1

Throughput Concepts

1.1 Introduction to Throughput

Throughput refers to “the amount of work, people, or things that a system deals with in a particular period” [Macmillan n.d.]. In the context of manufacturing, throughput denotes the quantity of products that can be produced within a period and the available resources.

Enhancing throughput is a central goal in manufacturing management, directly connected to financial performance and supported by various factors. These factors include daily management activities, methodologies, and technologies. Furthermore, these diverse factors can mutually influence each other in the pursuit of operational excellence.

Concerning the value creation of a business, operational management places significant emphasis on throughput in both manufacturing and nonmanufacturing sectors. Professionals widely acknowledge its importance, as exemplified by the statement, “throughput is king” [Miller 2021].

1.1.1 Role of Throughput on Business Success

1.1.1.1 Role of Manufacturing in Business

Business performance can be assessed from different perspectives and using various metrics, with key dimensions including financial health, customer satisfaction, and internal process effectiveness, as illustrated in Figure 1.1. At the core of internal processes for product-based businesses lies manufacturing operations.

Figure 1.1 highlights the interconnected nature of financial health, customer satisfaction, and internal processes. For instance, improving internal processes can boost productivity, positively affecting both financial health and customer satisfaction.

Manufacturing, as a central pillar for numerous companies, holds immense significance for overall business performance. Shortfalls in throughput targets lead to reduced production output, delayed deliveries, customer dissatisfaction, negative effects on the company’s reputation, and diminished revenues. This book primarily emphasizes the effectiveness of internal processes within manufacturing systems, focusing specifically on productivity and throughput.

1.1.1.2 Financial Significance of Throughput

A company’s operational profit can be expressed as the difference between the revenue generated by product sales and the expenses incurred from producing products and operating systems. Here

Manufacturing System Throughput Excellence: Analysis, Improvement, and Design, First Edition. Herman Tang.

Companion website: www.wiley.com/go/Tang/ManufacturingSystem

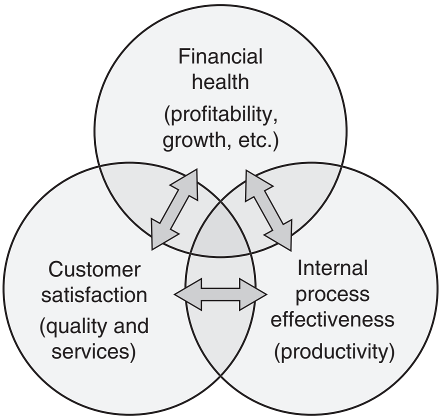


Figure 1.1 Main performance focuses of a manufacturing company.

is a simplified representation of the components contributing to profit:

Profit = Production rate × Unit sales
– Direct costs (production materials and labor per unit × units produced)
– Indirect production costs (utilities, other materials, indirect labor, and inventory, etc.)
– Other indirect costs (overhead, general and administrative, etc.)

In this equation, the production rate significantly influences profitability by determining the output volume for the market. Thus, system throughput is an integral part of a business's financial success. Enhancing throughput aligns with sound business logic and can have a significant impact.

Indeed, manufacturing performance extends beyond throughput and encompasses a broader spectrum of factors. Elements such as customer satisfaction, employee engagement, market share, supplier relationships, and societal impact all contribute to the overall evaluation of manufacturing performance. While these aspects are not the primary focus of the book, their examination in conjunction with system throughput can yield valuable insights into their interplay. A holistic understanding of manufacturing operational performance can pave the way for more comprehensive and effective management and improvement strategies.

1.1.1.3 Work Focuses

A survey of 240 professionals from various manufacturing sectors across North America highlighted their main concerns in an increasingly competitive landscape marked by rising input costs and shrinking margins. These professionals identified efficiency and productivity as their top priorities [Alithya 2023].

Another survey of 153 US manufacturing executives indicated robust growth expectations within the industry [Kronos 2016]. The survey also identified the following 14 main operational challenges:

1. Improving internal production processes
2. Strengthening customer relationships
3. Finding enough people with the right skills and talent
4. Increasing labor productivity
5. Increasing demand responsiveness

6. Maximizing capacity and asset utilization
7. Meeting customer demands for product customization
8. Achieving annual cost reductions
9. Improving product and service quality
10. Responding to customer requests for quotes and proposals
11. Improving labor flexibility
12. Enhancing supply chain collaboration
13. Optimizing supply chain performance
14. Faster and more frequent new product releases and launches

Particularly related to manufacturing throughput, several challenges identified in the survey, such as 1, 4, 6, 8, and 9, are closely related to manufacturing throughput topics addressed in this book. For instance, Chapter 3 discusses how to identify and remove system bottlenecks; Chapter 6 presents methodologies for enhancing throughput; Chapters 7 and 8 offer proactive design considerations for improving production processes, aligning with improving internal production processes.

Regarding financial implications and cost reduction, Chapter 2 addresses throughput finance. Chapters 4 and 5 introduce the concept of the total cost of integrating throughput performance with quality and maintenance management, relating to challenge 8 – achieving annual cost reductions.

1.1.1.4 Throughput Management

Throughput management can be visualized as a pyramid-shaped business model with multiple levels (see Figure 1.2). This model is driven by a long-term growth vision. Manufacturing professionals align with the organizational mission (goals) and strategies, following relevant principles and using appropriate approaches to achieve improved performance. At its core, manufacturing throughput is propelled by the overarching business mission, strategy, and financial considerations.

In addition to system throughput, product quality is another fundamental performance aspect that impacts the overall system's performance. Both system throughput and product quality can be influenced by other factors, such as product design, manufacturing processes, operational complexity, and their interactions, as illustrated in Figure 1.3.

As financial health is the ultimate objective of any business, achieving excellence in throughput directly contributes to this bottom line, as mentioned earlier. Accounting and economic analysis can elucidate the correlation between throughput performance and financial outcomes. This crucial topic will receive comprehensive coverage in Chapter 2 of the book.

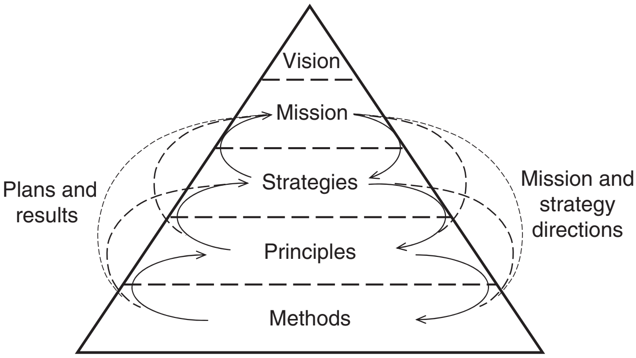


Figure 1.2 Business model for system throughput management.

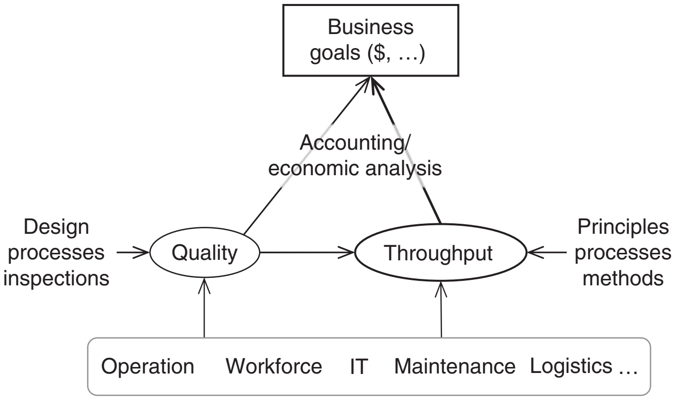


Figure 1.3 Manufacturing throughput management environment.

1.1.1.5 Throughput Work Collaboration

Effective system throughput relies on the collaboration among various departments involved in designing, operating, and supporting manufacturing operations. In this context, production management, maintenance management, and quality management emerge as three principal areas integral to throughput performance and enhancement, as illustrated in Figure 1.4. This book extensively covers these key areas, while not delving into other elements such as supply management and team management. Furthermore, Chapters 7 and 8 will explore in detail the significance of system design in shaping system capability and operational performance.

Managing and enhancing the performance of a manufacturing system is often considered both an art and a science, or perhaps a science-based art. Effective throughput management requires extensive knowledge, a diverse skill set, and substantial experience due to the system complexities arising from numerous variables and their intricate interactions.

Academic research in the realm of system throughput has a history dating back to the 1950s, with early examples such as Koenigsberg [1959]. Many analytical studies at that time focused on simple systems with only a few machines. Recently, computer simulation has gained prominence and will be explored in more detail later in this book.

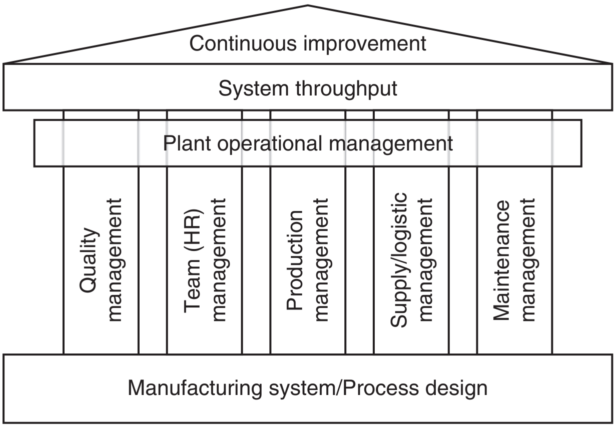


Figure 1.4 Pillars and foundation of manufacturing system throughput.

Subsection Summary: Manufacturing throughput plays a pivotal role in business, significantly impacting its financial performance and internal processes. Managing throughput improvement needs unique focuses and presents specific challenges.

1.1.2 Manufacturing Throughput Performance

1.1.2.1 Basics of Throughput

A manufacturing system transforms inputs, such as capital, materials, energy, machinery, labor, and information, into finished goods for customers. This transformation process includes a range of manufacturing functions, such as machining, assembly, and material handling, which may occur sequentially or concurrently. Operational management is concerned with the effectiveness of transformation processes, measuring productivity, throughput, and profitability, irrespective of process types and functions. Figure 1.5 illustrates how these terms relate to a manufacturing system.

