Reading: Ch. 3. Process Flow Measures (excerpt) *(Managing Business Process Flows: Principles of Operations Management)*

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Editor: N/A

Publisher: Prentice Hall Publication Date: 2012 Pages: 46-63

Course: COMR_V 398 201 202 2024W2 Introduction to Business Processes and Operations
Course Code: 202 Term: 2024 Winter Term 2

Department: COMR_V

Chapter

3

Process Flow Measures

INTRODUCTION

Vancouver International Airport Authority manages and operates the Vancouver International Airport. Its focus on safety, security, and customer service has contributed to Vancouver International Airport being named the winner of best airport in North America award at the 2010 Skytrax World Airport Awards. In order to maintain its excellent customer service standards and in anticipation of new government regulations, airport management wanted to reduce the time customers spent in the airport security checkpoints. They wanted to improve the way that customers flowed through the process. In other words, they sought to better their *process flow.*

BellSouth International is a provider of wireless services in 11 Latin American countries. As a service provider, the company leases its network capacity on a monthly basis to two categories of customers: prepaid and postpaid. One of the most time-consuming processes for the company in the Latin American market is the service activation process: getting a wireless telephone into the hands of interested potential customers.

The various steps in the activation process include determination of the type of wireless service, credit check, selection of phone and service plan, assignment of the phone number, making a test call, and providing a short tutorial. At one of its largest activation centers, the company serves an average of 10,000 customers per week with 21 percent being activated with a postpaid account and the remaining with a prepaid account.

To manage and improve this activation process, the following questions must be answered: What operational measures should a manager track as leading indicators of the financial performance of the process? How does the time to process a customer and the number of customers that are being served at any point in time impact the total number of customers that can be served per week? How do these process measures impact the financial performance of the process? Which specific outcomes can be called "improvements?" How can we prioritize our improvements into an executable action plan?

This chapter aims to provide answers to these questions. We will define process flow in Section 3.1 of this chapter. Then, in Sections 3.2 through 3.4, we will introduce the three fundamental measures of process performance: inventory, throughput, and flow time. In Section 3.5, we will explore the basic relationship among these three measures, called Little's law. Section 3.6 shows how Little's law can be used to analyze financial statements. We will discuss the related concepts of takt time and inventory turns in Section 3.7. Finally, Section 3.8 links these process flow measures to financial measures of performance to determine when a process change (e.g., reengineered process flows or allocation of additional resources) has been an improvement from both operational and financial perspectives.

3.1 THE ESSENCE OF PROCESS FLOW

Thus far, we have learned that the objective of any process is to transform inputs into outputs (products) to satisfy customer needs. We also know that while an organization's strategic position establishes *what* product attributes it aims to provide, its operational effectiveness measures *how well* its processes perform this mission. We have seen that product attributes and process competencies are classified in terms of cost, time, variety, and quality. We noted that, to improve any process, we need internal measures of process performance that managers can control. We also saw that if chosen carefully, these internal measures can serve as leading indicators of customer satisfaction and financial performance as well.

In this chapter we focus on **process flow measures**—*three key internal process performance measures that together capture the essence of process flow: flow time, flow rate, and inventory*. As we will see in subsequent chapters, these three process-flow measures directly affect process cost and response time, and they are affected by process flexibility (or lack thereof) and process quality.

Throughout this book, we examine processes from the perspective of *flow*. Specifically, we look at the process dynamics as inputs enter the process, flow through various activities performed (including such "passive activities" as waiting for activities to be performed), and finally exit the process as outputs. Recall from Chapter 1 that a flow unit is a unit flowing through a process. A flow unit may be a patient, a dollar, a pound of steel, a customer service request, a research-and-development project, or a bank transaction to be processed. In our study of process flow performance, we look at three measures and answer three important questions:

1. On average, how much time does a typical flow unit spend within the process boundaries?
2. On average, how many flow units pass through the process per unit of time?
3. On average, how many flow units are within the process boundaries at any point in time?

The case of Vancouver International Airport, described in Example 3.1, is an example of a business situation in which examining process flow performance is particularly useful. Later in this chapter, we will analyze this example to determine whether a process change leads to an improvement.

EXAMPLE 3.1

Now, let us begin to look at how the Vancouver International Airport Authority went about improving its customer flow through its airport security checkpoints. To understand customer flow, managers began by analyzing a single security screening line, which is comprised of an X-ray scanner with an operator and screening officers. Arriving customers either queue up or, if there is no queue on arrival, directly put their bags on the scanner. While customers can have 0, 1, 2, or 3 carry-on bags, including purses, wallets, and so on, on average, a typical customer has 1.5 bags. The X-ray scanner can handle 18 bags per minute. On average, about half the passengers arrive at the checkpoint about 40 minutes (±10 minutes) before departure for domestic flights. The first passenger shows up about 80 minutes before departure, and the last passenger arrives 20 minutes before departure. For a flight with 200 passengers, this gives the following approximate arrival rate pattern: About 75 passengers arrive 80 to 50 minutes early, 100 arrive 50 to 30 minutes early, and the remaining 25 arrive between 30 to 20 minutes before scheduled departure.

To minimize layover time for passengers switching flights, many of Vancouver's flights depart around the same time. As we look at the three key process measures, we will assume for simplicity that exactly three flights, each carrying 200 passengers, are scheduled for departure each hour: that is, three flights depart at 10 A.M., three flights at 11 A.M., and so forth. With increased security procedures, however, the simultaneous departures of flights were overwhelming scanner capacity and creating long waiting times. The airport authority needed to know how staggering flight departures—for example, spreading out departures so that one flight would depart every 20 minutes—would affect the flow and waiting times of passengers through the security checkpoint.

3.2 THREE KEY PROCESS MEASURES

Flow Time Recall from Chapter 1 that processes transform flow units through networks of activities and buffers. Thus, as a flow unit moves through the process, one of two things happens to it:

1. It undergoes an activity.
2. It waits in a buffer to undergo an activity.

In the airport example, passengers and their luggage are either security scanned or wait in line before the X-ray machine. Let us follow a specific passenger or flow unit from the time it enters the process until the time it exits. *The total time spent by a flow unit within process boundaries is called* **flow time**. Some flow units move through the process without any wait; perhaps they require only resources that are available in abundance (there are several X-ray scanners and operators available), or they arrive at times when no other flow units are present (there are no other passengers checking through security when they arrive), or they are artificially expedited (a first-class passenger conceivably could be given priority over economy-class passengers). Others, meanwhile, may spend a long time in the process, typically waiting for resources to become available. In general, therefore, flow time varies—sometimes considerably—from one flow unit to another.

