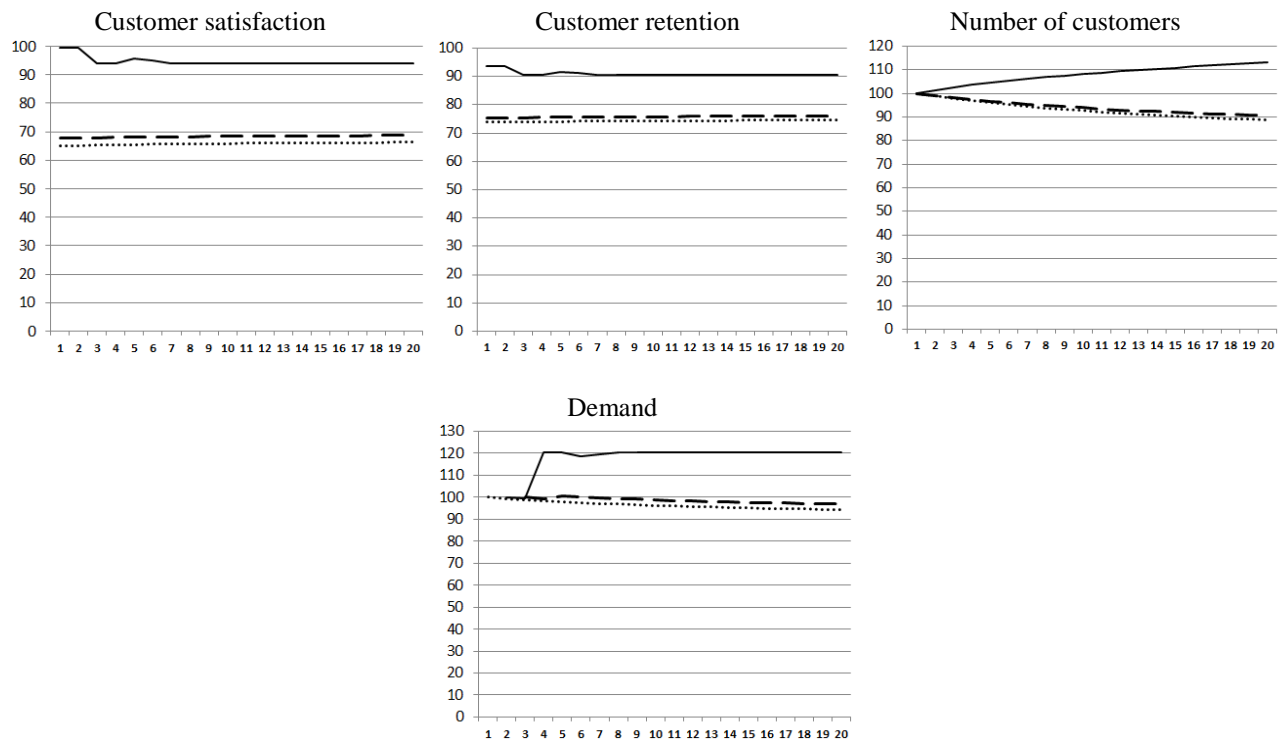


Figure 6.9: The comparison of market-oriented performance: Scenario 0 (dotted line), Scenario 2.1 (solid line), Scenario 4 (dashed line).

The final perspective is based on market-oriented performance. In Scenario 0, customer satisfaction and the number of customers decrease over time. As expected, demand diminished with the decreasing number of customers. In Scenario 2.1, a substantial amount of increase in customer satisfaction is observed due to lead time improvements. Likewise, customer retention improved in parallel. Despite the slight decrease in satisfaction over time, the number of customers still increased and stabilized towards the end of the simulation period. The same effect is observed for demand.

## **6.2 Sensitivity analysis based on demand and lead time interaction**

In this section, insights gathered through industrial applications are used to present a sensitivity analysis based on demand and lead time interaction. The integrated performance framework is used to analyze the long-term performance impacts of lead time reduction under the extreme conditions of market demand. Conditions to maintain the long-term sustainability of lead time reduction are questioned.

The main focus here is on the direct and indirect demand and lead time connection. Lead time and demand are interconnected in two directions. Any change in demand has an immediate and direct impact on lead time and accordingly, any changes in lead time indirectly influence future demand in the long-term. The sensitivity analysis is based on current short and long-term demand and lead time interaction:

*i) Demand – Lead time direct connection:* Demand – lead time direct connection has been explained in Chapter 3, Section 3.2.1 (*see page 54*) and is based on the principles of queuing theory and waiting line models (*see Equations 3.1 – 3.12 on pages 55 – 57*).

*ii) Lead time – demand (future) indirect connection:* Lead time – demand (future) indirect connection is relatively more complex in nature. The core is about the close connection of time-based measures with customer-oriented performance measures. This has been explained in Chapter 3, Section 3.2.2 (*see page 57*) through (i) lead time – customer satisfaction connection introduced by Kalló and Koltai (2010) (*see Equations 3.13 and 3.14 on page 62*) and (ii) related customer performance metric interactions introduced by Reiner and Natter (2007) and Reiner (2005) (*see Equations 3.15 – 3.23 on pages 63 – 65*).

Demand – lead time direct connection and lead time – demand (future) indirect connection are both illustrated in Figure 3.4 (*shown on page 70*).

### *Demand and lead time interaction – Phase I:*

It was observed that any change in the value of demand at period  $t$  directly affects the lead time of the same period, and any increase or decrease in the value of lead time (of period  $t$ ) indirectly affects the future demand at period  $t+2$ . The demand was name – lead time direct interaction as the *demand<sub>t</sub> – lead time<sub>t</sub>* interaction and the indirect lead time – demand (future) interaction as the *lead time<sub>t</sub> – demand<sub>t+2</sub>* interaction.

Furthermore, any changes in terms of improvement or deterioration of lead time from period  $t$  to  $t+1$  affects customer satisfaction ( $CS_{t+1}$ ), customer retention ( $CR_{t+1}$ ), the number of loyal customers ( $NLC_{t+1}$ ), the acquisition of new customers ( $CN_{t+1}$ ), lost customers ( $CL_{t+1}$ ) and finally, the total number of customers ( $NC_{t+1}$ ) of period  $t+1$ , as explained through equations (3.13) – (3.23) on pages 62 – 65. Since the demand of a period is expressed as a function of a number of new and loyal customers of the preceding period, the change in the number of loyal customers ( $NLC_{t+1}$ ) and new customers acquired ( $CN_{t+1}$ ) of period  $t+1$  affects the demand at period  $t+2$  ( $D_{t+2}$ ).

In order to better explain the lead time  $t$  – demand  $t+2$  interaction, a simulation run is used to illustrate the integrated performance framework for twenty consecutive periods. All experimentation is based on the same production system and quantitative data, which is explained in Section 6.1.1 (*see page 118*) and Section 6.1.2 (*see page 119*).