The throughput rate (TR) of a system is a key metric used in operational management, defined as the number of product units produced within a specific period:

$$\mathrm{TR} = \frac{\text{Product units}}{\text{Period}}$$

The unit of TR depends on production volume. For systems that produce large products like vehicles, TR is typically measured on an hourly basis, for example, 90 jobs per hour (JPH). Meanwhile, for small parts with high production volume, system throughput may be measured in pieces per minute.

TR has two basic types: design and measured. Design TR represents the target output or capability according to the system design. On the contrary, measured TR indicates system performance, largely related to operational management and measured on the production floor.

Throughput performance is typically assessed by expressing measured TR as a percentage of design TR. For instance, a measured TR at 95% of the design TR indicates that the operation fell short of the target by 5%, suggesting improvement potential for throughput performance.

In most of repetitive and continuous productions with a fixed design TR or process pace, total production output can also be used as a measurement of throughput or be presented as at both a rate and an amount.

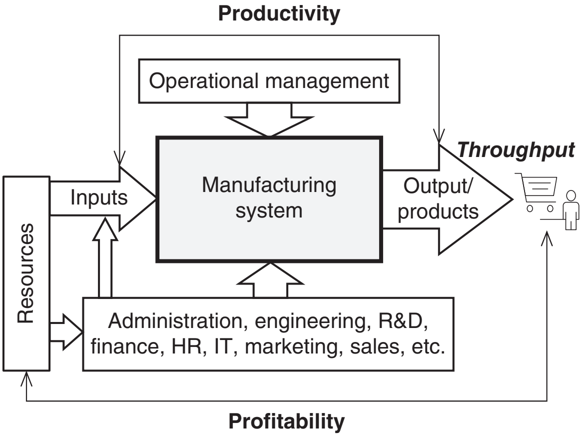


Figure 1.5 Systems view on manufacturing performance.

These concepts also apply to various nonmanufacturing sectors, such as retailing and financial services. In those sectors, throughput signifies the volume of material, service, or product that passes through the system and the final products delivered to customers. In healthcare settings such as hospitals, patient throughput can be assessed by measuring wait times and the length of stay.

1.1.2.2 Operational Availability

In managing a manufacturing system, terms like "availability" or "operational availability" are frequently used alongside TR. In many cases, throughput and availability are considered similar concerns and are related to factors such as process capability, product quality, and equipment maintainability.

The operational availability (A) of a system (or equipment, operation, etc.) is defined as:

$$A = \frac{\text{Actual production time}}{\text{Planned production time}}\ (\%)$$

In this equation, actual production time is the time spent producing products, excluding all nonworking time due to failures and other reasons. The planned production time represents the expected operating time.

For example, if a shift ran for 7 hours with a planned production of 7.5 hours, the system availability is,

$$A = \frac{\text{Actual production time}}{\text{Planned production time}} = \frac{7}{7.5} = 93.3\%$$

Organizations may have their own definitions. Toyota, for instance, considers starved time, equipment time, and work delay time when calculating the actual production time for the operational availability of a system [Sakai and Li 2020]:

$$A_{\text{toyota}} = \frac{\text{Planned production time} - \text{Starved time} - \text{Equipment time} - \text{Work delay time}}{\text{Planned production time}}$$

Here, starved time is the waiting time for parts from the upstream and other operations (discussed in Section 1.4); equipment time represents the equipment's downtime; and work delay time accounts for any additional time taken for the operations.

For example, if a shift was planned to run production for 7.5 hours, with a starved time of 0.3 hour, downtime of 0.2 hour, and work delay time of 0.1 hour, the corresponding availability would be:

$$A_{\text{toyota}} = \frac{7.5 - 0.3 - 0.2 - 0.1}{7.5} = \frac{6.9}{7.5} = 92.0\%.$$

The term "reliability" is often used to describe operational availability as the primary factor associated with availability. The reliability of a system (or workstation, work cell, equipment, etc.) will be discussed in detail in Chapters 2 and 4 of the book.

1.1.2.3 System Productivity

TR and productivity are sometimes used interchangeably because productivity often focuses on throughput and quantity. Typically associated with larger systems, productivity addresses individual or aggregate input and output, involving various resources and functions, such as labor, material, energy, and their combinations. A manufacturing system is deemed productive if the deployed resources and activities effectively add value to the products for customers. In the long run, high productivity leads to increased profitability.

As depicted in Figure 1.5, productivity is a ratio of input to output, calculated as:

$$\text{Productivity} = \frac{\text{Output}}{\text{Input}}$$

Here, the output represents the result of a process (measured by quantity, money, etc.) and the input represents the resources or effort put into that process (measured by money, time, etc.). The productivity ratio can be a dimensionless percentage or a value per unit, such as revenue per hour, per employee, or per piece of equipment.

For instance, in a vehicle assembly plant with 2200 employees producing 155,000 cars in a year (2290 working hours), labor productivity can be measured in several ways:

- Units per employee: $\dfrac{\text{Produced units}}{\text{Number of employees}} = \dfrac{155{,}000}{2200} = 70.45\ \text{units/employee}$
- Plant production rate: $\dfrac{\text{Produced units}}{\text{Production hours}} = \dfrac{155{,}000}{2290} = 67.69\ \text{units/hour}$
- Hours per unit: $\dfrac{\begin{matrix}\text{Number of}\\ \text{employees}\end{matrix} \times \begin{matrix}\text{Production}\\ \text{hours}\end{matrix}}{\text{Produced units}} = \dfrac{2290 \times 2200}{155{,}000} = 32.50\ \text{man-hours/unit}$

If the profits of the car models are known, the plant's financial productivity can be calculated at $/hour. Moreover, productivity can be calculated at various levels within an organization, including specific processes, areas, equipment, and so on.

1.1.2.4 Considerations in Productivity

Improvement in productivity may be achieved by increasing output, using reduced resources, or employing a combination of both strategies. For instance, higher maintenance costs or added investments in new technology, treated as system input variables, can improve productivity. In such cases, the measurement of the productivity ratio becomes more important than measuring TR itself, as it helps evaluate the effects of input changes on system performance.

In some cases, especially in mass production, the primary inputs, such as direct labor and materials, remain consistent over a certain period. In such situations, operational performance can be measured solely by system throughput, without considering the variations in input. This implies that higher throughput yields more output with the same input of resources, such as labor and materials.

It is worth mentioning that continuously increasing labor productivity can be challenging. For instance, a study indicated that the labor productivity in the US fell by 2.8% between 2011 and 2021 after a significant increase between 2001 and 2011. Between Q4 of 2020 and Q4 of 2022, it declined by 0.4% [Clay 2023]. On the production floor, the challenge holds true for other types of productivity and throughput improvement.

Subsection Summary: Various aspects of throughput performance, including TR, availability, and productivity, form the foundation for understanding throughput performance and further analysis.

1.2 Discussion of Manufacturing Throughput

1.2.1 Characteristics of Manufacturing Throughput

1.2.1.1 Cost Perspective

Cost control, aimed at reducing both direct and indirect production costs, is an integral part of manufacturing management. Direct costs include expenses directly associated with production, including labor, parts, and materials. While indirect costs comprise expenses not directly tied to production, covering areas such as equipment, utilities, overhead, and support functions.

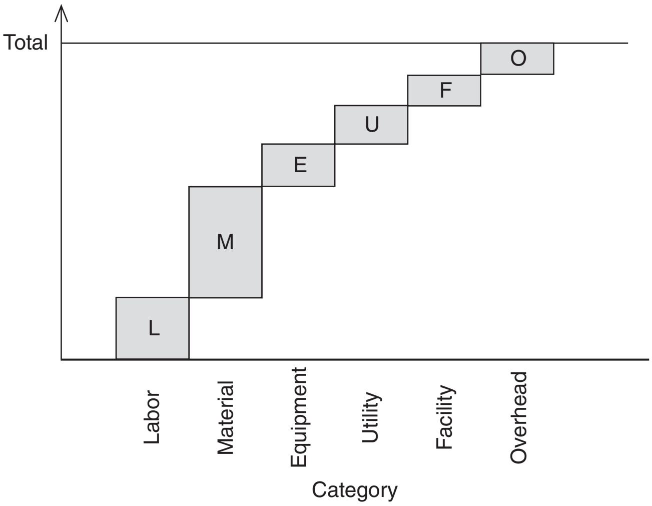


Figure 1.6 Main cost categories of manufacturing operations.

The total cost of a manufacturing operation within a given period can be presented as the sum of the following categories (refer to Figure 1.6):

$$C_{\text{total}} = C_{\text{labor}} + C_{\text{material}} + C_{\text{equipment}} + C_{\text{utility}} + C_{\text{facility}} + C_{\text{overhead}}$$

where

- C_{labor} represents direct labor costs, proportional to the number of production workers and front-line team leaders.
- C_{material} includes the costs of materials directly used in product manufacturing.
- $C_{\text{equipment}}$ represents equipment costs, based on depreciation of all machines, tools, and facilities (excluding the initial costs).
- C_{utility} accounts for utility costs, including expenses related to electricity, natural gas, as well as water for the system, etc. (some may be categorized as indirect costs).
- C_{facility} encompasses facility costs, including building depreciation, operations, maintenance, and related expenses.
- C_{overhead} refers to overhead costs, which are a predefined distribution of indirect costs covering items such as indirect materials, indirect labor, inspections, financial costs, and many others.

The relative sizes of the cost category blocks in Figure 1.6 are for illustration purposes, and the actual significance of each cost category varies depending on the types of manufacturing processes, system sizes, etc. For instance, energy-intensive processes, such as painting operations in an automotive assembly plant, incur high utility costs (C_{utility} in the equation). Processes involving extensive manual labor tend to incur significant direct labor costs (C_{labor}), particularly in countries with high wage levels.

It is important to note that the direct material cost (C_{material}) is proportional to the number of products produced. In contrast, other cost items (e.g., $C_{\text{equipment}}$, C_{utility}, and C_{overhead}) exhibit small variations in many cases within a given period. Direct labor costs increase with the quantity of products produced and the number of working hours.