As a measure of process performance, flow time indicates the time needed to convert inputs into outputs and includes any time spent by a flow unit waiting for processing activities to be performed. It is thus useful information for a manager who must promise a delivery date to a customer. It also indicates how long working capital, in the form of inventory, is tied up in the process.

Flow Rate An important measure of process flow dynamics is *the number of flow units that flow through a specific point in the process per unit of time*, which is called **flow rate**. In many settings, flow rates may change over time so that in addition to the specific point in the process, we also must specify the time when the measurement was taken. In Example 3.1, the inflow rate of passengers at a security checkpoint at Vancouver International Airport changes over time. Recall that for each of the three flights, about half the 200 passengers for each flight arrive between 50 and 30 minutes before flight departure. So for each of the three flights departing at 10 A.M., about 100 passengers arrive between 9:10 and 9:30 A.M., a 20-minute interval. This means that a total of 300 passengers arrive during this time period for the three flights, giving an inflow rate of roughly 15 passengers per minute. The remaining 300 passengers for the three flights arrive between 8:40 and 9:10 A.M. (about 80 to 50 minutes before departure) and between 9:30 and 9:40 A.M. (about 30 to 20 minutes before departure). That is, the remaining 300 passengers arrive during a total time period of 40 minutes, giving an inflow rate of 7.5 passengers per minute, which is half the inflow rate during the peak time period from 9:10 to 9:30 A.M. The outflow rate of the checkpoint, however, is limited by the X-ray scanner, which cannot process more than 18 bags per minute or, with an average of 1.5 bags per passenger, 12 passengers per minute.

When we consider the flow rate at a specific point in time t, we call it the *instantaneous* flow rate and denote it by $R(t)$. For example, if we focus on the flow through entry and exit points of the process at time t, we can denote the instantaneous total inflow and outflow rates through all entry and exit points, respectively, as $R_i(t)$ and $R_o(t)$.

The process that is shown graphically in Figure 3.1 features two entry points and one exit point. Total inflow rate $R_i(t)$, then, is the sum of the two inflow rates, one each from the two entry points. Remember that inputs may enter a process from multiple points and that outputs may leave it from multiple points.

Inventory When the inflow rate exceeds the outflow rate, the number of flow units inside the process increases. Inventory is the total number of flow units present within process boundaries. In the airport example, during the peak period of 9:10 to 9:30 A.M., the inflow rate is 15 passengers per minute, while the outflow rate is 12 passengers per minute. Hence, an inventory of passengers will build in the form of a queue. We define the total number of flow units present within process boundaries at time t as the *process inventory at time t* and denote it by $I(t)$. To measure the process inventory at time t, we take a snapshot of the process at that time and count all the flow units within process boundaries at that moment. Current inventory thus represents all flow units that have entered the process but have not yet exited.

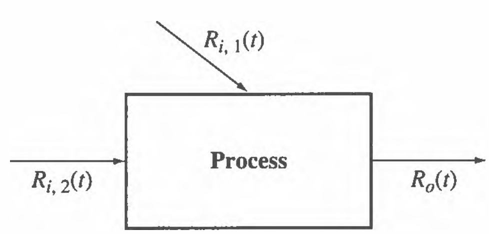

FIGURE 3.1 Input and Output Flow Rates for a Process with Two Entry Points

Inventory has traditionally been defined in a manufacturing context as material waiting to be processed or products waiting to be sold. Our definition considers a general flow unit and thus takes a much broader view that applies to any process, whether it is a manufacturing, a service, a financial, or even an information process. Inventory can thus encompass products, customers, cash, and orders. Our definition of inventory includes all flow units within process boundaries—whether they are being processed or waiting to be processed. Thus, raw materials, work in process (partially completed products), and finished goods inventories are included. This broader definition of inventory allows us to provide a unified framework for analyzing flows in all business processes.

What constitutes a flow unit depends on the problem under consideration. By defining the flow unit as money—such as a dollar, a euro, or a rupee—we can analyze financial flows. Adopting money as the flow unit and our broader view of inventory, we can use inventory to identify the working capital requirements. A key financial measure for any process is investment in working capital. Accountants define working capital as current assets minus current liabilities. Current assets include the number of dollars within process boundaries in the form of inventory as well as in the form of cash and any accounts receivable. Thus, inventory is like money that is tied up: A reduction in inventory reduces working capital requirements. Reduced working capital requirements reduce the firm's interest expense or can make extra cash available for investment in other profitable ventures. (Reducing inventory also reduces flow time and improves responsiveness, as we shall see later in this chapter.)

3.3 FLOW TIME, FLOW RATE, AND INVENTORY DYNAMICS

Generally, both inflow and outflow rates fluctuate over time. When the inflow rate exceeds the outflow rate in the short term, the inventory increases, or builds up. In contrast, if outflow rate exceeds inflow rate in the short term, the inventory decreases. Thus, inventory dynamics are driven by the difference between inflow and outflow rates. We define the **instantaneous inventory accumulation (buildup) rate**, $\Delta R(t)$, as *the difference between instantaneous inflow rate and outflow rate:*

Instantaneous inventory accumulation (or buildup) rate $\Delta R(t)$ = Instantaneous inflow rate $R_i(t)$ − Instantaneous outflow rate $R_o(t)$

or

$$\Delta R(t) = R_i(t) - R_o(t) \qquad \textbf{(Equation 3.1)}$$

Thus, the following holds:

- If instantaneous inflow rate $R_i(t) >$ instantaneous outflow rate $R_o(t)$, then inventory is accumulated at a rate $\Delta R(t) > 0$.
- If instantaneous inflow rate $R_i(t) =$ instantaneous outflow rate $R_o(t)$, then inventory remains unchanged.
- If instantaneous inflow rate $R_i(t) <$ instantaneous outflow rate $R_o(t)$, then inventory is depleted at a rate $\Delta R(t) < 0$.