The simulation run starts with an initial demand value (the original demand value of the company). At any period  $t$ , for a given demand ( $D_t$ ), the Rapid Modeler is used to calculate the related operational performance (i.e. total machine and labor utilizations, setup utilization, total work-in-process inventory and average flow-time). These operational measures are used to run the System Dynamics model to calculate customer oriented measures of the same period  $t$ . Based on the number of new and loyal customers of period  $t$ , the demand of the next period ( $D_{t+1}$ ) is calculated. Consecutively, this demand ( $D_{t+1}$ ) is used to re-initiate the process until twenty periods are reached.

The *demand<sub>t</sub> – lead time<sub>t</sub>* interaction and the *lead time<sub>t</sub> – demand<sub>t+2</sub>* interaction are illustrated in Figure 6.10 and Figure 6.11 (*shown on page 137*). The *x-axis* represents a twenty-year period, whereas the *y-axis* represents the percentage of change in related variables from period  $t-1$  to  $t$ . The square dots on the lead time graph represents the direction of change in value of the lead time ( $L_t - L_{t-1}$ ). In parallel, the round dots on the demand line represent the direction of change in value of the demand ( $D_t - D_{t-2}$ ).

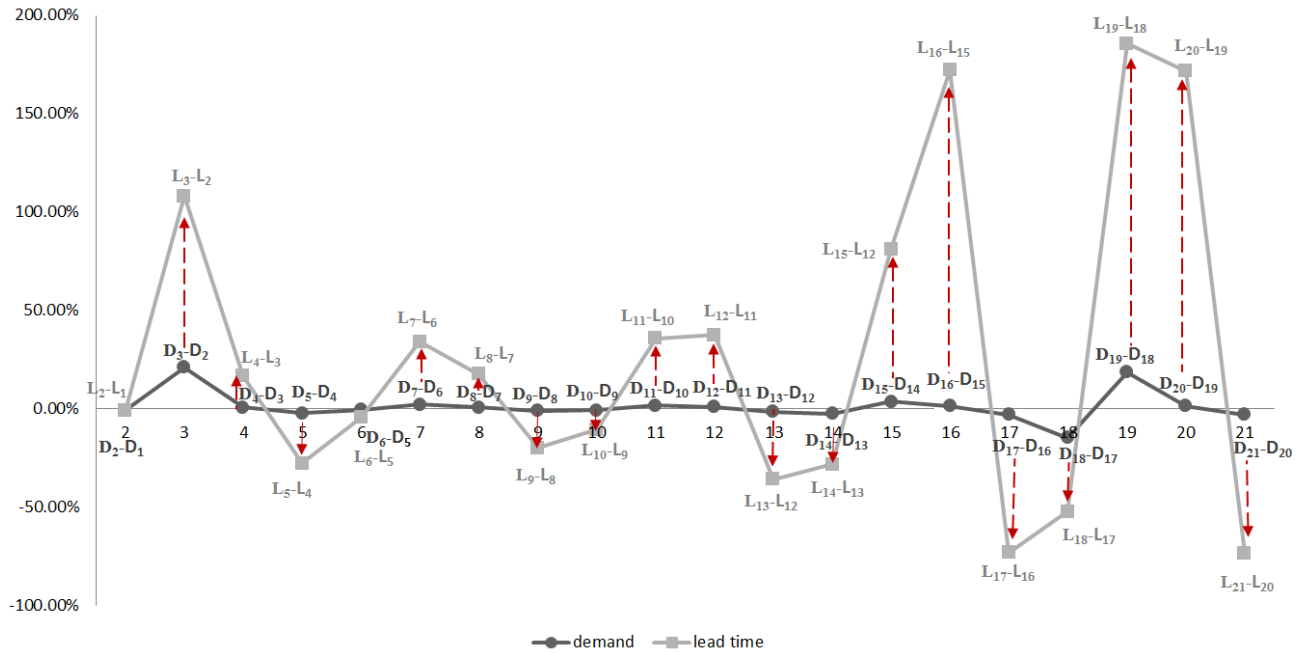


Figure 6.10: Demand  $\tau$  – lead time  $\tau$  interaction for twenty periods.

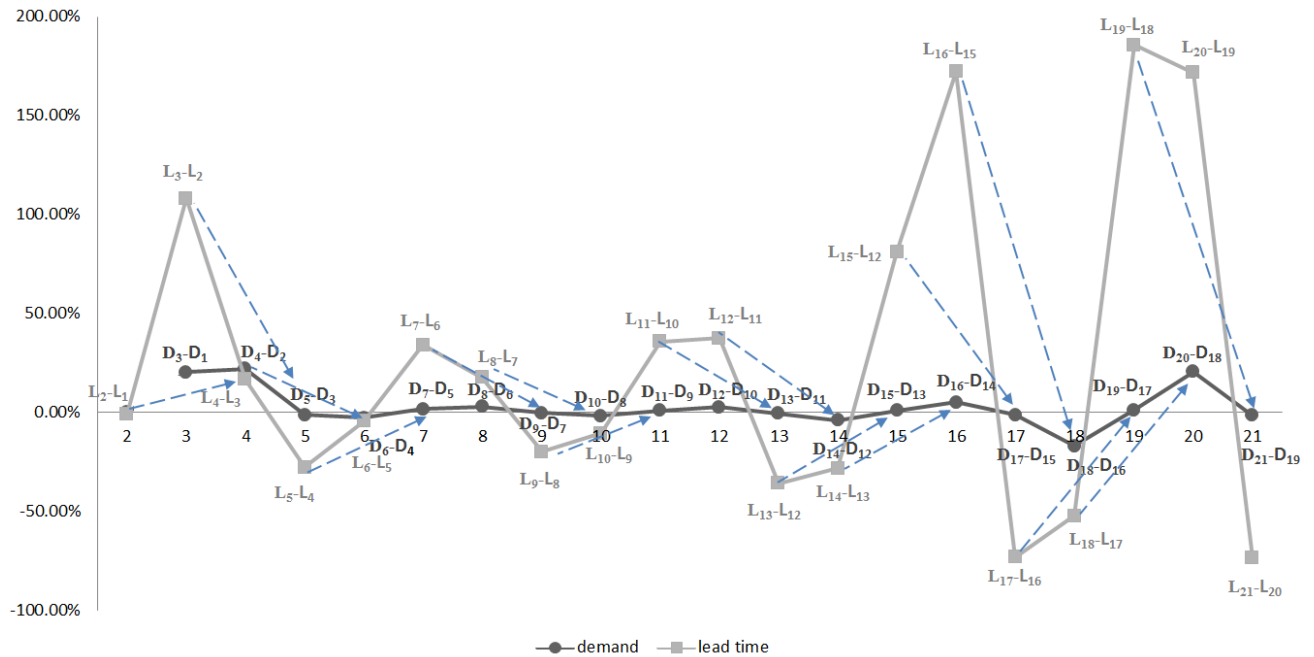


Figure 6.11: Lead time  $\tau$  – demand  $\tau+2$  interaction for twenty periods.