Total cost can be expressed as a unit cost or cost per unit, serving as an indicator of operational effectiveness, productivity, and throughput performance. In many manufacturing scenarios, an objective is to reduce unit costs, with predetermined targets guided by historical data and the strategic goals of the production plant. Enhancing overall productivity can effectively lower unit costs, highlighting the value of throughput improvement.

1.2.1.2 Throughput and WIP

Within a manufacturing system, there exist many unfinished products, collectively known as work in process (WIP). While WIP does not generate value, it consumes capital through additional work, including tracking, storage, reprocessing, and inspection. Therefore, in alignment with the Lean principles and the pursuit of cost reduction, it is advisable to keep WIP as an operating expense at a minimal level.

In manufacturing, throughput time (TT) refers to the total time a product unit takes to traverse from the system's beginning to its end. TT serves as a tool for estimating the number of WIP units within the system, as illustrated in Figure 1.9 in the next subsection 1.2.2.

Little's Law, initially proven by John Little [1961] and subsequently examined by other researchers, establishes a relationship that remains unaffected by factors such as arrival process distribution, service distribution, service order, or any other considerations [Simchi-Levi and Trick 2011].

The long-term average WIP in a system can be calculated using Little's Law, given the known TT and TR:

$$\text{WIP} = \text{TT} \times \text{TR}$$

For instance, if the average TT for a system is 40 minutes (or $\frac{40}{60}$ hour), and the measured TR is 70 JPH, then the average of WIP units over an extended period would be:

$$\text{WIP} = \frac{40}{60} \times 70 = 46.7 \approx 47$$

When issues in the system impact throughput, such as system downtime or product defects, the actual TT may exceed the designated one, leading to a corresponding increase in the number of WIP units.

Elevated WIP levels lead to higher inventory costs, which may not be always considered in throughput studies. Reducing WIP levels is a strategic business move, albeit challenging, as efforts must be directed toward decreasing either TT, TR, or both. In certain situations, decreasing TT can be achieved through the implementation of Lean principles, workflow optimization, and the adoption of new technologies. Conversely, improving the measured TR to align with the design TR can also be an effective method for reducing WIP.

1.2.1.3 Continuous Improvement vs. Optimization

To enhance throughput performance on the production floor, a widespread practice is continuous improvement (CI). Although the terms "continuous improvement" and "optimization" are often used interchangeably in various cases, they differ in several aspects.

- *Conceptually*, *CI* involves an ongoing effort to incrementally enhance system performance. It is a routine and never-ending process, often recognized as both a mindset and a strategic approach. Breakthroughs can occasionally be achieved via CI efforts.

  In contrast, *optimization* involves the pursuit of the best possible outcome under a given situation, signifying a one-time effort to attain an optimal outcome. As a more academic term, optimization requires an in-depth study of mathematical modeling and computer programming. In some cases, optimization efforts may fail to produce solutions with certain algorithms and/or constraints.

- *Methodologically*, *CI* employs established approaches, such as PDCA and DMAIC (discussed in Chapter 6), conducted by field practitioners. It often integrates with other principles, such as Lean and Six Sigma, utilizing methods such as statistical analysis.

  Optimization encompasses specific methods aimed at maximizing or minimizing an objective function with specific mathematical models. Due to the technical complexity involved, optimization studies are typically conducted by well-trained engineers and researchers.
- *Process wise*, *CI* involves identifying opportunities for improving effectiveness/efficiency, enhancing quality, reducing waste. This process typically involves a manual interactive approach with multiple steps, including brainstorming, review, root cause analysis.

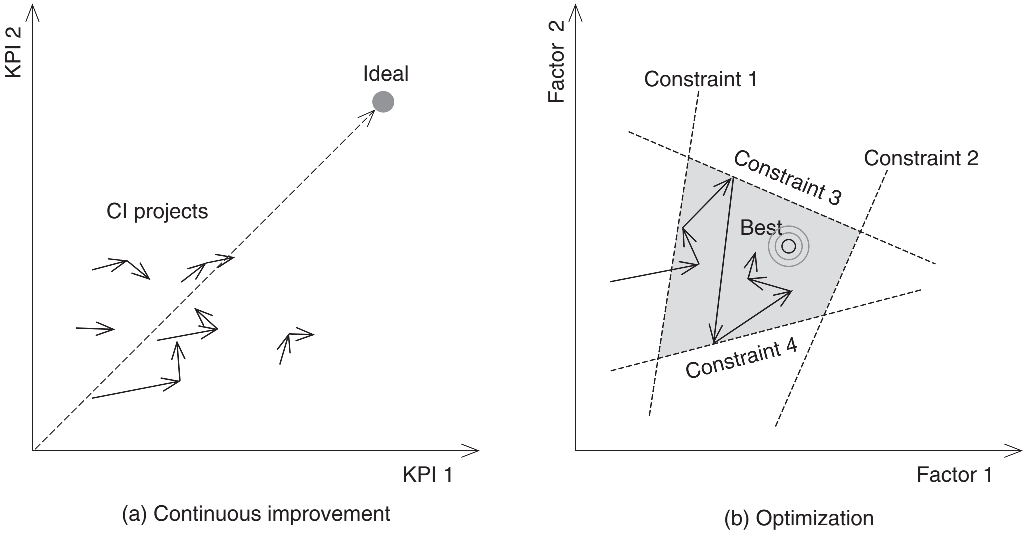
  In contrast, *optimization* aims to maximize or minimize a function output with input factors and constraints. It is typically conducted using a computer with optimization algorithms that automatically seek the best solution. However, the results must still be reviewed and interpreted for their feasibility in the real world.
- *Application wise*, CI is a universally applicable concept, implementable across various fields and widely used, especially in manufacturing.

  On the contrary, *optimization* is particularly suitable for engineering system design (discussed in Chapters 7 and 8), aiming to optimize resource utilization, achieve maximum performance, and potentially reach an ideal balance within theoretically designed systems.

Figure 1.7 depicts the processes of CI and optimization in a simplified two-dimensional world, acknowledging that both processes can involve more dimensions.

There is a wealth of literature available on both CI and optimization, with recent review papers by Skalli et al. [2022] and Cunha et al. [2023] for CI, and Yelles-Chaouche et al. [2021] and Renna et al. [2023] for optimization.

Integrating both methodologies for industrial applications is recommended, as it can offer complementary benefits. However, it can also be technically challenging due to the distinct nature of these approaches.



(a) Continuous improvement

(b) Optimization

Figure 1.7 (a) Continuous improvement versus (b) Optimization.

Subsection Summary: Enhancing manufacturing throughput involves cost control, WIP reduction, and CI. Little's Law establishes a link between TT and WIP. Integrating optimization and CI can optimize throughput excellence.

1.2.2 Time Analysis in Manufacturing Operations

1.2.2.1 Time Elements of Operations

Manufacturing operations do not always run perfectly because of unavailable equipment and blocked operations, among other factors. Understanding their time characteristics can aid in problem identification and solution.

The time elements during production can be recognized based on the state and task of an operation, as depicted in Figure 1.8 for their relationship:

- Planned time: Planned time is the total production time planned, excluding scheduled breaks, for example, 7.5 hour production time in an 8-hour shift, excluding 30 minutes of three breaks.
- Effective planned time: Effective planned time is typically calculated as available time + time loss due to some slow operations.
- Available time: Available time includes actual production time, blocked time, and starved time.
- Unavailable time: Unavailable time includes downtime resulting from failures and setup.
- Actual production time: Actual production time is the time of a system running to produce products.
- Blocked and starved time: Blocked and starved time is the waiting time due to external factors, to be discussed in Section 1.4.
- Setup time: Setup time is for support tasks, such as planned maintenance, adjustments, and tool changes.

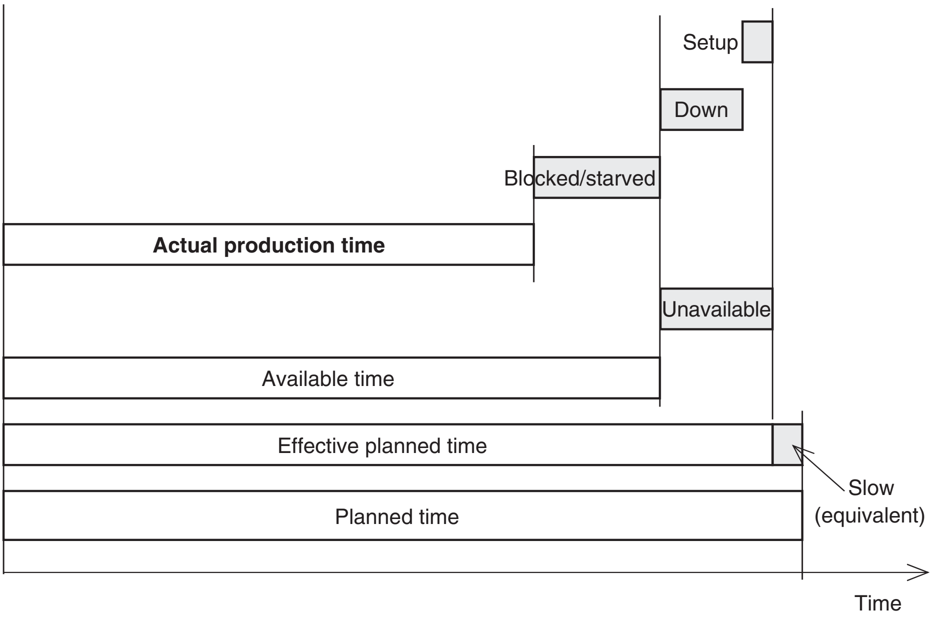


Figure 1.8 Time elements of an operation (or equipment).

These time elements and their relationships apply to various types of operations, such as equipment, workstations, assembly lines, and areas with multiple lines. Some elements may be broken into detailed items. For example, downtime may be due to equipment problems or quality issues. With clear definitions, categorizing actual data into these time elements can be straightforward.

Note that the quality of the products produced is not factored in here. If needed, the equivalent time of producing defective parts and/or reprocessing can be included. The influence of product quality is discussed in depth in Chapter 4.