For example, if we pick a time interval (t_1, t_2) during which the inventory buildup rate ΔR is constant, the associated change in inventory during that period is

Inventory change = Buildup rate × Length of time interval

or

$$I(t_2) - I(t_1) = \Delta R \times (t_2 - t_1) \qquad \textbf{(Equation 3.2)}$$

Given an initial inventory position and dividing time into intervals with constant accumulation rates, we can construct an **inventory buildup diagram** that depicts *inventory fluctuation over time.* On the horizontal axis we plot time, and on the vertical axis we plot the inventory of flow units at each point in time. Assuming that we start with zero inventory, the inventory at time t is the difference between the cumulative inflow and outflow up to time t. Example 3.2 provides an illustration of an inventory buildup diagram.

EXAMPLE 3.2

MBPF Inc. manufactures prefabricated garages. The manufacturing facility purchases sheet metal that is formed and assembled into finished products—garages. Each garage needs a roof and a base, and both components are punched out of separate metal sheets prior to assembly. Production and demand data for the past eight weeks are shown in Table 3.1. Observe that both production and demand vary from week to week.

We regard the finished goods inventory warehouse of MBPF Inc. as a process and each garage as a flow unit. The production rate is then the inflow rate, while demand (sales) is the outflow rate. Clearly, both have fluctuated from week to week.

MBPF Inc. tracks inventory at the end of each week, measured in number of finished garages. Let $I(t)$ denote the inventory at the end of week t. Now suppose that starting inventory at the beginning of week 1 (or the end of week 0) is 2,200 units, so that

$$I(0) = 2{,}200$$

Now, subtracting week 1's production or inflow rate $R_i(1) = 800$ from its demand or outflow rate $R_o(1) = 1{,}200$ yields an inventory buildup rate:

$$\Delta R(1) = 800 - 1{,}200 = -400 \text{ for week 1}$$

So, the ending inventory at week 1 is

$$I(1) = I(0) + \Delta R(1) = 2{,}200 + (-400) = 1{,}800$$

We can similarly evaluate buildup rates and inventory for each week, as shown in Table 3.1. Clearly, the inventory of flow units varies over time around its average of 2,000 garages.

With these data, we can construct an inventory buildup diagram that depicts how inventory fluctuates over time. Figure 3.2 shows the inventory buildup diagram for MBPF over the eight weeks considered, where we have assumed, for simplicity, that inventory remains constant during the week and changes only at the end of the week when sales take place.

Table 3.1 Production, Demand, Buildup Rate, and Ending Inventory for MBPF Inc.

Week	0	1	2	3	4	5	6	7	8	Average
Production		800	1,100	1,000	900	1,200	1,100	950	950	1,000
Demand		1,200	800	900	1,100	1,300	1,300	550	850	1,000
Buildup rate ΔR		−400	300	100	−200	−100	−200	400	100	0
Ending inventory	2,200	1,800	2,100	2,200	2,000	1,900	1,700	2,100	2,200	2,000

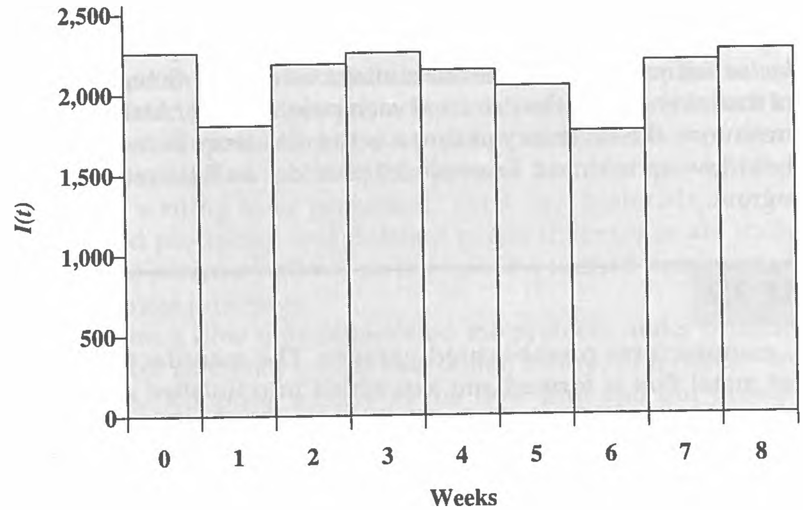

FIGURE 3.2 Inventory Buildup Diagram for MBPF Inc.

We can also analyze the airport security process of Example 3.1 by deriving the build-up of an inventory of passengers (and their associated waiting times) from the flow accumulation rate. We will define the X-ray scanner as our process and consider the representative example of three flights that are scheduled to depart at 10 A.M. Assume that we start at 8:40 A.M., when no passengers are waiting in line.

As derived earlier, the inflow rate during 8:40 to 9:10 A.M. is 7.5 passengers per minute. The outflow rate from the queue is the rate at which baggage is scanned. While the X-ray scanner can process up to 12 passengers per minute, it cannot process more passengers than are arriving, so the outflow rate also is 7.5 per minute. Thus, as summarized in Table 3.2, from 8:40 to 9:10 A.M., the buildup rate in the queue is zero: The X-ray scanner can easily keep up with the inflow, and no passengers have to wait in line. During the peak arrival period of 9:10 to 9:30 A.M., however, the inflow rate of 15 passengers per minute exceeds the maximal scanner outflow rate of 12 passengers per minute, so that a queue (inventory) starts building at $\Delta R = 3$ passengers per minute. At 9:30 A.M., the line for the scanner has grown to $\Delta R \times (9{:}30 - 9{:}10) = 3$ passengers per minute $\times$ 20 minutes = 60 passengers! After 9:30 A.M., the X-ray scanner keeps processing at the full rate of 12 passengers per minute, while the inflow rate has slowed to the earlier lower rate of 7.5 passengers per minute, so that the passenger queue is being depleted at a rate of 4.5 passengers per minute. Thus, the 60-passenger queue is eliminated after $60/4.5 = 13.33$ minutes. In other words, at 9:43 and 20 seconds, the queue is empty again, and the X-ray scanner can keep up with the inflow.