The short-term direct impact of demand changes on lead time is relatively easy to observe. As can be seen in Figure 6.10 (*see page 137*), any change of demand ( $D_t - D_{t-1}$ ) at period  $t$  directly affects the lead time of the same period  $t$  ( $L_t - L_{t-1}$ ) in same direction. For instance, an increase in demand at period 3 (as  $D_3 - D_2$  is positive; 21.14%) also leads to an increase in lead time in the same period (as  $L_3 - L_2$  is positive; 108.34%). Likewise, a demand decrease at period 5 (as  $D_5 - D_4$  is negative; -2.11%) also leads to a decrease in lead time in the same period (as  $L_5 - L_4$  is negative; -27.62%). The effect of changing the demand value on lead time is shown with the red dotted arrows in Figure 6.10 (*shown on page 137*).

The long-term effect of lead time on future demand is relatively more complex to illustrate. Any changes in lead time value at period  $t$  ( $L_t - L_{t-1}$ ), in terms of performance improvement or distortion, affects the demand at period  $t+2$  ( $D_{t+2} - D_t$ ). For instance, a deterioration of lead time performance at period 3 (since there is an increase in lead time value as  $L_3 - L_2$  is positive; 108.34%), negatively affects the demand on period 5. At period 5, there is a decrease in the demand value is observed (as  $D_5 - D_3$  is negative; -1.30%) due to the deterioration of lead time performance and decreased customer satisfaction. Similarly, lead time continues to increase at period 4 (since  $L_4 - L_3$  is positive; 16.75%). However, the magnitude of increase is relatively smaller when compared to the previous period. Therefore, decreasing behavior in demand is observed during period 6 (as  $D_6 - D_4$  is still negative; -2.56%), but the magnitude of the decrease is relatively small in comparison to the previous period. This is due to the small lead time increase of period 4 (a partially improved lead time).

Conversely, an improvement of lead time performance at period 5 (as  $L_5 - L_4$  is negative; -27.62%) positively affects the demand of period 7, as a slight increase in demand (as  $D_7 - D_5$  is positive; 1.77%) is observed. The increase in demand is due to improved lead time performance and increased customer satisfaction. Similar lead time and demand interactions can be observed for the remaining periods. The effect of changing lead time performance on demand is shown with blue dotted arrows in Figure 6.11 (*shown on page 137*).

Based on these experimental results, the short-term direct impact of demand changes on lead time in the long-term have an effect on lead time changes on future demand, which is illustrated below in Figure 6.12 (*shown on the following page*):

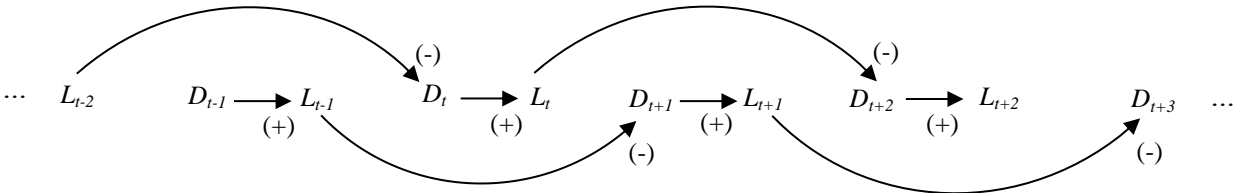


Figure 6.12: Demand  $t$  – lead time  $t$  and lead time  $t$  – demand  $t+2$  interaction.

*Demand and lead time interaction – Phase II:*

In phase I, demand  $t$  – lead time  $t$  and lead time  $t$  – demand  $t+2$  interactions are analyzed through a single twenty-period run, which was initiated by the original demand value of the company. In Phase II, the main objective is to better analyze the behavior of demand and lead time interaction for varying values of initial demand; in particular, for extreme values of initial demand. For this purpose, the entire demand range [demand<sub>min</sub>, demand<sub>max</sub>] is covered.

The mechanics of the simulation runs at this phase are slightly different when compared to Phase I. In order to prevent bias, independent simulation runs were designed. Each simulation run starts with an initial demand value ( $D_t$ ). The Rapid Modeler is used to calculate operational performance measures and the System Dynamics model is used to calculate customer oriented measures of the same period  $t$ . Based on the number of new and loyal customers of period  $t$ , the demand of the next period ( $D_{t+1}$ ) is calculated. Consecutively, demand ( $D_{t+1}$ ) is used to re-initiate the process for period  $t+1$ . The simulation continuous until the demand for period  $t+2$  is obtained ( $D_{t+2}$ ). The entire experiment begins with the maximum value of demand (demand<sub>max</sub>) and continues until the minimum value of demand (demand<sub>min</sub>) is reached. Thus, there are thirty independent simulation replications, where the first simulation run is initiated with  $D_t = \text{demand}_{\text{max}}$  and the thirtieth simulation run is initiated with  $D_t = \text{demand}_{\text{min}}$  value.

The minimum demand value is the point where the system reaches the minimum possible lead time value (a single day). The maximum demand value is the point where the system reaches the maximum resource utilization level (99.30%) and the maximum lead time value. The entire demand range is divided into equal values (thirty independent simulation runs) in order to satisfy statistical consistency (see Table 6.2 shown on page 140):

Table 6.2: Brief explanation of Phase II simulation replications

Independent simulation runs		Demand initiated	Explanation	
Independent	1	$D_{\max}$	demand $_t = D_{\max}$	lead time $_t \dots \dots$ demand $_{t+2}$
	.	.	.	.
	30	$D_{\min}$	demand $_t = D_{\min}$	lead time $_t \dots \dots$ demand $_{t+2}$

Two types of customer profile are considered: Type I customers, who are moderately sensitive to changes in lead time, and type II customers who are very sensitive to lead time changes. In this way, the sensitivity of demand changes are analyzed under moderate and high lead time sensitivity. Customer satisfaction and lead time interaction is based on Equations (3.13) and (3.14) (*see page 62*). Based on company data, for Type I customers maximum tolerable lead time is considered as twenty-four days and for Type II customers maximum tolerable lead time is considered as four days.

In Figure 6.13.1 and 6.13.2 (*shown on page 141*), the demand  $_t -$  demand  $_{t+2}$  interaction is shown for type I and type II customers. The *x-axis* represents thirty independent simulation runs where for the first simulation run  $D_t = D_{\max}$  and for the last simulation run  $D_t = D_{\min}$ , whereas, the *y-axis* represents the corresponding  $D_t$  and  $D_{t+2}$  values.

Figure 6.14.1 and 6.14.2 (*shown on page 142*) illustrate lead time  $_t -$  lead time  $_{t+2}$  interaction for type I and type II customers. The *x-axis* represents thirty independent simulation runs where, for the first simulation run  $L_t = L_{\max}$  and for the last simulation run  $L_t = L_{\min}$ , whereas, the *y-axis* represents corresponding  $L_t$  and  $L_{t+2}$  values.