Operational slowness is often minor and distributed throughout work time. Identifying and resolving slow operations require special attention. Slow operations often include minor stoppages. The classification of a stoppage as "minor" varies based on the specific operation. For instance, in the context of mass production, a stoppage lasting less than ten seconds might be considered minor downtime.

Moreover, with proper planning, setup, and maintenance times can be minimized or eliminated in the production time frame in most cases.

1.2.2.2 Definitions of Cycle Time (CT)

Cycle time (CT) is widely used in manufacturing and service industries as the fundamental operational pace. There are two common definitions of CT:

1. CT is the amount of time to complete one cycle of an operation, such as a workstation and system, from start to finish. Under this definition, the CT of a workstation and a line may differ (see Figure 1.9).
2. CT is the amount of time to complete work for a unit. This definition aligns with the CT meaning as a production rhythm or the time interval between consecutive products coming out at the end of a continuous operation. Under this definition, the CT of a workstation and a line are at the same level and are easy to compare.

The second definition facilitates a more consistent and comparable measure, especially when evaluating the throughput performance of a system at different levels. This definition is used throughout the book. Regardless of which CT definition is used, it is important to maintain consistency in throughput management to avoid confusion.

For throughput monitoring and improvement, manually measuring and verifying the CT of target operations is often necessary. Commonly, a stopwatch app on a smartphone is used for CT measurement. Due to the variation and interaction of processes, CT measurement should be repeated at least five times to obtain a representative mean value. A more effective method for CT measurement is videotaping using a camera app. Video recordings can be replayed as evidence in reviews of improvement opportunities.

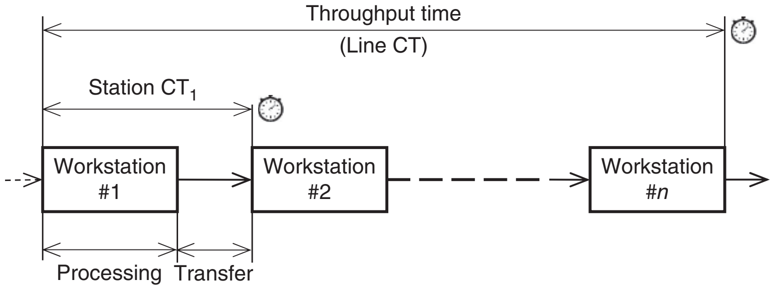


Figure 1.9 Workstation's cycle time and line's cycle/throughput time.

1.2.2.3 CT and Throughput

Similar to TR, CT has two fundamental types: design CT and measured CT. Design CT signifies the CT capability as per the design, whereas measured CT reflects the actual performance on the production floor.

In a repetitive process, when the CT is in seconds and the corresponding gross TR is in JPH, their theoretical relationship is expressed as:

$$\text{TR}_{\text{gross}} = \frac{3600}{\text{CT (seconds)}} \text{ (JPH)}$$

Note that when CT and/or TR are in different units, the coefficient “3600” in the equation needs to be changed accordingly.

This equation demonstrates that TR and CT have a reciprocal relationship, as illustrated in Figure 1.10a. When the CT of an operation deviates from the CT, the TR changes inversely. For instance, if CT increases (slower) by 3%, the corresponding TR will decrease by approximately 3%. Figure 1.10b provides a close-up view of the region around CT = 60 seconds in Figure 1.10a.

In the formula of TR and CT, gross TR is based on the assumptions of perfect operational availability (or reliability), no interactions (i.e., starvation and blockage) between operations, and no variability. However, these assumptions do not hold true and are addressed in the later chapters. Given these limitations, the calculations based on this equation serve only as rough estimates. Considering the actual situation and relevant variables leads to the concepts of net TR, standalone TR, and measured TR, which are discussed in depth in subsection 7.2.1.

In a batch process, CT can be measured either per batch or per piece on average. For example, in a machining process that can cut 20 pieces within 15 minutes as a batch, the average CT of the process would be:

$$\text{CT} = \frac{15 \times 60 \text{ (seconds)}}{20 \text{ pieces}} = 45 \text{ seconds (per piece)}$$

For a repetitive process, internal transfer time within a system is typically included in CT (refer to Figure 1.9). For a batch process, transfer time can be averaged on a per-piece or per-batch basis. If a transfer function is external and/or not related to the start time of the next operation, it may be counted separately.

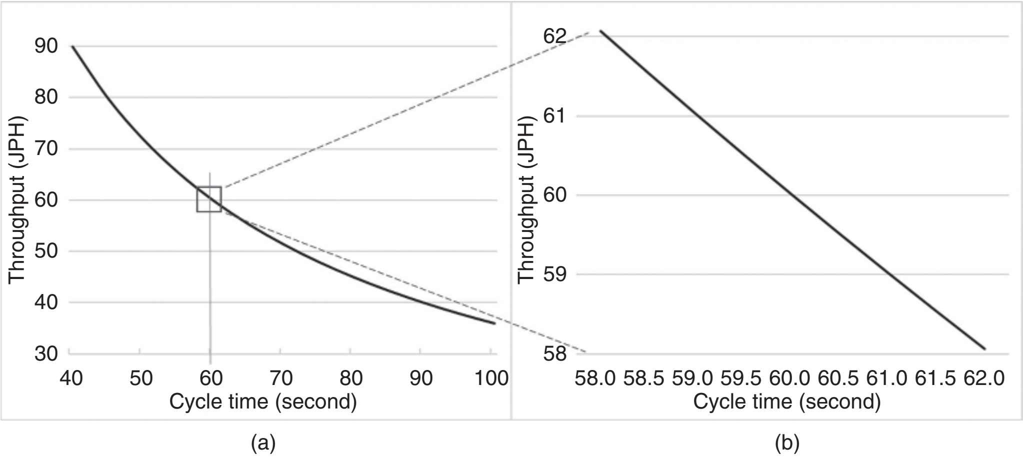


Figure 1.10 Relationship between cycle time and throughput rate.

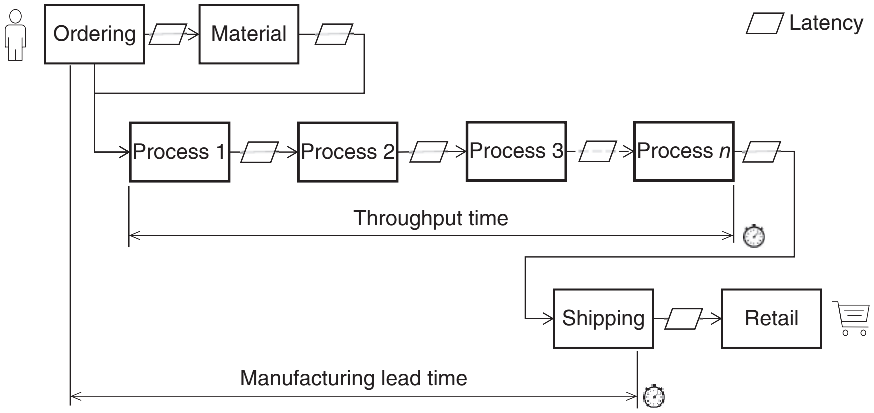


Figure 1.11 Throughput time and lead time of a manufacturing system.

1.2.2.4 Lead Time and Throughput

As mentioned in an early subsection 1.2.1.2, TT is the time span from start to finish for a product, as shown in Figure 1.9. TT is an important performance indicator, as it constitutes the major portion of the lead time to customers, showing system efficiency.

TT is primarily determined by product and process designs, especially in repetitive processes and certain batch processes. In TT, queue time (waiting time in the system) and setup time vary, which primarily depends on operational management and execution. Such elements of TT, including queue time, setup time, process flow gaps, and stops, do not add value to customers. Therefore, they should be focused on reducing TT for throughput management.

Another related term is manufacturing lead time, representing the entire time between receiving a customer order and delivering the product, as shown in Figure 1.11. In the figure, “latency” refers to the time spent on transfer, inventory, and other related activities. They can also be considered non-value-added to customers.

Illustrated in Figure 1.11, the TT of a manufacturing system is the core element of lead time, along with additional nonproduction latency time spent. As a metric, TT measures the internal efficiency of manufacturing processes, while lead time reflects the overall responsiveness to customer orders. Manufacturing professionals sometimes use the two terms interchangeably when focusing on production operations. Understanding and reducing them can enhance manufacturing system performance and benefit customer satisfaction.

Subsection Summary: Time perspectives, including time elements, CT, and the reciprocal relationship between CT and TR, offer effective lenses for analyzing manufacturing operations. Lead time and TT are also crucial measures of manufacturing efficiency.

1.3 Characteristics of Manufacturing Systems

1.3.1 Overview of Manufacturing Process Types

1.3.1.1 Four Major Types of Processes

Manufacturing processes can be categorized into four main types in terms of production volume and product variety (see Figure 1.12):

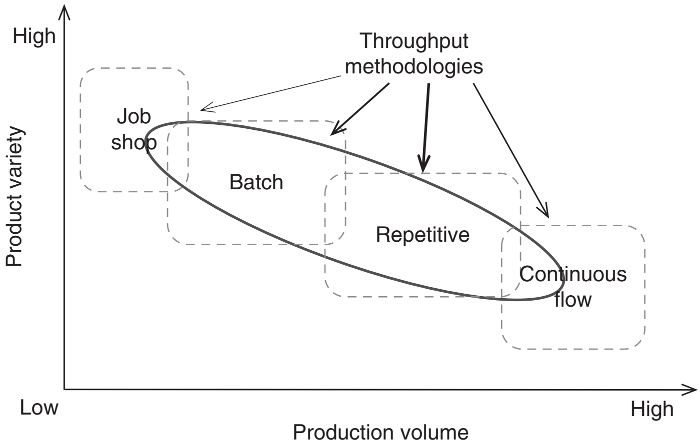


Figure 1.12 Characteristics of four types of manufacturing processes.