Table 3.2 Buildup Rates and Ending Inventory Data: Vancouver Airport Security Checkpoint of Example 3.1

Time	8:40 A.M.	8:40–9:10 A.M.	9:10–9:30 A.M.	9:30–9:43:20 A.M.	9:43:20–10:10 A.M.
Inflow rate R_i		7.5/min.	15/min.	7.5/min.	7.5/min.
Outflow rate R_o		7.5/min.	12/min.	12/min.	7.5/min.
Buildup rate ΔR		0	3/min.	4.5/min.	0
Ending inventory (number of passengers in line)	0	0	60	0	0

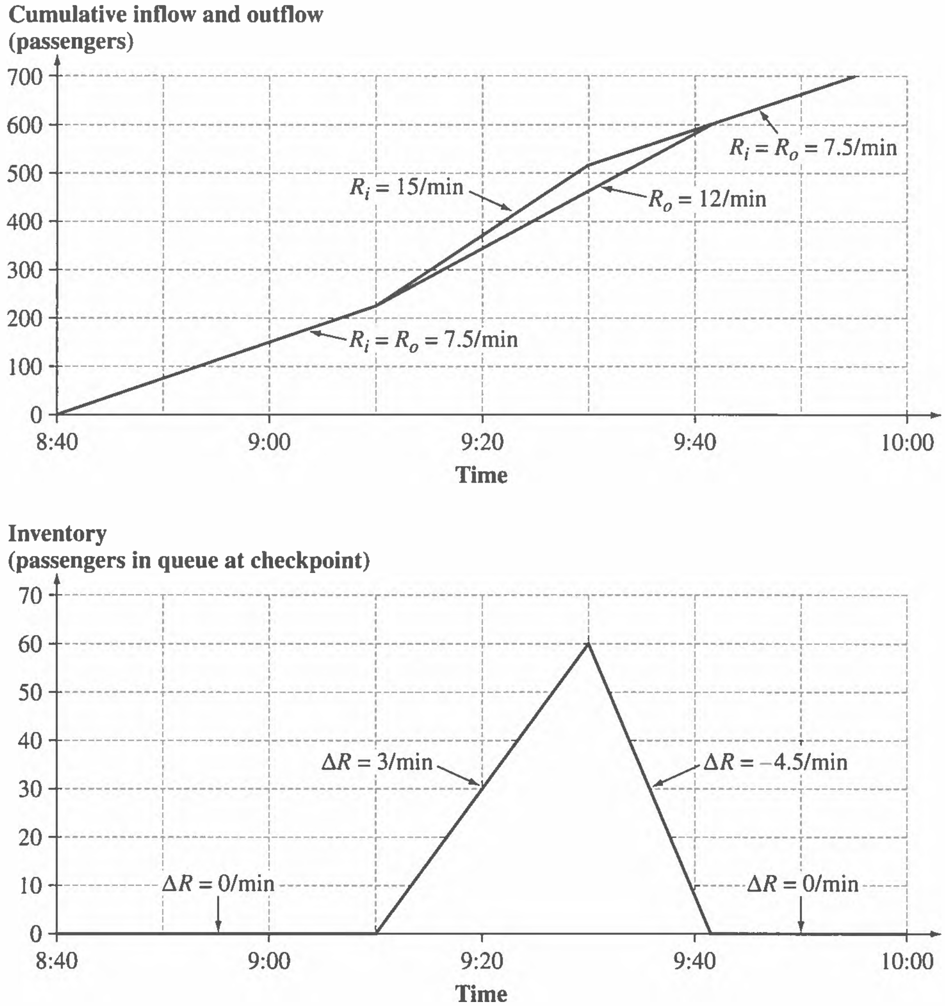

FIGURE 3.3 Inventory Buildup Diagram for Vancouver Airport Security Checkpoint

Observe that while the lower inflow rate of 7.5 passengers per minute for the 10 A.M. flights ends at 9:40 A.M., the first set of passengers start arriving for the 11 A.M. flights at 9:40 A.M. Just as the queue starts building up at 9:10 A.M. for the 10 A.M. flight, it will start building up again at 10:10 A.M. for the 11 A.M. flights. Thus, the cycle repeats itself for the next set of flight departures. Figure 3.3 shows the inventory buildup diagram together with the associated cumulative number of passengers arriving to and departing from the checkpoint process and clearly indicates that the difference between cumulative inflows and outflows is inventory.

Now, if flight departures are staggered, the peaks and valleys in arrival rates for different flights cancel each other out, as illustrated in Table 3.3. (The shaded time buckets correspond to the passenger arrivals for a particular flight.) Spreading out flight departures thus gives a constant arrival rate of 600 passengers per hour, which equals 10 passengers per minute at any point in time throughout the day. This is well below the process capacity of the X-ray scanner, so that the buildup rate would be zero. In short, by staggering the flights, no queues would develop at the security checkpoint. (The previous analysis is approximate because it ignores the short-time variability of passenger arrivals within any small time interval. This impact of short-time variability on process performance will be discussed in Chapter 8.)

Table 3.3 Inflow Rates with Staggered Departures for Vancouver Airport Security Checkpoint of Example 3.1

Time (start of period)	8:40	8:50	9:00	9:10	9:20	9:30	9:40	9:50	10:00	10:10	10:20	10:30
Inflow rate for flights arriving on the hour, $R_{i,1}$	2.5/min.	2.5/min.	2.5/min.	5/min.	5/min.	2.5/min.	2.5/min.	2.5/min.	2.5/min.	5/min.	5/min.	2.5/min.
Inflow rate for flights arriving 20 minutes past the hour, $R_{i,2}$	5/min.	2.5/min.	2.5/min.	2.5/min.	2.5/min.	5/min.	5/min.	2.5/min.	2.5/min.	2.5/min.	2.5/min.	5/min.
Inflow rate for flights arriving 40 minutes past the hour, $R_{i,3}$	2.5/min.	5/min.	5/min.	2.5/min.	2.5/min.	2.5/min.	2.5/min.	5/min.	5/min.	2.5/min.	2.5/min.	2.5/min.
Total inflow rate R_i	10/min.	10/min.	10/min.	10/min.	10/min.	10/min.	10/min.	10/min.	10/min.	10/min.	10/min.	10/min.