Figure 6.15.1 and 6.15.2 (*shown on page 143*) illustrates resource utilization  $_t -$  resource utilization  $_{t+2}$  interaction for type I and type II customers. The *x-axis* represents thirty independent simulation runs where, for the first simulation replication  $U_t = U_{\max}$  and for the last simulation run  $U_t = U_{\min}$ , whereas, the *y-axis* represents corresponding  $U_t$  and  $U_{t+2}$  values.

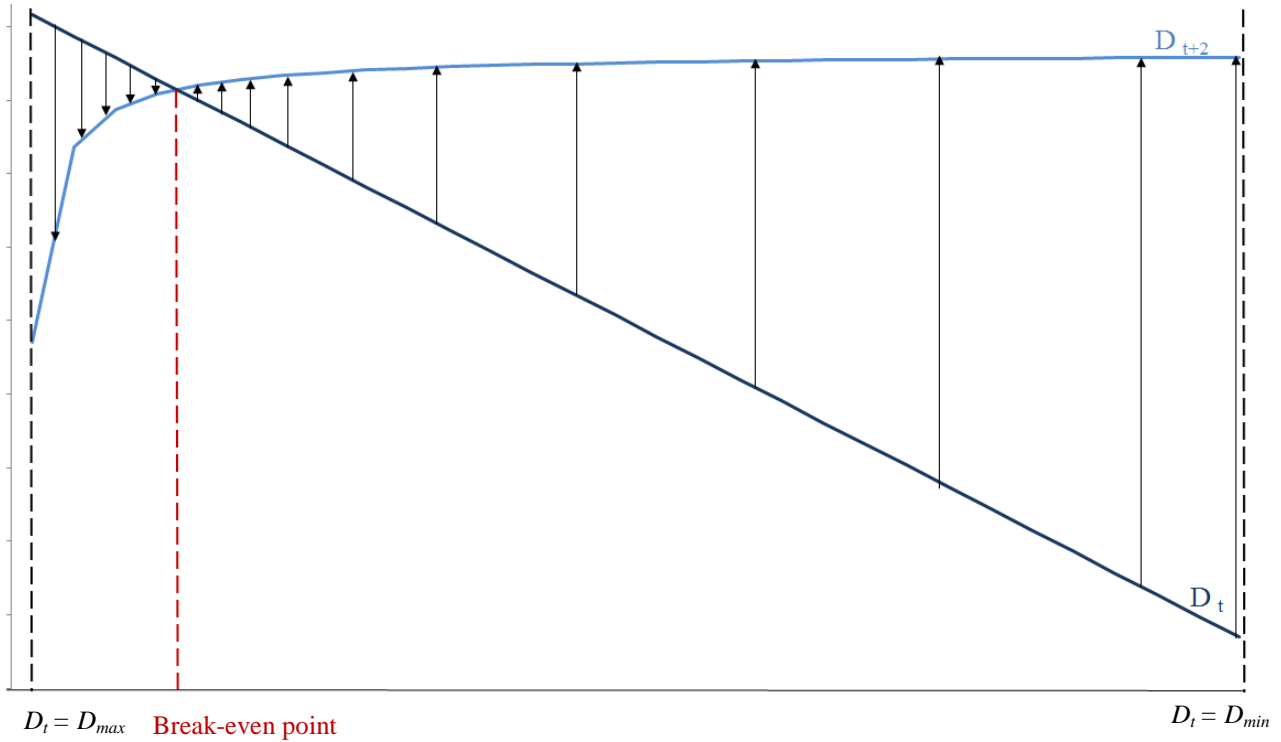


Figure 6.13.1: Demand  $t$  – demand  $t+2$  interaction for moderate lead time sensitivity.

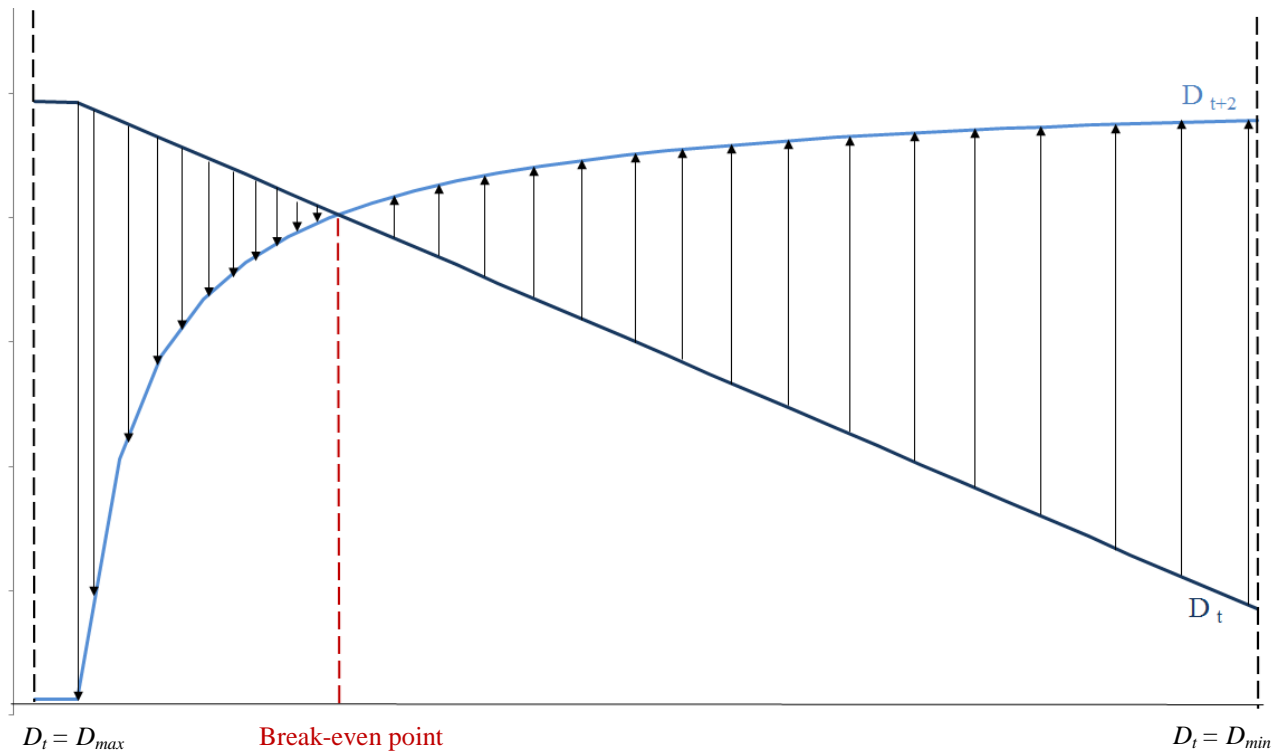


Figure 6.13.2: Demand  $t$  – demand  $t+2$  interaction for high lead time sensitivity.