- Job shop process: In a job shop process, a single or small lot size of a customer's product is produced. The products and their manufacturing process are typically unique and not fully standardized. Setup conditions and process steps can vary. Examples of job shop processes include a large machine assembly and work in a repair shop, as well as services provided in hospitals and sit-down restaurants.
- Batch process: In a batch production, product units are grouped together with common process steps and tools. Products are typically manufactured in small batches of several units. Examples of batch production include biotech product manufacturing, food processing, sheet metal stamping for vehicle assembly, and fast-food restaurants. Depending on production volume and other factors, batch production can be either synchronous or asynchronous.
- Repetitive process: A repetitive process, also referred to as a discrete-product or transfer line process, entails the sequential processing of products for an extended duration. The manufacturing activities are repetitive for process steps. Repetitive processes often use a synchronous or one-piece-flow approach. An example is vehicle assembly, where the scale of plants can range from midsize to mega-sized facilities.
- Continuous process: A continuous process, also known as process manufacturing, operates continuously around the clock, maintaining a constant flow of materials or products. The process industry is typically characterized by large-scale operations and at high-automation levels. Industries that utilize continuous flow systems include oil refining, chemical processing, pharmaceuticals, and the food industry.

Throughput management and improvement is a shared concern across all four types with different focuses due to distinct characteristics. The methodologies of throughput improvement discussed in this book are most suitable for repetitive processes, easily adaptable to batch and continuous processes, a useful reference to job shop processes, refer to Figure 1.12. More discussion follows in the next subsection 1.3.1.2.

1.3.1.2 Comparison of Process Characteristics

A comparison of the characteristics of these four types of processes enhances our understanding of their differences, providing valuable insights for operational management and throughput improvement. Table 1.1 succinctly summarizes these characteristics. It is important to note that these characteristics are relative, with notable overlaps between process modes in many cases.

Table 1.1 General comparison of four types of manufacturing processes.

Attribute	Job Shop	Batch	Repetitive	Continuous
Cost per unit	High	Moderate	Low	Very low
Equipment	For general purposes	Some for special purposes	Most for special purposes	For special purposes
Worker skills	High	Moderate	Low	Various
Automation	None/low	Medium/high	High	Fully
Scheduling	Complex	Moderately complex	Routine	Routine
Main throughput KPI	TT	TT and TR	TR and quality	Cost and quality

With a shared concern on system throughput performance, there may be distinct aspects and key performance indicators (KPIs), as outlined in the bottom row of Table 1.1. These differences highlight the need for customized throughput management approaches and focuses for each process type. For example, in a batch process, due to the product variety from process, material, and batch sizes, etc., operational management typically addresses TT and TR as main KPIs. Conversely, due to high production volume in a continuous process, KPIs tend to be cost and quality.

There are other KPIs. For example, in batch and repetitive processes, two basic scenarios exist: assemble-to-stock (ATS) and assemble-to-order (ATO). In ATS, inventory availability is an important performance metric to support throughput. In ATO operations, delivery speed and reliability are crucial KPIs. Further discussion on KPIs is provided in Chapter 2.

Following market demands, a manufacturing system operating in a repetitive mode may need to produce more products with distinctive designs. This can prompt a transition from a repetitive mode to a batch mode in the manufacturing system. In such cases, in addition to the system's flexible capability to swiftly adapt its process mode, it is important to adjust throughput management to maintain effectiveness. Manufacturing flexibility is discussed in Chapter 8.

Subsection Summary: The throughput approaches and methods presented are readily applicable to batch and repetitive processes, requiring some adjustments for the job shop and continuous processes. The principles of throughput management can benefit all four types of manufacturing processes.

1.3.2 Settings of Manufacturing System

1.3.2.1 Systems View and Configuration

Manufacturing is a physical process that involves the conversion or transformation process of materials into finished products. As depicted in Figure 1.13, a manufacturing system comprises machinery, processes, methods, and personnel working together to convert raw materials into customer products. The goal of a manufacturing system is to produce products that meet customer expectations in functionality while minimizing resource use, costs, and delivery time.

This systems view focuses on understanding a system as a whole, considering the contributions and interactions of individual parts to the overall functionality and output of a system, rather than focusing on their individual functions. The understanding of systems views on manufacturing establishes a good foundation to discuss the configurations and composition of manufacturing systems.

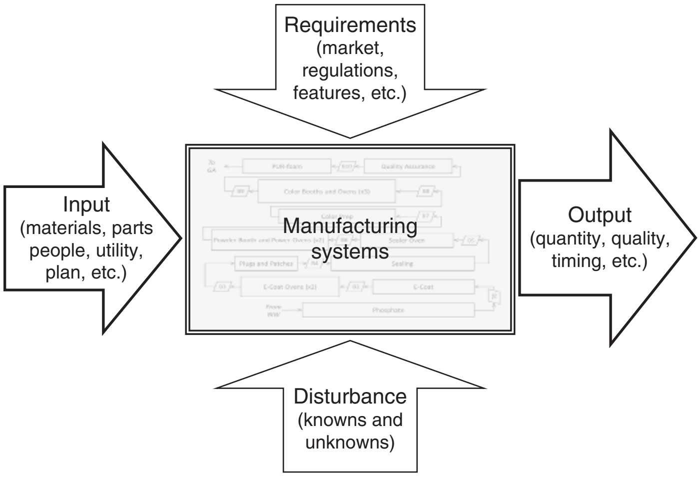
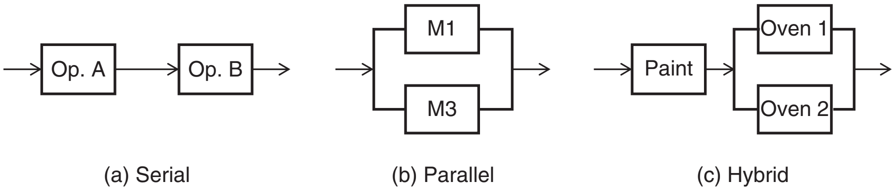


Figure 1.13 Conversion view of a manufacturing system.



(a) Serial (b) Parallel (c) Hybrid

Figure 1.14 Basic configurations of manufacturing systems.

Manufacturing systems and their process flows can be categorized into three basic styles of system layout based on their operational sequences. This is depicted in Figure 1.14.

A serial configuration is prevalent in manufacturing systems, which accounts for most mass production, such as vehicle assembly. Furthermore, despite varying local configurations, the overall flow and layout of a complex manufacturing system are typically in serial.

A parallel configuration is commonly employed in situations involving slower operations and/or high-volume production. For instance, if a single machine tool can support half of the production volume required by the market, two machine tools can be designed in parallel to meet the production volume.

A hybrid configuration, combining serial and parallel elements, is common in large systems to balance process paces. For example, two or three parallel curing ovens are designed for a painting system, because the curing process takes much more time than the painting process.

Local branches and loops often exist within a manufacturing system to accommodate functional requirements, including repair, reprocess, scrap pull-out, and bypass. Two examples of such processes are shown in Figure 1.15. These local arrangements add to the complexity of the manufacturing system, which may have a significant impact on manufacturing throughput.

There are other layout configurations in manufacturing systems, which will be discussed in the later chapters. During bottleneck analysis, there are instances when hybrid and complex configurations may require decomposition into simpler serial and parallel elements, a topic that will be further discussed in Chapter 6.

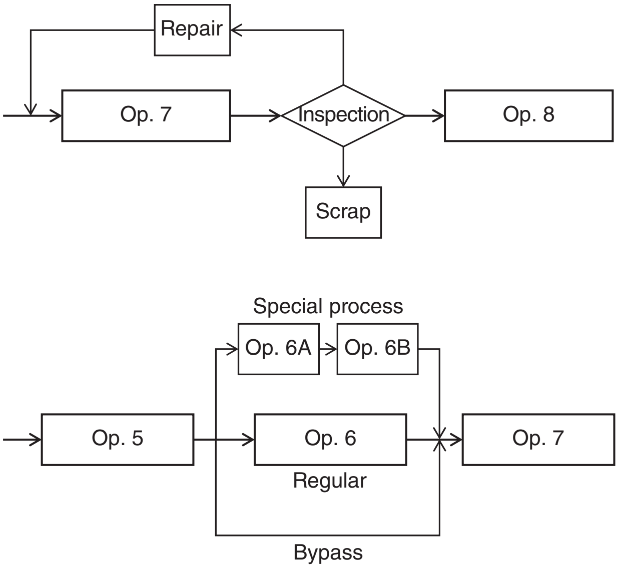


Figure 1.15 Local configuration examples in manufacturing systems.

1.3.2.2 System Composition

Manufacturing systems are complex networks that must be examined holistically using a systems-view approach. Recognizing the configurations and composition of the entire system is essential for analyzing and improving throughput performance.

In addition to system configurations, the systems perspective can be applied to the composition of a manufacturing system. System composition analysis is vital for addressing throughput problems at multiple levels. The system structure can be presented hierarchically, akin to an organizational chart, guiding an in-depth investigation. Figure 1.16 illustrates a manufacturing system in a simplified cascade view.

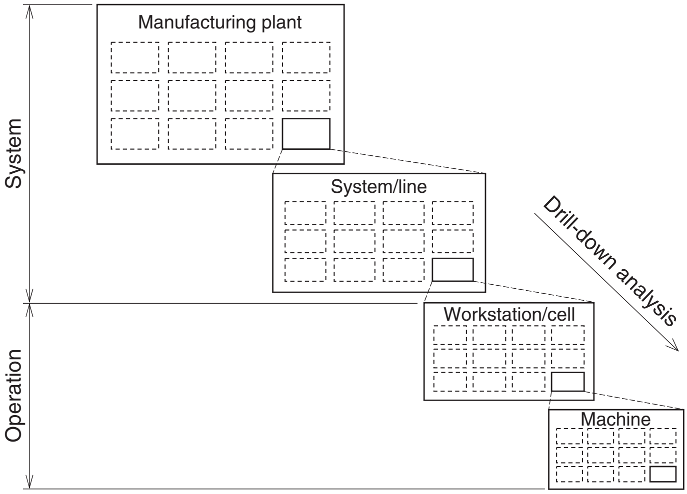


Figure 1.16 Cascade view of operations in a manufacturing system.