3.4 THROUGHPUT IN A STABLE PROCESS

A **stable process** *is one in which, in the long run, the average inflow rate is the same as the average outflow rate.* In the airline checkpoint example, while inflow and outflow rates change over time, the *average* inflow rate is 600 passengers per hour. Because the X-ray scanner can process up to 12 passengers per minute, equaling 720 passengers per hour, it can easily handle the inflow over the long run so that the *average* outflow rate also is 600 passengers per hour. Thus, the security checkpoint with the unstaggered flights is a stable process.

When we have a stable process, we refer to average inflow or outflow rate as **average flow rate**, or **throughput**, which is *the average number of flow units that flow through (into and out of) the process per unit of time.* We will denote the throughput simply as R to remind ourselves that throughput is a rate. As a measure of process performance, throughput rate tells us the average rate at which the process produces and delivers output. Ideally, we would like process throughput rate to match the rate of customer demand. (If throughput is less than the demand rate, some customers are not served. If the converse is true, the process produces more than what is sold.)

Consider the inventory dynamics *of the original situation* in a stable process we can define the average inventory over time and denote this by I. For example, let us find the average inventory at the Vancouver International Airport. Consider the inventory dynamics as shown in the bottom picture of Figure 3.3. From 8:40 to 9:10 A.M., the inventory or queue before the airline checkpoint is zero. From 9:10 through 9:43 A.M., the inventory builds up linearly to a maximum size of 60 and then depletes linearly to zero. Thus, the average inventory during that period is $60/2 = 30$. (Recall that the average height of a triangle is half its maximum height.) Finally, the inventory is zero again from 9:43 to 10:10 A.M., when the cycle repeats with the next inventory buildup. To estimate the average queue size, it is then sufficient to consider the 60-minute interval between the start of two consecutive inventory buildups; for example, from 9:10 A.M. (when inventory builds up for the 10 A.M. flights) to 10:10 A.M. (when inventory starts to build up for 11 A.M. flights). As we have seen, during this interval there is an average of 30 passengers between 9:10 and 9:43 A.M. and zero passengers between 9:43 and 10:10 A.M. Thus, the average queue size is the time-weighted average:

$$I = \frac{33 \text{ min.} \times 30 \text{ passengers} + 27 \text{ min.} \times 0 \text{ passengers}}{60 \text{ min.}}$$
$$= 16.5 \text{ passengers}$$

While the average inventory accumulation rate ΔR must be zero in a stable process (remember, average inflow rate equals average outflow rate), the average inventory, typically, is positive.

Now, let us look at **average flow time**. While the actual flow time varies across flow units, we can define the average flow time as *the average (of the flow times) across all flow units that exit the process during a specific span of time.* We denote the average flow time by T. One method to measure the average flow time is to track the flow time of each flow unit over a long time period and then compute its average. Another method is to compute it from the throughput and the average inventory, which we will explain next.

3.5 LITTLE'S LAW: RELATING AVERAGE FLOW TIME, THROUGHPUT, AND AVERAGE INVENTORY

The three performance measures that we have discussed answer the three questions about process flows that we raised earlier:

1. On average, how much time does a typical flow unit spend within process boundaries? The answer is the *average flow time T*.

2. On average, how many flow units pass through the process per unit of time? The answer is the *throughput R*.
3. On average, how many flow units are within process boundaries at any point in time? The answer is the *average inventory I*.

Little's Law We can now show that in a stable process, there is a fundamental relationship among these three performance measures. This relationship is known as **Little's law**, which states that *average inventory equals throughput multiplied by average flow time:*

$$\text{Average Inventory } (I) = \text{Throughput } (R) \times \text{Average Flow Time } (T)$$

or

$$I = R \times T \qquad \textbf{(Equation 3.3)}$$

To see why Little's law must hold, let us mark and track an arbitrary flow unit. After the marked flow unit enters the process boundaries, it spends T time units before departing. During this time, new flow units enter the process at rate R. Thus, during the time T that our marked flow unit spends in the system, $R \times T$ new flow units arrive. Thus, at the time our marked flow unit exits the system, the inventory is $R \times T$. Because our marked flow unit was chosen at random and because the process is stable, the average inventory within process boundaries that a randomly picked flow unit sees, I, must be the same as $R \times T$.

Little's law allows us to derive the flow time averages of all flow units from the average throughput and inventory (which are averages over time and typically easier to calculate than average flow units). In the airport security checkpoint example, we found that average queue size $I = 16.5$ passengers, while throughput was $R = 600$ passengers per hour $= 10$ passengers per minute. To determine the average time spent by a passenger in the checkpoint queue, we use Little's law, $I = R \times T$ and solve for T so that

$$T = I/R = 16.5 \text{ passengers}/10 \text{ passengers per minute} = 1.65 \text{ minutes}$$

Recall that many passengers do not wait at all, while the passenger who waits longest is the one who arrives when the queue is longest at 60 passengers. That unfortunate passenger must wait for all 60 passengers to be processed, which implies a waiting time of 60/12 minutes = 5 minutes. Example 3.3 illustrates Little's law for the MBPF Inc. example.

EXAMPLE 3.3

Recall that average inventory at MBPF Inc. in Example 3.2 was $I = 2000$ garages. Computing the average production over the eight weeks charted in Table 3.1 yields an average production rate of 1,000 garages per week. Average demand experienced by MBPF Inc. over the eight weeks considered in Table 3.1 is also 1,000 garages. Over the eight weeks considered, therefore, average production at MBPF has matched average demand. Because these rates are equal, we conclude that MBPF Inc. is a stable process with a throughput of 1,000 garages per week.

Now suppose that in terms of material and labor, each garage costs \$3,300 to produce. If we consider each dollar spent as our flow unit, MBPF Inc. has a throughput of $R = \$3{,}300 \times 1{,}000$ garages $= \$3{,}300{,}000$ per week. Thus, we have evaluated the throughput rate of MBPF Inc. using two different flow units: garages and dollars. Similarly, I, inventory can be evaluated as 2,000 garages, or 2,000 × \$3,300 (the cost of each garage) = \$6,600,000.