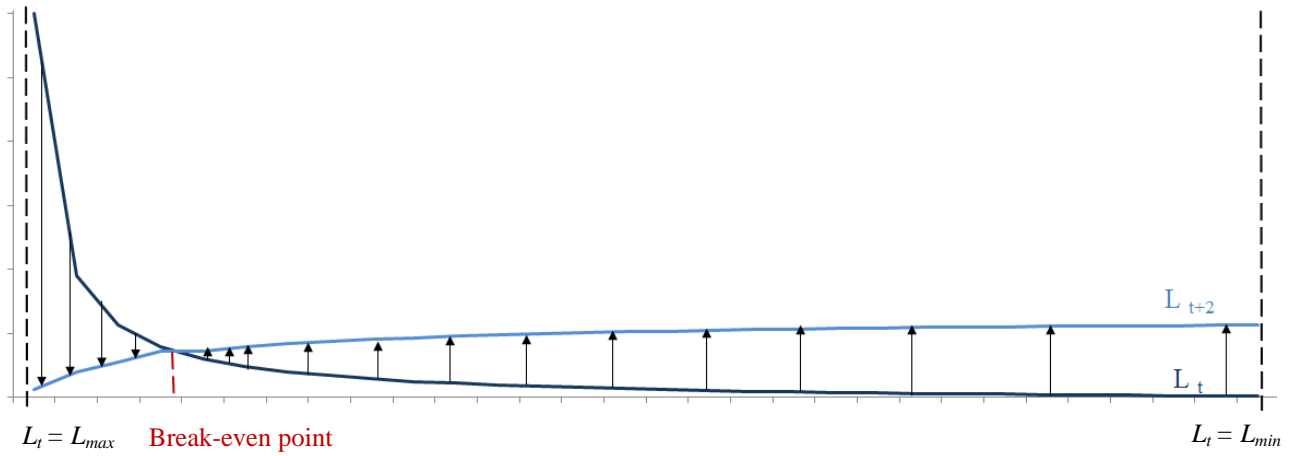


Figure 6.14.1: Lead time  $t$  – lead time  $t+2$  interaction for moderate lead time sensitivity.

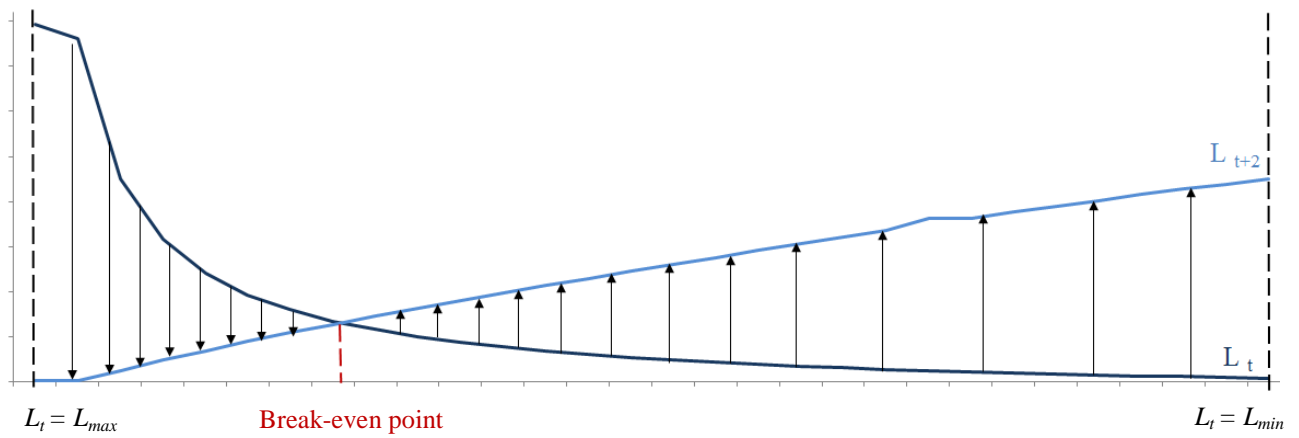


Figure 6.14.2: Lead time  $t$  – lead time  $t+2$  interaction for high lead time sensitivity.

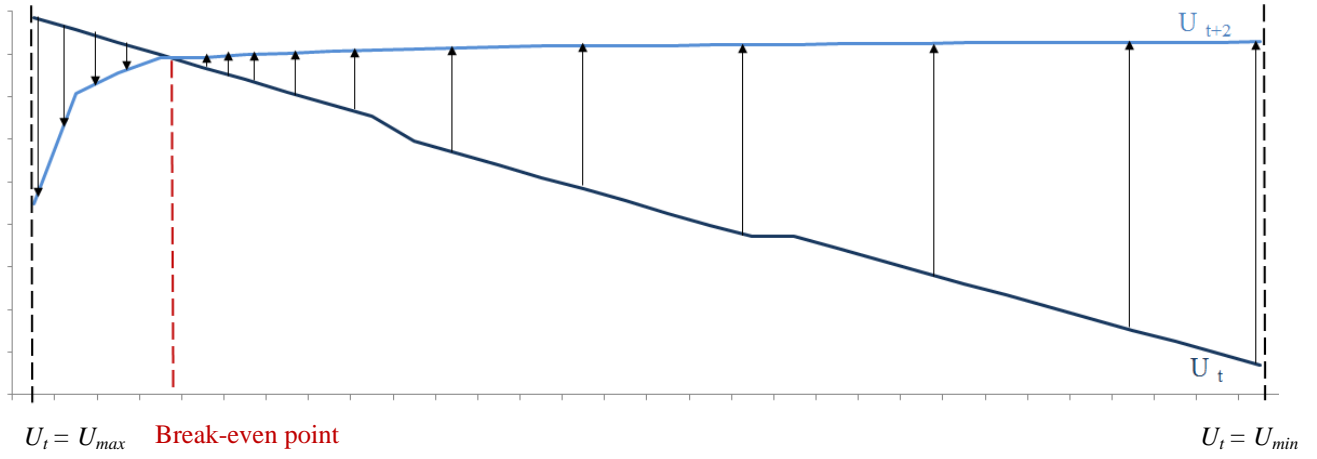


Figure 6.15.1: Utilization  $t$  – utilization  $t+2$  interaction for moderate lead time sensitivity.