A comprehensive systems view is crucial for effective throughput improvement. Throughput problems and issues are often identified at a system level. Addressing and solving throughput issues in a system, bottleneck identification and root cause analysis involve analyzing multiple levels, drilling down to a specific machine or process. A solid understanding of the structure, flow, and relationships within a manufacturing system is essential to find root causes and resolve the problems. This process is discussed in more detail in Chapter 6.

The systems view of a manufacturing system extends beyond recognizing its structural complexity. It involves understanding the system as a network of interrelated subsystems, where the operational states and functions of each subsystem are not independent. The effects of subsystem interactions over time on system behaviors must be examined, in addition to identifying problematic issues.

For example, a problem occurring in one subsystem may have its root causes originating from other subsystems. Performance indicators, such as OEE (discussed in Chapter 2), can reflect a complex interplay of multiple factors. Without adopting a systems-view approach, throughput improvement is unlikely to be fully effective. Furthermore, improving an individual subsystem may or may not result in an overall performance improvement for the entire system, a critical point discussed in depth in Chapter 3.

Subsection Summary: A holistic systems view of manufacturing systems recognizes their functionality and complexity, considering both various configurations and compositions, enabling a better understanding for achieving throughput excellence.

1.3.3 Additional Throughput Considerations

1.3.3.1 Throughput Performance Pillars

To effectively manage throughput in a manufacturing system, it is essential to consider various factors. These factors can be grouped into three major categories or pillars, along with other miscellaneous factors:

1. System design
2. Production planning and control
3. CI on the floor
4. Other (miscellaneous) factors

Each pillar plays a unique supporting role, influencing throughput performance and presenting opportunities for improvement. Beginning with system design, it establishes a foundation for system throughput capacity. Engineering design professionals should address throughput during the design phases, a topic that will be discussed in-depth in Chapters 7 and 8.

The next pillar is production planning and control, which plays a crucial role in ensuring the smooth flow of operations and meeting production demands efficiently. It is an integral part of operational management, involving scheduling activities and considerations to allocate machinery, production processes, human resources, and raw materials. The control aspect of the pillar is for any necessary adjustments and corrective actions. While this book does not focus on this subject, it acknowledges its importance.

CI is a main activity of throughput management and a central theme of this book. After this introductory chapter, Chapters 2–5 will delve into the respective aspects of throughput management, and Chapter 6 will provide a more detailed introduction to the approaches and processes for throughput CI.

These factors are all important to any type of manufacturing operation, while their significance may vary depending on the specific context, which will be addressed in the next subsection 1.3.3.2.

In addition to the three main pillars, there are other or miscellaneous factors. They include numerous known and unknown ones, such as consistent changes and variations, on the production floor. Some common factors are discussed in the related throughput aspects in the corresponding chapters.

1.3.3.2 Throughput Improvement Potential

Associated with different types of manufacturing processes, the three main pillars exhibit varying potentials for improving throughput performance. Figure 1.17 illustrates the different significance of these pillars for discussion purposes. For example, in a repetitive process, the three pillars (system design, production planning and control, and CI) contribute approximately 45%, 20%, and 25% to the total potential, respectively. The actual relative improvement potentials vary depending on the specific manufacturing system and its context.

In the figure, CI presents distinct opportunities to enhance system throughput on the production floor (further discussed in subsection 6.4.3 in Chapter 6). For instance, the room for CI may be relatively smaller for continuous processes, as they are largely determined by system design. In addition, CI has limited room for improvement as some potentials are more related to other factors, such as system design or production planning and control.

The improvement potential of each pillar is rarely studied, and the limits of improvement are not extensively explored either. However, many experienced professionals understand that as time progresses, improving throughput through CI alone may plateau and become increasingly challenging without making major system or process design changes. Therefore, operational management should consider multiple pathways for improving throughput, frequently assess the effectiveness of their CI efforts, and closely cooperate with the engineering design teams.

1.3.3.3 Issues in Batch Process

Batch processes can handle a wide range of products, but their throughput depends more on production planning and control. This is because products may require unique process routes and durations. Figure 1.18 provides an illustrative example of batch production for multiple products with different processes across eight workstations within the same system.

In addition, tooling and fixture changes can occur often when switching between different products. Measuring and improving system throughput in such systems can be more complex due to the variety of process flows and timings.

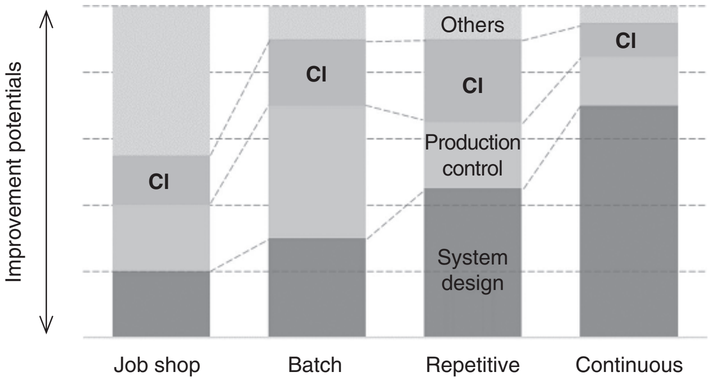


Figure 1.17 Relative potentials of system throughput improvement.

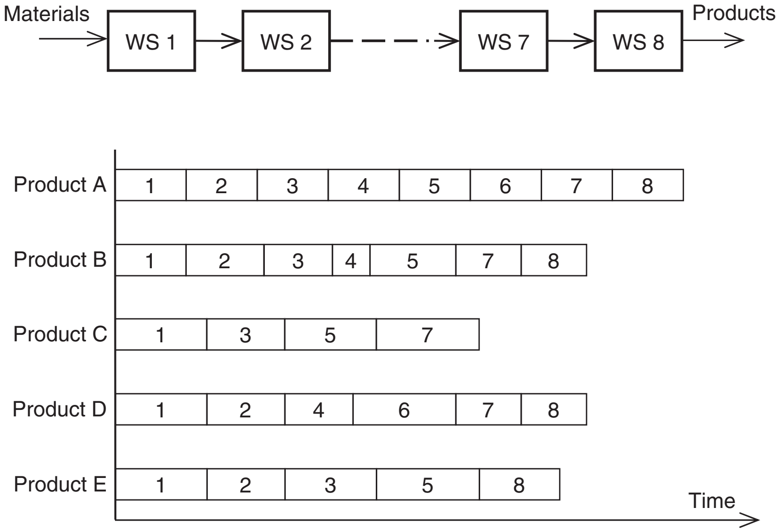


Figure 1.18 Multiple products and different processes in a manufacturing system.

Production planning and control plays a primary role in bath and job shop processes. It considers multiple factors, such as batch size, frequency, and process time, to optimize operational throughput and process utilization. When dealing with known processes, batch size is often a key consideration for resource utilization optimization (see Shafeek and Marsudi [2015] as an example).

Production planning and control for batch processes also considers factors such as order priority and WIP. A simple scheduling approach is First In, First Out (FIFO). Other scheduling approaches may aim for the shortest processing time, constant WIP (CONWIP), batch processing based on process similarity [Olaitan et al. 2017], or re-sequencing product mix considering part and process constraints [Fradkin et al. 2017].

To effectively manage and improve system throughput, a holistic approach across system design, production planning and control, and CI can reach its full potential (refer to Figure 1.17). The importance of each pillar needs further studies to address the special needs of a batch process.

Subsection Summary: Enhancing system throughput needs to address the following three pillars: system design, production planning and control, and CI. System design sets the capability, planning and control manages resources, and CI maximizes production potential. Different processes, like batch processes, pose distinct considerations.

1.4 Operational States of Production

1.4.1 Operational States of Systems

1.4.1.1 Nonworking States

To analyze system throughput levels, it is essential to know the operational states of a system. For throughput management, there are four types of stoppage or nonworking states:

1. Downtime due to the system's own failures (called faulted)
2. Starvation from parts by its upstream system (called starved)

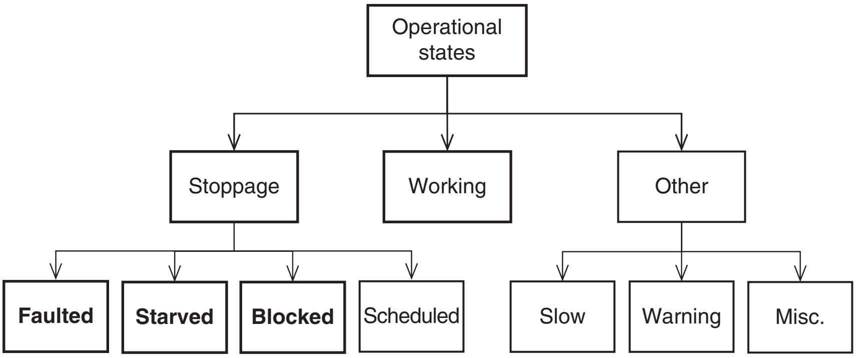


Figure 1.19 Operational states of manufacturing systems.

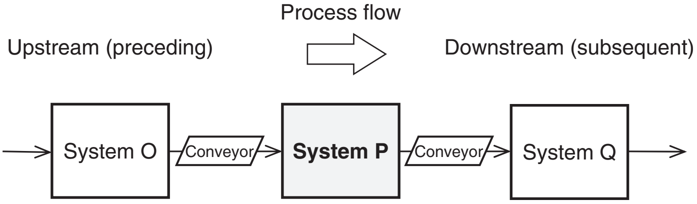


Figure 1.20 Three production systems in a serial configuration.

3. Blockage by its downstream system (called blocked)
4. Scheduled stoppage, such as for maintenance and setup

Figure 1.19 summarizes operational states for a manufacturing system, emphasizing four types of stoppage.

For instance, Figure 1.20 illustrates three connected systems using conveyors serially. If System P does not receive parts from its upstream System O on time, it is starved by System O and stops operating. Similarly, if System P cannot send the finished jobs to its downstream System Q, it is blocked by System Q and stops. In both cases, System P nonwork is not at fault but caused by *external* factors.