Because this is a stable process, we can apply Little's law to yield the average flow time of a garage, or of a dollar tied up in each garage, as

$$T = I/R = \$6{,}600{,}000/\$3{,}300{,}000 = 2 \text{ weeks}$$

Two immediate but far-reaching implications of Little's law are the following:

1. Of the three operational measures of performance—average flow time, throughput, and average inventory—*a process manager need only focus on two measures because they directly determine the third measure from Little's law.* It is then up to the manager to decide which two measures should be managed.
2. For a given level of throughput in any process, the only way to reduce flow time is to reduce inventory and vice versa.

Now let us look at some brief examples that well illustrate the wide range of applications of Little's law in both manufacturing and service operations. It will be helpful to remember the following:

Average inventory is denoted by I.

Throughput is denoted by R.

Average flow time is denoted by T.

3.5.1 Material Flow

A fast-food restaurant processes an average of 5,000 kilograms (kg) of hamburgers per week. Typical inventory of raw meat in cold storage is 2,500 kg. The process in this case is the restaurant and the flow unit is a kilogram of meat. We know, therefore, that

$$\text{Throughput } R = 5{,}000 \text{ kg./week}$$

and

$$\text{Average inventory } I = 2{,}500 \text{ kg.}$$

Therefore, by Little's law,

$$\text{Average flow time } T = I/R = 2{,}500/5{,}000 = 0.5 \text{ week}$$

In other words, an average kilogram of meat spends only half a week in cold storage. The restaurant may use this information to verify that it is serving fresh meat in its hamburgers.

3.5.2 Customer Flow

The café Den Drippel in Ninove, Belgium, serves, on average, 60 customers per night. A typical night at Den Drippel is long, about 10 hours. At any point in time, there are, on average, 18 customers in the café. These customers are either enjoying their food and drinks, waiting to order, or waiting for their order to arrive. Since we would like to know how long a customer spends inside the restaurant, we are interested in the average flow time for each customer. In this example, the process is the café, the flow unit is a customer, and we know that

$$\text{Throughput } R = 60 \text{ customers/night}$$

$$\text{Since nights are 10 hours long, } R = 6 \text{ customers/hour}$$

and

$$\text{Average inventory } I = 18 \text{ customers}$$

Thus, Little's law yields the following information:

$$\text{Average flow time } T = I/R = 18/6 = 3 \text{ hours}$$

In other words, the average customer spends three hours at Den Drippel.

3.5.3 Job Flow

A branch office of an insurance company processes 10,000 claims per year. Average processing time is three weeks. We want to know how many claims are being processed at any given point. Assume that the office works 50 weeks per year. The process is a branch of the insurance company, and the flow unit is a claim. We know, therefore, that

$$\text{Throughput } R = 10{,}000 \text{ claims / year}$$

and

$$\text{Average flow time } T = 3/50 \text{ year}$$

Thus, Little's law implies that

$$\text{Average inventory } I = R \times T = 10{,}000 \times 3/50 = 600 \text{ claims}$$

On average, then, scattered in the branch are 600 claims in various phases of processing—waiting to be assigned, being processed, waiting to be sent out, waiting for additional data, and so forth.

3.5.4 Cash Flow

A steel company processes \$400 million of iron ore per year. The cost of processing ore is \$200 million per year. The average inventory is \$100 million. We want to know how long a dollar spends in the process. The value of inventory includes both ore and processing cost. The process in this case is the steel company, and the flow unit is a cost dollar. A total of \$400 million + \$200 million = \$600 million flows through the process each year. We know, therefore, that

$$\text{Throughput } R = \$600 \text{ million / year}$$

and

$$\text{Average inventory } I = \$100 \text{ million}$$

We can thus deduce the following information:

$$\text{Average flow time } T = I/R = 100/600 = 1/6 \text{ year} = 2 \text{ months}$$

On average, then, a dollar spends two months in the process. In other words, there is an average lag of two months between the time a dollar enters the process (in the form of either raw materials or processing cost) and the time it leaves (in the form of finished goods). Thus, each dollar is tied up in working capital at the factory for an average of two months.

3.5.5 Cash Flow (Accounts Receivable)

A major manufacturer bills \$300 million worth of cellular equipment per year. The average amount in accounts receivable is \$45 million. We want to determine how much time elapses from the time a customer is billed to the time payment is received. In this case, the process is the manufacturer's accounts-receivable department, and the flow unit is a dollar. We know, therefore, that

$$\text{Throughput } R = \$300 \text{ million / year}$$

and

$$\text{Average inventory } I = \$45 \text{ million}$$

Thus, Little's law implies that

$$\text{Average flow time } T = I/R = 45/300 \text{ year} = 0.15 \text{ year} = 1.8 \text{ months}$$

On average, therefore, 1.8 months elapse from the time a customer is billed to the time payment is received. Any reduction in this time will result in revenues reaching the manufacturer more quickly.

3.5.6 Service Flow (Financing Applications at Auto-Moto)

Auto-Moto Financial Services provides financing to qualified buyers of new cars and motorcycles. Having just revamped its application-processing operations, Auto-Moto Financial Services is now evaluating the effect of its changes on service performance. Auto-Moto receives about 1,000 loan applications per month and makes accept/reject decisions based on an extensive review of each application. We will assume a 30-day working month.

Until last year (under what we will call "Process I"), Auto-Moto Financial Services processed each application individually. On average, 20 percent of all applications received approval. An internal audit showed that, on average, Auto-Moto had about 500 applications in process at various stages of the approval/rejection procedure. In response to customer complaints about the time taken to process each application, Auto-Moto called in Kellogg Consultants (KC) to help streamline its decision-making process. KC quickly identified a key problem with the current process: Although most applications could be processed fairly quickly, some—because of insufficient and/or unclear documentation—took a disproportionate amount of time. KC, therefore, suggested the following changes to the process (thereby creating what we will call "Process II"):

1. Because the percentage of approved applications is fairly low, an Initial Review Team should be set up to preprocess all applications according to strict but fairly mechanical guidelines.
2. Each application would fall into one of three categories: *A* (looks excellent), *B* (needs more detailed evaluation), and *C* (reject summarily). *A* and *B* applications would be forwarded to different specialist subgroups.
3. Each subgroup would then evaluate the applications in its domain and make accept/reject decisions.