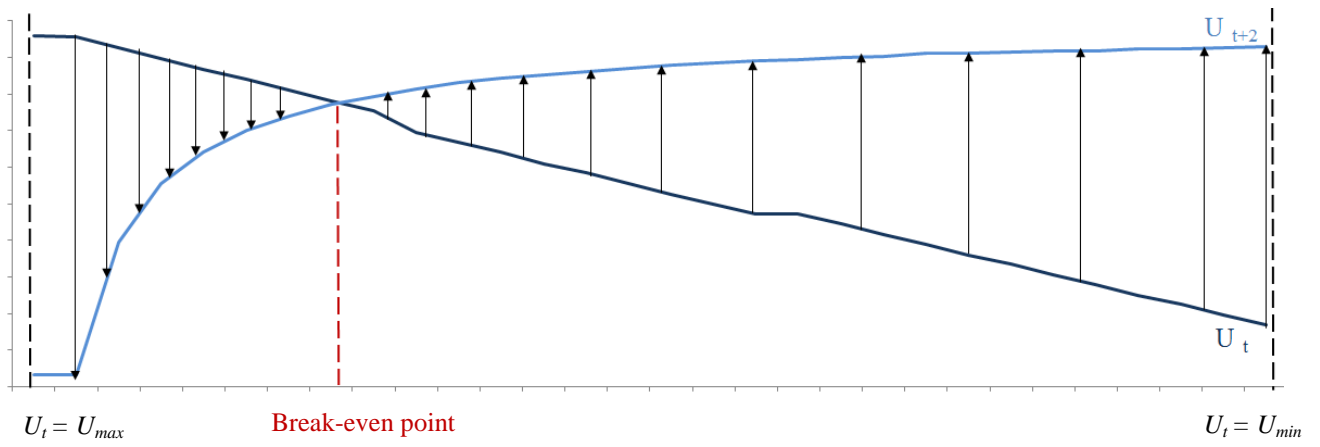


Figure 6.15.2: Utilization  $t$  – utilization  $t+2$  interaction for high lead time sensitivity.

The experiment begins with the maximum demand value ( $D_t = D_{max}$ ), which is a difficult target to satisfy. In order to satisfy maximum demand, the system work with maximum capacity. This leads resource utilization to reach the highest value ( $U_t = U_{max}$ ) and lead times to reach the maximum value ( $L_t = L_{max}$ ). Due to limited capacity, the system is not able to satisfy complete demand ( $D_t$ ). Unsatisfied demand (i.e. lost sales and unmatched customer expectations) and long lead times affect future performance ( $D_{t+2}$ ,  $L_{t+2}$  and  $U_{t+2}$ ), in terms of reduced customer satisfaction and customer loyalties. As a result, some customers are lost and future demand ( $D_{t+2}$ ) is minimized and corresponding lead times ( $L_{t+2}$ ) and utilization values ( $U_{t+2}$ ) decrease dramatically.

When the system is exposed to moderate values of demand ( $D_t$ ), it is possible to satisfy more demand with relatively smaller utilization ( $U_t$ ) and shorter lead times ( $L_t$ ), compared to the previous situation where demand ( $D_t$ ) was higher. Improved lead time ( $L_t$ ) affects future performance in terms of increased customer satisfaction and increased future demand ( $D_{t+2}$ ). Furthermore, a reduction in utilization ( $U_t$ ) leaves more capacity to cope with future demand. Alongside increasing future demand, corresponding lead time ( $L_{t+2}$ ) and utilization values ( $U_{t+2}$ ) also increase.

As the experiment continues, further reductions in the lead time ( $L_t$ ) results in a further increase in future demand ( $D_{t+2}$ ), as well as in lead time ( $L_{t+2}$ ) and utilization ( $U_{t+2}$ ) values. At this point, the core of the experiment is related to the identification of the critical lead time value where further reduction of lead time ( $L_t$ ) results in a critical increase in future demand, lead time and utilization.

In fact, there exists a critical threshold value, where further reduction of lead time beyond this break-even point is harmful to future performance. Beyond this critical threshold value, further reduction of the lead time ( $L_t$ ) triggers an unmanageable increase in future demand ( $D_{t+2}$ ). Unmatched demand leads to a reduction in customer satisfaction, which is due to the limited capacity of resources, where future utilization ( $U_{t+2}$ ) increases up to an unproductive level once again; and furthermore, the system is exposed to unexpected long future lead times ( $L_{t+2}$ ). In the long-term, this creates a snowball effect; a *better-before-worse* situation (Repenning and Sterman, 2001; Keating *et al.*, 1999).

In this regard, there exists a safe area for lead time (the area under the  $L_t$  curve, starting with the point where  $L_t = L_{max}$  and ending at the break-even point) where reduction of lead time ( $L_t$ ) within the limits of this area is safe and sustainable without distorting future performance ( $L_{t+2}$  and

$U_{t+2}$ ). This area is referred to as the '*sustainable lead time reduction area*.' Outside of this area, further lead time reductions do more harm than good and lead time reduction is not sustainable in terms of future performance. The sustainable lead time reduction area is illustrated in Figure 6.16.1 and Figure 6.16.2 (*shown on page 146*) for type I and type II customers.

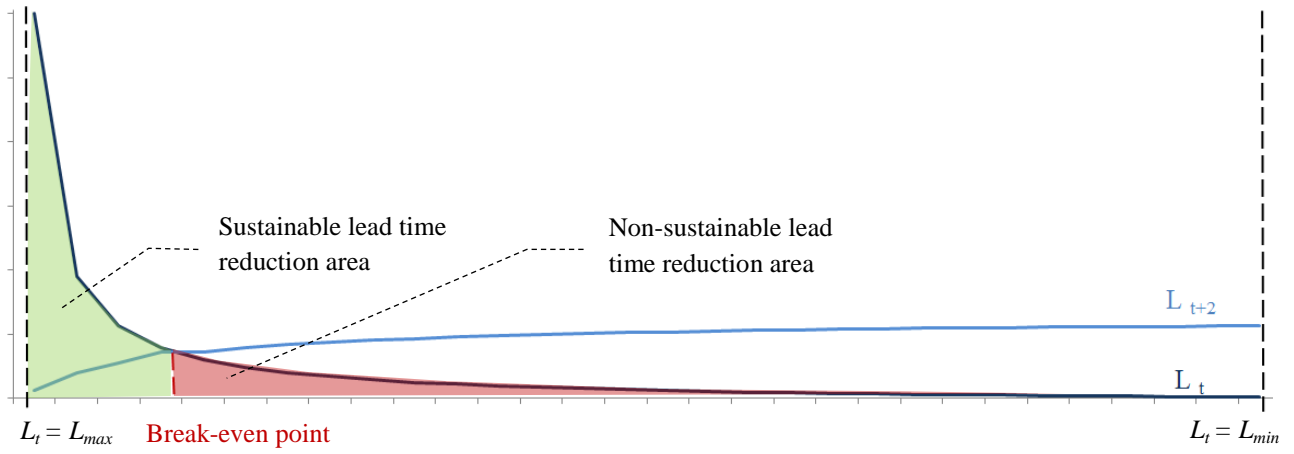


Figure 6.16.1: Sustainable lead time reduction area for moderate lead time sensitivity.