Furthermore, due to countless variations in operations, a system rarely achieves perfect synchronization inside even if it is designed to operate smoothly. Consequently, there are starvation and blockage situations between workstations within a production line. These internal starvation and blockage may be considered normal as long as their time remains minimal, typically less than 2% of the design CT. More discussion on internal interactions is in Chapter 8.

There can be also situations known as scheduled stoppages. Examples include maintenance scheduled during production and setup required for batch production. Even if a production planning and control department attempts to schedule them into nonoperational time, some tasks, such as equipment adjustments, may be unavoidable during production.

1.4.1.2 Discussion of Operational States

In the last subsection (Figure 1.19), the operational states of a system are discussed. For each type of state, there can be several substrates based on reasons. Table 1.2 lists some typical subtypes of operational states in mass production as an example.

Table 1.2 Operational states and types and their internal/external reasons.

Reporting priority	State	Type (sub-state)	Internal reason	External reason
100	Normal working	In design cycle	N/A	N/A
9	Scheduled stoppage	Scheduled break time		x
		Setup and changeover		x
		Scheduled maintenance		x
1	Stoppage (due to *Internal* issues)	Equipment fault	x	
		Computer/control fault	x	
		Safety fault	x	
		Quality fault	x	
		Manual production stop	x	
		Internal blockage	x	
		Internal starvation	x	
2	Stoppage (due to *External* factors)	Blockage (waiting)		x
		Starvation (waiting)		x
		No material/part		x
		Defective material/part		x
		Network/communication		x
3	Slowness	Automation slow cycle	x	
		Manual operation over the cycle	x	
		Minor stoppage	x	
		Quality alert	x	x
4	Warning	Low material alert		x
		Assistance required	x	x
		Manual intervention		x
5	Miscellaneous items	Nonscheduled production		x
		Tryout or test		x
		Idle		x
		Other/undefined	?	?

Subtypes, such as scheduled maintenance, can be further categorized based on activities, for instance, inspection, adjustment, calibration, cleaning, among others. In addition, there are warning types that serve as alerts before an actual failure occurs. The classification of categories and subcategories depends on the system's specificities and the process's characteristics.

Identifying operational state types enables effective system throughput management with quick responses and efficient problem-solving. Automated systems typically feature real-time reporting and data analysis, allowing operational management to promptly assess situations and respond.

1.4.1.3 Additional Thoughts on Operational States

Defining operational states for monitoring and tracking purposes is a critical task in system design. To enhance throughput performance and effectively address problems, engineering design professionals should have a comprehensive understanding of the possible internal and external reasons for each state. The right two columns, i.e., "Internal reason" and "External reason" of Table 1.2, offer the identification of internal/external reasons for the states, as a reference example.

Defining these subcategories of operational states is an ongoing effort when developing complex manufacturing systems. Thus, it is essential to include an "other/undefined" category in a state list to account for unknown or unclear situations that may arise beyond the defined items. Once the root causes of a specific situation are fully understood, it can be categorized into an existing state or defined as a new type of state. Continuously refining the state reporting enables accurate state identifications for operational management.

Monitoring screens typically display one system state at a time. However, sometimes multiple states may occur concurrently, such as equipment failure and blocking happening simultaneously. In such cases, the computer system needs to prioritize which state to display and report. Therefore, it is necessary to determine the reporting priority for each state, ensuring that the computer system displays the highest-priority state when multiple states occur. In Table 1.2, the left column, "Reporting priority," shows an example of the reporting priority, where "1" is the highest.

Defining the reporting priority of operational states, the stoppages because of the internal issues should receive the highest priority, marked as "1" in the table. Conversely, a normal working state should be given the lowest priority, such as "100," ensuring that any type of abnormal state can be reported without being concealed. Likewise, setting individual priorities for subcategories may be needed. Reporting priority settings are determined by operations management.

Subsection Summary: Identifying and interpreting various operational states, particularly nonworking states due to internal and external influences, is essential for assessing system status. A deeper discussion of the nonworking states follows in the next subsection 1.4.2.

1.4.2 Applications of Standalone State

1.4.2.1 Standalone State Concept

As discussed earlier, when a system is not working, the reasons can be either internal or external causes. External factors involve upstream or downstream functions or states that exist independent of the system. When problem-solving focusing on the system itself, it is essential to identify and exclude the external factors in the analysis for system throughput improvement.

A standalone state describes a situation in which the system operates independently of all other systems and external factors. The standalone concept for manufacturing production was introduced over 30 years ago [Hopp and Simon 1993] and has since been theoretically studied [Li et al. 2013, Aboutaleb et al. 2017].

Understanding the standalone concept is crucial because improvement efforts should be directed toward identifying and addressing the system's internal root causes rather than external factors. This standalone approach ensures the accurate identification and resolution of throughput issues. Mixing internal and external root causes of throughput issues can mislead problem-solving efforts and reduce improvement effectiveness.

Apart from the influences of upstream and downstream systems, production part logistics – supporting manufacturing operations with parts and materials – is another common cause of system starvation. Logistics issues, such as delays and misplacement, can result in system starvation and directly impact system throughput. Fortunately, these logistics issues are often visible and not technically challenging to identify and rectify.

1.4.2.2 Standalone Availability

To accurately evaluate a system's true performance, capability metrics are needed that exclude external factors. Standalone availability (A_{sa}) achieves this by considering only the system's internal failures and faulted downtime. A_{sa} is calculated using the following formula:

$$A_{\text{sa}} = \frac{\text{Actual production time}}{\text{Planned production time} - \textbf{Starved time} - \textbf{Blocked time}}$$

Comparing this to the operational availability (A) discussed in subsection 1.1.2.2, A_{sa} is higher because starved time and blocked time are normally present and deduced from the planned production time in the equation. Table 1.3 provides an example to demonstrate the difference between A and A_{sa}. Figure 1.21 illustrates the four operational states of this example.

The operational availability and standalone availability can be calculated as follows:

$$A = \frac{6.85}{7.5} = 91.3\%$$

$$A_{\text{sa}} = \frac{6.85}{7.5 - 0.15 - 0.3} = 97.2\%$$

Following the same concept, an alternative calculation of A_{sa} is:

$$A_{\text{sa}} = \frac{\text{Actual production time} + \textbf{Starved time} + \textbf{Blocked time}}{\text{Planned production time}}$$

Table 1.3 Example of a system's operational states.

State	Time	
Scheduled	7.5 hours	100%
Operational	6.85	91.3%
Stoppage:	0.65	8.7%
Faulted	0.2	2.7%
Staved	0.15	2.0%
Blocked	0.3	4.0%

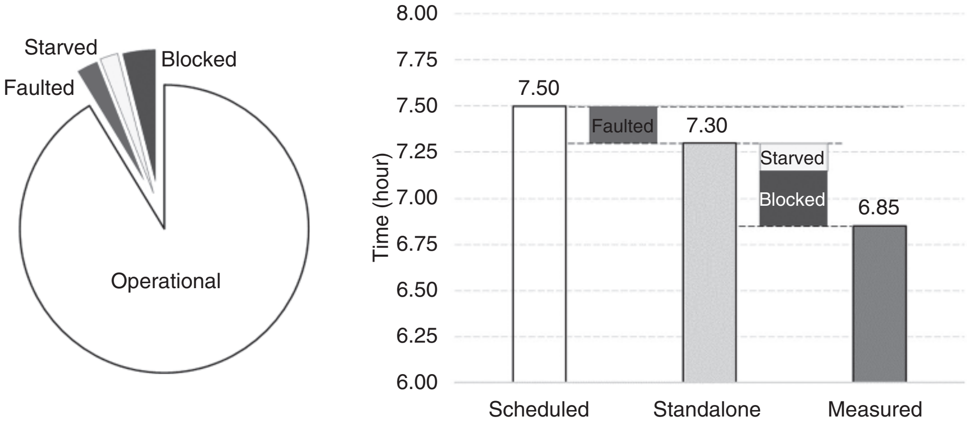


Figure 1.21 Example of four states of manufacturing operations.

By employing this alternative equation, the A_{sa} of the above example is calculated to be 97.3%, a slight deviation from the previous calculation of 97.2%. Either equation can be utilized, provided consistency is maintained with one method.

In industry practice, there are variations in the treatment of starvation and blockage when calculating standalone metrics. For example, Toyota includes starvation into operational availability [Sakai and Li 2020]. As a result, the availability and standalone availability across different companies may not be directly comparable due to the differing considerations.

1.4.2.3 Standalone TR

In addition to applying to operational availability, the standalone concept can apply to TR and OEE (to be discussed in Chapter 2) as system throughput KPIs, to exclude external influences on these metrics.

The standalone TR, denoted as $\mathrm{TR}_{\mathrm{sa}}$, can be defined and calculated based on the known values of A_{sa}, A, and measured TR:

$$\mathrm{TR}_{\mathrm{sa}} = \frac{A_{\mathrm{sa}}}{A} \times \mathrm{TR}$$

In this equation, the key is the ratio $\frac{A_{\mathrm{sa}}}{A}$:

$$\frac{A_{\mathrm{sa}}}{A} = \frac{\dfrac{\text{Actual production time}}{\text{Planned production time} - \textbf{Starved time} - \textbf{Blocked time}}}{\dfrac{\text{Actual production time}}{\text{Planned production time}}}$$

$$= \frac{\text{Planned production time}}{\text{Planned production time} - \textbf{Starved time} - \textbf{Blocked time}}$$

According to the equation, if a manufacturing system experiences no starved time and blocked time in a period, the system exhibits a ratio of $\frac{A_{\mathrm{sa}}}{A} = 1$ or $A_{\mathrm{sa}} = A$. Consequently, $\mathrm{TR}_{\mathrm{sa}} = \mathrm{TR}$. When starved time and/or blocked time are present, the ratio $\frac{A_{\mathrm{sa}}}{A} > 1$. That implies that $\mathrm{TR}_{\mathrm{sa}} > \mathrm{TR}$. Using the data of the above example,

$$\frac{A_{\mathrm{sa}}}{A} = \frac{97.2\%}{91.3\%} = 1.065$$

Based on the standalone concept, both A_{sa} and $\mathrm{TR}_{\mathrm{sa}}$ reflect the true throughput performance of a manufacturing system but are from different perspectives. In industry practice, both metrics are often used at the same time.