Process II was implemented on an experimental basis. The company found that, on average, 25 percent of all applications were *A*s, 25 percent *B*s, and 50 percent *C*s. Typically, about 70 percent of all *A*s and 10 percent of all *B*s were approved on review. (Recall that all *C*s were rejected.) Internal audit checks further revealed that, on average, 200 applications were with the Initial Review Team undergoing preprocessing. Just 25, however, were with the Subgroup A Team undergoing the next stage of processing and about 150 with the Subgroup B Team.

Auto-Moto Financial Services wants to determine whether the implemented changes have improved service performance.

Observe that the flow unit is a loan application. On average, Auto-Moto Financial Services receives and processes 1,000 loan applications per month. Let us determine the impact of the implemented changes on customer service.

Under Process I, we know the following:

$$\text{Throughput } R = 1{,}000 \text{ applications/month}$$

and

$$\text{Average inventory } I = 500 \text{ applications}$$

Thus, we can conclude that

$$\text{Average flow time } T = I/R$$

$$T = 500/1{,}000 \text{ month} = 0.5 \text{ month} = 15 \text{ days}$$

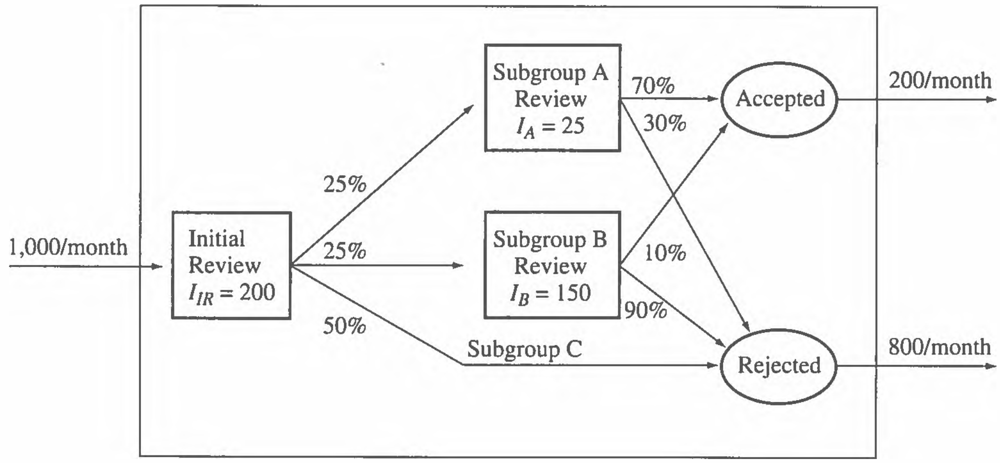

FIGURE 3.4 Flowchart for Auto-Moto Financial Services

In Process I, therefore, each application spent, on average, 15 days with Auto-Moto before receiving an accept/reject decision.

Now, let us consider Process II. Because this process involves multiple steps, it is better to start with the process flowchart in Figure 3.4. (We will discuss process flowcharts more fully in Chapter 4.) Note that, on average, 1,000 applications arrive per month for initial review. After initial review, 50 percent of these are rejected, 25 percent are categorized as Type A (looks excellent) and 25 percent are categorized as Type B (needs more detailed evaluation). On detailed evaluation by Subgroup A Team, 70 percent of Type A applications are accepted and 30 percent rejected. On evaluation by Subgroup B Team, 10 percent of Type B applications are accepted and 90 percent rejected. Thus, each month, an average of 200 applications is accepted and 800 rejected.

Furthermore, on average, 200 applications are with the Initial Review Team, 25 with the Subgroup A Team, and 150 with the Subgroup B Team. Thus, we can conclude that for Process II

$$\text{Throughput } R = 1{,}000 \text{ applications/month}$$

and

$$\text{Average inventory } I = 200 + 150 + 25 = 375 \text{ applications}$$

Thus, we can deduce that

$$\text{Average flow time } T = I/R$$

$$T = 375/1{,}000 \text{ month} = 0.375 \text{ month} = 11.25 \text{ days}$$

Under Process II, therefore, each application spends, on average, 11.25 days with Auto-Moto before an accept/reject decision is made. Compared to the 15 days taken, on average, under Process I, this is a significant reduction.

Another way to reach the same conclusion that $T = 11.25$ days is to do a more detailed analysis and calculate the average flow time of each *type* of application. (Recall that the Initial Review Team at Auto-Moto Financial Services categorizes each application received as Type A, B, or C.) To find the average flow time over *all* applications, we can then take the weighted average of the flow times for each type—in other words, break down Process II into its three subprocesses, initial review, Subgroup A review, and Subgroup B review, and find out how much time applications spend in each of these subprocesses. From that knowledge we can then compute the flow time of each type of application. The remainder of this section illustrates the detailed computations behind this argument.

As we can see in Figure 3.4, each application starts out in initial review. On average, there are 200 applications with the Initial Review Team. For initial review, the performance measures are denoted with subscript *IR* and are as follows:

$$\text{Throughput } R_{IR} = 1{,}000 \text{ applications / month}$$

and

$$\text{Average inventory } I_{IR} = 200 \text{ applications}$$

From this information we can deduce that for initial review,

$$\text{Average flow time } T_{IR} = I_{IR} / R_{IR}$$
$$T_{IR} = 200/1{,}000 \text{ month} = 0.2 \text{ month} = 6 \text{ days}$$

Thus, each application spends, on average, six days in initial review.

Now consider the applications classified as Type A by initial review. Recall that, on average, there are 25 applications with the Subgroup A Review Team. Because 25 percent of all incoming applications are categorized as Type A, on average, 250 of the 1,000 applications received per month are categorized as Type A. We will denote this group with a subscript *A*. So, we have

$$\text{Throughput } R_A = 250 \text{ applications / month}$$
$$\text{Average inventory } I_A = 25 \text{ applications}$$

We can, thus, deduce that

$$\text{Average flow time } T_A = I_A / R_A$$
$$T_A = 25/250 \text{ month} = 0.1 \text{ month} = 3 \text{ days}$$

Type A applications spend, on average, another three days in the process with the Subgroup A Review Team.