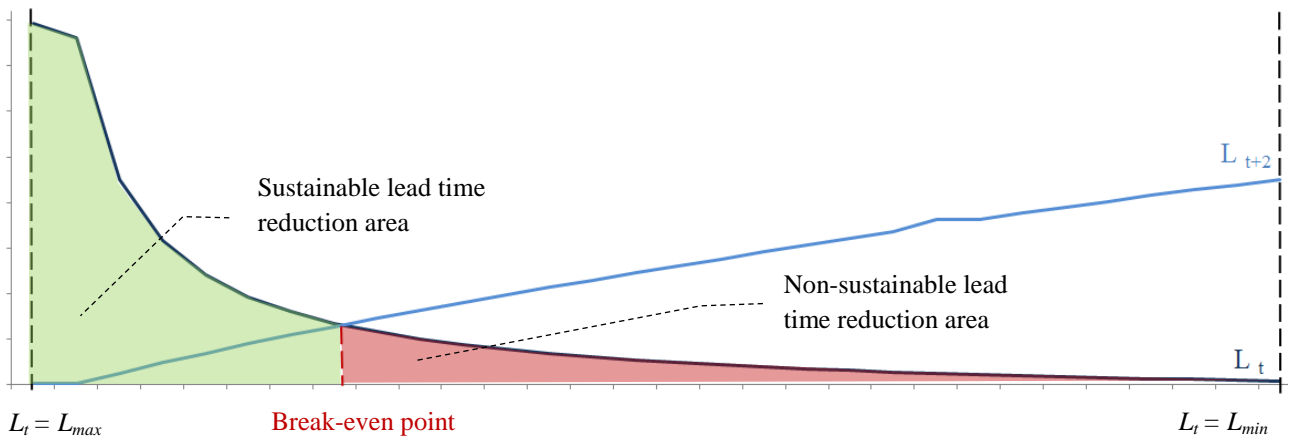


Figure 6.16.2: Sustainable lead time reduction area for high lead time sensitivity.

## 6.3 Conclusion

This chapter provides a real-life industrial case and provides further illustration of the integrated performance measurement framework.

The core of this thesis shows the dynamic dependencies between lead time and lead time related factors. Furthermore, lead time reduction has been shown to not only have a direct effect on, for example, reduced WIP inventories and reduced costs, but that there are indirect effects on service levels, customer satisfaction, customer loyalty, related penalties and retention costs, as well as having long-term effects on sales and profits. In the long-term, improved flexibility and investment capabilities provide the capacity and capability to hedge variability and an unexpected demand increase without worsening customer satisfaction and market shares. Complex relationships between time-based performance, market-oriented capabilities and the related financial situation were better demonstrated by the industrial case. Moreover, these two examples provide additional insight into the dynamic behavior of the framework.

Based on the empirical settings and assumptions of this case, the possibility of significant lead time and cost reductions are shown, along with a significant increase in profits. The combined use of lead time reduction strategies (i.e. resource pooling and batch-size optimization) may provide significant performance improvements when compared to the individual use of each strategy.

The sensitivity analysis provided additional insight into the dynamic behavior of the demand and lead time interaction. It is common to think that the reduction of lead times will always be desirable in terms of improving operational performance, better financials, improved responsiveness/service quality and increased customer satisfaction (Tersine and Hummingbird, 1995; Stalk and Hout, 1990; Suri, 1998). However, in the long-term, the dynamic impact of lead time reduction should also be considered in order to maintain the sustainability of lead time improvements.

Based on quantitative results, it has been observed that the incentive for reducing lead time may change dynamically over time. Due to lead time, demand and other factor interactions, it has been observed that after a certain lead time value is reached; further reductions in lead time bring no added value. Beyond this lead time value, further reductions in lead time deteriorates future performance in terms of increased resource utilization, extended lead times and higher work in

progress inventories. Therefore, in the long-term, consideration of this break-even point will sustain the durability of performance improvement reached by the reduction of lead time.

*Note: The fundamentals of this study are first introduced in the following study: 'Evaluation of the Dynamic Impacts of Lead Time Reduction on Finance Based on Open Queuing Networks,' (Gläßer et al., 2010a) and the results provided here are partly presented as 'A Dynamic Evaluation of Lead Time Reduction Improvements: A Hybrid Approach of System Dynamics and Queuing Network Analysis,' (Alp, 2012).*

## Chapter 7

# Conclusion and further research

This thesis focuses on analyzing the long-term and dynamic impact of lead time reduction approaches on operational, customer-oriented and financial performance. An integrated dynamic performance measurement framework has been developed to cover operational, customer-oriented and financial performance dependencies dynamically over time.

Compared to previous studies where the benefits of lead time reduction are only shown through a few cost measures and without taking any performance interactions into consideration, the approach developed here provides a detailed perspective where multiple facets of performance are directly and indirectly affected by the reduction of lead time. Furthermore, the complete interaction of time-based and non-time based performance metrics provides a more realistic perspective of the dynamic impact of lead time reduction approaches.

The findings of this study comprehensively demonstrate how performance trade-off characteristics and situational factors play a critical role between lead time reduction decisions and related effects on performance. In particular, the industrial example presented in Chapter 5 (*see page 97*) shows how dynamic dependencies and related factor interactions between buffer characteristics and bottleneck station loading policies impacts operational performance. In light of the quantitative results, it is shown that when the impact of lead time related factor interactions are considered, better performance is obtainable, even if variability is increasing. Furthermore, the results also illustrate that lead time reduction improvements can be achieved without the need for any significant investments, such as increasing bottleneck resources, buying a new machine or hiring new employees. Chapter 6 (*see page 117*) demonstrates the long-term effects and dynamic

dependencies between lead time and lead time related factors. In particular, complex relationships between time-based performance, market-oriented capabilities and the related financial situation were highlighted based on an industrial case. It was observed that the combined use of lead time reduction strategies may provide significant profit increases and performance improvements compared to the individual use of each strategy. Lead time reduction was shown to not only have a direct effect on operational performance measures, but there are indirect effects on service levels, customer satisfaction, penalty and customer retention costs, as well as long-term effects on sales and profits. In the long-term, flexibility and investment capabilities are improved, which provides extra capacity and capability to hedge variability and an unexpected demand increase without worsening customer satisfaction and market shares. Improvements in flexibility and investment capabilities are critically important to maintain the continuity of performance improvement in the long-term. Conversely, failing to maintain the continuity of improvement initiatives has unanticipated side effects. Poor improvement decisions and incorrect lead time reduction strategies have immediate, short-term impacts and long-term destructive effects on overall system performance. Due to dynamic factor interactions, in the long run, performance distortions create a snowball effect where performance worsens and the system gets stuck in a vicious loop. Sensitivity analysis contributed, in a way, to extending the research scope and analyzing the impact of lead time reduction on long-term performance, when compared to short-term effects. Based on quantitative results, it has been observed that the incentive for reducing lead time may change dynamically over time and under certain conditions, lead time improvement may not be sustainable in the long-term. There is a threshold value of lead time where further reduction of lead time deteriorates future performance. Consequently, the long-term dynamic impact of lead time reduction should also be considered in order to maintain the sustainability of lead time improvements.