1.4.2.4 Discussion Examples

Figure 1.22 illustrates an example of applying the standalone concept. In this example, a vehicle assembly plant consists of the following three shops: body frame, body paint, and general assembly, arranged in a serial setting and operating independently. Their design TRs are 80, 79, and 78 JPH, respectively. The figure displays each shop's throughput performance in a week with TR, standalone TR, itemized throughput losses due to faulted, starved, and blocked states.

From Figure 1.22, it is evident that the body frame shop had the lowest standalone TR and the longest faulted downtime, contributing to the starved time of both the body paint shop and general assembly shop. Thus, it is recommended that the body frame shop be identified as the first target for throughput improvement in the plant.

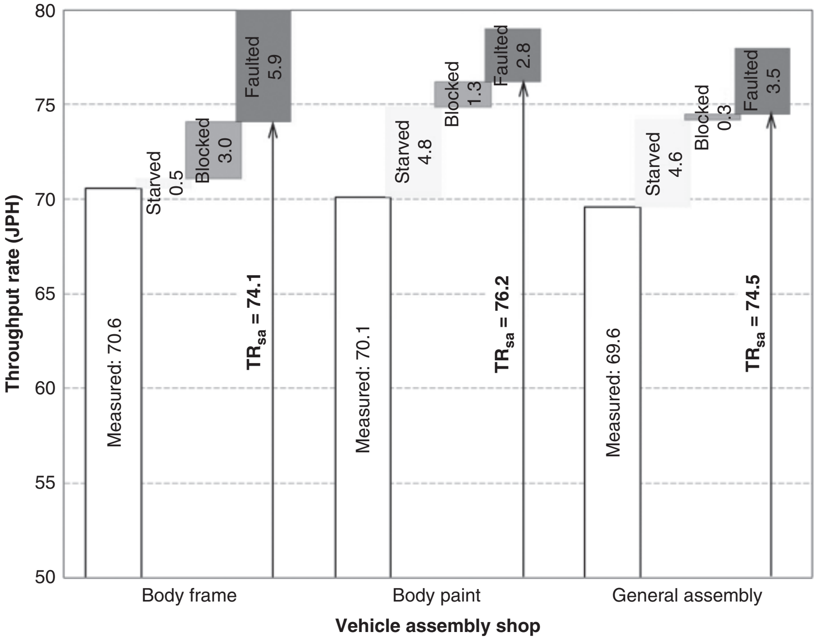


Figure 1.22 Example of throughput rate elements of three manufacturing systems.

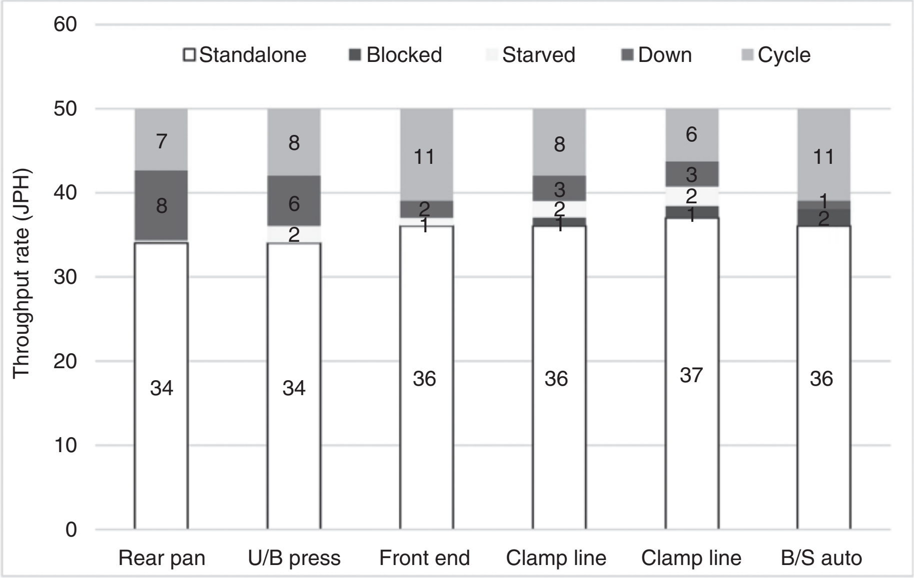


Figure 1.23 Example of throughput status of six subsystems (Valdés and Leoncio 2003/with permission of Massachusetts Institute of Technology).

Here is another example of using standalone throughput metrics [Valdés and Leoncio 2003]. Figure 1.23 illustrates a system with six subsystems, and the TRs of each subsystem are categorized as standalone, down, starved, or blocked. In this case, the authors referred to the unknown throughput loss as a "cycle" at the time. The rear pan area has the lowest standalone TR, making it the first target for throughput improvement.

Subsection Summary: The standalone concept, applied to availability and TR, improving their accuracy in reflecting true system performance and offering meaningful insights for throughput management. More discussion and applications continue in the later chapters.

Chapter Summary

1.1. Introduction to Throughput

1. Manufacturing system productivity, or throughput, is a crucial indicator of internal process effectiveness for overall business success.
2. Top manufacturing priorities include efficiency, productivity, addressing challenges in production processes, and maximizing capacity utilization.
3. Throughput management integrates system throughput, product quality, and financial outcomes, requiring cross-functional collaboration for long-term business growth.
4. Throughput, the transformation of inputs into goods, can be measured by TR and Operational Availability (A), etc.
5. System productivity involves enhancing output, resource utilization, and adapting to input changes.

1.2. Discussion of Manufacturing Throughput

6. Total cost breakdown includes labor, material, equipment, utilities, overhead, facility costs, etc., often measured as a unit cost.
7. Little's Law links TT and design TR.
8. CI and optimization differ conceptually, methodologically, and in application. The work on the production floor focuses on CI.
9. CT, a fundamental operational pace, is recommended as the time to complete a single unit of work for consistency.
10. CT and TR have a reciprocal relationship in an assumed perfect operational scenario.
11. TT and lead time are key indicators of manufacturing efficiency and customer responsiveness.

1.3. Characteristics of Manufacturing Systems

12. Manufacturing systems and processes are classified into the following four types: job shop, batch, repetitive, and continuous, with different considerations and influencing factors for throughput management.
13. A systems view analyzes the entire manufacturing system, considering configurations and composition.
14. System layouts include serial, parallel, and hybrid configurations, adding complexity with branches.
15. System design, production planning, and CI influence throughput, each with unique opportunities.

16. Batch size, frequency, order priority, and WIP require a holistic approach for effective throughput management.

1.4. Operational States of Production

17. Understanding nonworking states (downtime, starvation, blockage, scheduled nonproduction) is crucial for analyzing system throughput.
18. Categorizing and prioritizing reporting operational states enables effective throughput management and problem-solving.
19. Standalone state focuses on a system operating independently of external factors, pinpointing internal root causes accurately.
20. Standalone state can be applied to metrics, such as A_{sa} and TR_{sa}.

Exercise and Review

Exercises

1.1 A shift has 7.5 hours of planned production time. The actual production time in a shift was 6.8 hours. The shift experienced 0.15 hour of starved time, 0.25 hour of blocked time, 0.2 hour of equipment downtime, and 0.1 hour of work delay time. Calculate the operational availability and Toyota's formula availability for this shift.

1.2 A manufacturing system employs 320 people. Over one week, it utilized 13,400 labor hours and produced 4800 units. Calculate the productivity per employee and per hour for this week.

1.3 In one week, a shop incurred a direct labor cost of \$100k, material cost of \$150k, equipment cost of \$45k, utility cost of \$7k, and overhead cost of \$13k. Calculate the percentage of direct labor cost in the total cost.

1.4 An operation has a known throughput time of 4.5 hours and a throughput rate of 50 jobs per hour. Calculate the average WIP level for this operation in the long run based on Little's Law.

1.5 A production line has eight workstations with cycle times of 58, 56, 57, 60, 59, 56, 55, and 59 seconds, respectively. Estimate the long-run average WIP for this production line.

1.6 If a process has a cycle time of 48 seconds, estimate the corresponding theoretical throughput rate in JPH.

1.7 Based on the data from Exercise 1.1 and known production output of 480 units, calculate the standalone availability (A_{sa}) and standalone throughput rate (TR_{sa}).

Review Questions

(The chapter covers these topics. For further discussion, it is recommended to seek additional information and examples. Diverse perspectives are encouraged.)

1.1 Discuss the relationship between internal process (operations or production) effectiveness and financial health, providing an example.

1.2 Address one of the top 14 manufacturing challenges mentioned and offer a solution based on a particular case.

1.3 Review how product quality directly and indirectly contributes to manufacturing throughput performance, providing an example.

1.4 Explore the similarities and differences between operational effectiveness, productivity, and throughput in a manufacturing operation with examples.

1.5 Differentiate between common operational availability calculation and Toyota's availability calculation, providing a simple case.

1.6 Using a case study, discuss how the role of direct labor cost impacts the total cost of a manufacturing system.

1.7 Discuss an application of Little's Law in a manufacturing system.

1.8 Review the necessity of WIP and its impact on a manufacturing operation.

1.9 Explain the differences between an optimization project and a continuous improvement project.

1.10 Analyze a production operation and identify its time elements (refer to Figure 1.8).

1.11 Compare the two definitions of cycle time with a real-world example and provide your insight into which one is more applicable.

1.12 Using an example from your workplace, discuss the type of process and associated KPIs and throughput concerns (refer to Table 1.1).

1.13 Review a manufacturing system from both a conversion view and composition view, providing an example.

1.14 Discuss system layout configurations for their characteristics, providing examples.

1.15 Comment on the opportunities and constraints of continuous throughput improvement on the production floor for distinct types of systems (refer to Figure 1.17).

1.16 Use an example to explain the characteristics of a batch process for multiple products.

1.17 Review situations of starvation and blockage in a production environment, providing examples.

1.18 Discuss the meaning of the standalone concept, providing an example.

1.19 Review considerations for reporting priority in operational states for a production line.

1.20 Discuss an application of the standalone concept to throughput indicators, such as operational availability and throughput rate, providing an example.

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