The comparison of short-term effects and long-term performance provided additional insight into the dynamic behavior of the demand and lead-time interaction. It is common to think that the reduction of lead times will always be desirable in terms of improving operational performance, better financials, improved responsiveness/service quality and increased customer satisfaction (Tersine and Hummingbird, 1995; Stalk and Hout, 1990; Suri, 1998). Managers focusing on short-term effects of lead time reduction may be the victims of their own success. For some managers, trying to satisfy higher demand may seem attractive in the short-term. However, it has been shown that in the long term, there are certain side effects.

Based on quantitative results, it has been shown that the incentive for reducing lead time may change dynamically over time. Due to lead time, demand and other factor interactions, it has been

observed that after a certain lead time value is reached, further reductions in lead time deteriorate future performance in terms of increased customer satisfaction, increased demand, increased resource utilization, extended lead times and higher work in progress inventories. Thus, lead time reduction should not be over emphasized. In the long-term, consideration of this break-even point will sustain the durability of performance improvement reached by the reduction of lead time. The dynamic impact of lead time reduction in the long-term should be considered in order to maintain the sustainability of lead time improvements.

The integrated performance framework provided in this study facilitates a closed-loop continuous performance evaluation over-time by connecting customer-oriented measures and external demand. In this regard, the approach contributed, in a way, to accepting and designing the performance management process as a closed-loop system. In this way, a dynamic and comprehensive feedback gathering and evaluation mechanism is maintained and integrated into the performance measurement process.

The methodology demonstrated in this study provided a hybrid use of both Queuing-theory-based modeling and System Dynamics modeling. The integration of these two approaches provides a synergy, a better way of exploring the complexity of the system, while at the same time, providing enriched analyzing capabilities, larger selection of critical scenarios and higher levels of detail. This enhances the complete understanding of the stationary and dynamic behavior of the system, the mechanics of lead time reduction, critical factor interactions and complexity issues raised by multiple use performance dimensions. This study demonstrates the effective use of such dynamic hybrid performance measurement methodology. The idea demonstrated in this study can be adopted to improve the efficiency and effectiveness of existing performance management frameworks.

In parallel, there are managerial implications and practical contributions made by this study. For manufacturing and service companies, significant levels of productivity and profitability are achievable by establishing the link between non-financial and financial performance measures; and integrating time-based performance measures into the performance evaluation process (Ittner and Larcker, 2003 and 1998; Banker *et al.*, 2000).

Companies still have a limited understanding as to how Rapid Modeling tools can help covering performance tradeoffs and coping with complexities of real-life industrial problems (Rabta *et al.*, 2009; Reiner *et al.*, 2010; Gläßer *et al.*, 2010a and 2010b). In this regard, the industrial cases introduced in this thesis help to improve understanding on how the proposed hybrid modeling

approach can be integrated into the real-life problems in order to gain insights on performance factor interactions, cause-and-effect relationships and related system dynamics. Although the findings presented in this study are limited with assumptions and certain characteristics of the industrial cases; it is possible to adopt the integrated performance framework and generalize the solution approach to fit other industries or service processes with similar system characteristics and bottleneck station problems. For instance, the integrated performance measurement framework was used to analyze the impact of lead time reduction strategies on service operations of a non-profit humanitarian organization. In particular, the framework was used to develop an integrated and profound capacity management approach to help the organization cope short-term demand fluctuations and maintain their long-term growth. In this regard, the service lead time was successfully reduced. The approach provided extra time, capacity and flexibility to managers to secure the growth of the organization and maintain the continuity of the service process improvement activities. Considering limited number of integrated performance measurement in nonprofit sector, this example successfully demonstrated the added value of the integrated performance measurement approach for service sector and non-profit organizations. Further information is provided in the following study: *'Quick Response Service: The case of a Non-profit Humanitarian Service Organization,'* (Alp et al., 2010) and *'Process Evaluation with Rapid Modeling,'* (Alp, 2011).

The integrated performance measurement framework has been developed for competitive markets with perfect competition (Stigler, 1957). However, strategic interactions under oligopolistic or monopolistic environments are different when compared to markets with perfect-competition (Griffith and Rust, 1993 and 1997). In this regard, it is possible to modify the current performance evaluation framework in order to adapt the effects of different market conditions. For instance the effect of imperfect competition or monopolistic environments on the model behavior can be analyzed. Making comparisons among different market conditions will provide a more general understanding when compared to competitive market conditions.

The generality of the model is limited as it is based on the assumptions of current industrial cases. However, the performance measurement framework and idea of hybrid Queuing-theory-based modeling and System Dynamics modeling is applicable to a wider range of situations where understanding system dynamics plays an important role. In this case, further research is needed to study the dynamics of integrated performance measures in a wide range of business circumstances and extreme cases.

The findings of this study can be used to contribute to classroom teaching and student learning. Further information is provided in the following study: *'Rapid Modeling for Teaching Lead Time*

*Reduction Principles: A Hybrid Approach Based on a Continuous Improvement Concept,*  
(Reiner *et al.*, 2012).



# Appendix

Relevant initial values of input parameters are given in Table A (*shown below*).

Table A: Initial values of input parameters (in alphabetical order)

Parameter	Explanation	
$r_{int}$	annual interest rate	5 %
$A$	assumed worth of customers time	1.00 ( <i>see Kalló and Koltai, 2010</i> )
$c_{retention}$	average customer retention cost (per customer)	0.120 euro (per customer)
$\lambda$	average repurchase cycle	8 years
$T_o$	customer's expectation for the waiting time	1.00 ( <i>see Kalló and Koltai, 2010</i> )
$D$	demand	85,169,237.89 units
$\gamma$	effect of the expected waiting time on satisfaction	0.80 ( <i>see Kalló and Koltai, 2010</i> )
$r$	extend of customer's risk awareness in term of time	1.2 ( <i>see Kalló and Koltai, 2010</i> )
$h_k$	unit holding cost for product $k$	0.01 euro /per unit item
$ir$	investment ratio	17 %
$LC_1$	cost of an operator	34.06 euro
$LC_2$	cost of a packer	27.30 euro
$LC_3$	cost of a transfer operator	27.30 euro
$IC_m$	machine $m$ idle cost per hour	36.65 euro
$RC_m$	machine $m$ running cost per hour	55.95 euro
$MP$	market potential	19,615,209.80 customers
$a$	marketing effectiveness	0.03599
$NC_0$	number of customers at time $t=0$	12,378,384.19 customers
$m$	number of machines (parallel resources)	4 machines
$n_1$	number of operators	4 operators
$n_2$	number of packers	3 packers
$n_3$	number of transfer operators	3 transfer operators
$c_{penalty}$	penalty cost per backorder	120,000 euro
$p$	price (per meter finished article)	0.120 euro
$T_{pp}$	production period of one year in minutes	518,400.00 minutes
$r_t$	run time per unit	0.02 minutes
$c_1$	run time coefficient of variation	0.428836418
$St_b$	setup time (batch)	42.05 minutes
$c_2$	setup time coefficient of variation	0.595522376
$c_{km}$	setup cost for a machine $m$	0.92 euros/per minute



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