Similarly, the Subgroup B Review Team receives 25 percent of incoming applications, or 250 applications per month. It is also given that there are 150 applications with Subgroup B. That is,

$$\text{Throughput } R_B = 250 \text{ applications / month}$$
$$\text{Average inventory } I_B = 150 \text{ applications}$$

We can, thus, deduce that

$$\text{Average flow time } T_B = I_B / R_B$$
$$= 150/250 \text{ month} = 0.6 \text{ month} = 18 \text{ days}$$

Thus, Type B applications spend, on average, another 18 days in the process with the Subgroup B Review Team.

Recall that 50 percent of all incoming applications, or 500 applications per month, are rejected by the Initial Review Team itself. These applications are classified as Type C applications and leave the process immediately. (For sake of consistency, one could say that their additional time spent after IR is $T_C = 0$ so that their inventory $I_C = T_C \times R_C = 0$.)

Recall that the Initial Review Team at Auto-Moto Financial Services categorizes each application received as Type A, B, or C. Each application spends, on average, six days with the Initial Review Team. Type A applications are then reviewed by the Subgroup A Review Team, where they spend an additional three days. Type B applications are reviewed by the Subgroup B Review Team, where they spend, on average, another 18 days. Type C applications are rejected by the Initial Review Team itself.

Summarizing, we now have computed the average flow time of each *type* of application under Process II:

- Type A applications spend, on average, 9 days in the process.
- Type B applications spend, on average, 24 days in the process.
- Type C applications spend, on average, 6 days in the process.

Finally, we can now find the average flow time across all applications under Process II using this more detailed analysis by taking the weighted average across the three application types. Average flow time across all application types, therefore, is given as follows:

$$T = \frac{R_A}{R_A + R_B + R_C}(T_{IR} + T_A) + \frac{R_B}{R_A + R_B + R_C}(T_{IR} + T_B) + \frac{R_C}{R_A + R_B + R_C}(T_{IR})$$

So,

$$T = \frac{250}{250 + 250 + 500}(6 + 3) + \frac{250}{250 + 250 + 500}(6 + 18) + \frac{500}{250 + 250 + 500}(6)$$

$$T = \frac{250}{1{,}000}(9) + \frac{250}{1{,}000}(24) + \frac{500}{1{,}000}(6) = 11.25 \text{ days}$$

This, indeed, agrees with our earlier (shorter) computation of the average flow time of 11.25 days.

In the analysis so far, we defined flow units according to categories of applications. When evaluating service performance, however, Auto-Moto Financial Services may want to define flow units differently—as applications, approved applications, or rejected applications. Indeed, only approved applications represent customers who provide revenue, and Auto-Moto Financial Services would probably benefit more from reducing their flow time to less than 11.25 days.

Under Process I, the average time spent by an application in the process is 15 days—regardless of whether it is finally approved. Let us now determine how much time the *approved* applications spend with Auto-Moto, under Process II. Under Process II, 70 percent of Type A applications (175 out of 250 per month, on average) are approved, as are 10 percent of Type B applications (25 out of 250 per month, on average). Thus, the aggregate rate at which all applications are approved equals 175 + 25 = 200 applications per month. The average flow time for *approved* applications, denoted by $T_{approved}$, is, again, a weighted average of the flow times of each type of approved application:

Average flow time for approved applications =

$$\begin{aligned} T_{approved} &= \frac{175}{175+25}(T_{IR}+T_A)+\frac{25}{175+25}(T_{IR}+T_B) \\ &= \frac{175}{200}(6+3)+\frac{25}{200}(6+18) \\ &= 10.875 \text{ days} \end{aligned}$$

Similarly, let us now determine the average time an eventually *rejected* application spends with Auto-Moto under Process II, denoted by T_{reject}. Under Process II, 30 percent of Type A applications (75 out of 250 per month, on average) are rejected, as are 90 percent of Type B applications (225 out of 250 per month, on average), as are 100 percent of Type C applications (500 per month, on average).

Average flow time for rejected applications, T_{reject}, is then the weighted average across each of these three types and is given by

$$\begin{aligned} T_{reject} &= \frac{75}{75+225+500}(T_{IR}+T_A)+\frac{225}{75+225+500}(T_{IR}+T_B)+\frac{500}{75+225+500}(T_{IR}) \\ &= \frac{75}{800}(6+3)+\frac{225}{800}(6+18)+\frac{500}{800}(6) \\ &= 11.343 \text{ days} \end{aligned}$$

Process II, therefore, has not only reduced the average overall application flow time but also reduced it *more* for approved customers than for rejected customers. However, 12.5 percent of all approved applications (25 that are categorized as Type B, out of 200 approved each month) spend a lot longer in Process II than in Process I (an average of 24 instead of 15 days). This delay may be a problem for Auto-Moto Financial Services in terms of service performance. Since approved applications represent potential customers, a delay in the approval process may cause some of these applicants to go elsewhere for financing, resulting in a loss of revenue for Auto-Moto.

3.6 ANALYZING FINANCIAL FLOWS THROUGH FINANCIAL STATEMENTS

Our business process-flow paradigm can also be used to analyze financial statements by considering the flow of a financial unit (say, a dollar) through the corporation. Let us return to MBPF Inc. of Example 3.2 and analyze its three financial statements: the firm's income statement, balance sheet, and the more detailed cost of goods sold (COGS) statement for 2011. With an appropriate use of Little's law, this analysis will not only help us understand the current performance of the process but also highlight areas for improvement.

Recall that a key financial measure for any process such as MBPF Inc. is the working capital, which includes the value of process inventories and accounts receivables. The following analysis shows us how to find areas within MBPF Inc. in which a reduction in flow time will result in a significant reduction in inventories and, therefore, the working capital.

In 2011, MBPF operations called for the purchase of both sheet metal (raw materials) and prefabricated bases (purchased parts). Roofs were made in the fabrication area from sheet metal and then assembled with prefabricated bases in the assembly area. Completed garages were stored in the finished goods warehouse until shipped to customers.

In order to conduct our analysis, we need the data contained in the following tables:

- Table 3.4: MBPF's 2011 income statement
- Table 3.5: MBPF's consolidated balance sheet as of December 31, 2011
- Table 3.6: Details concerning process inventories as of December 31, 2011, as well as production costs for 2011

Note that all values in these tables are in millions of dollars and that all data represent end-of-the-year numbers, although we will assume that inventory figures represent average inventory in the process.

3.6.1 Assessing Financial Flow Performance

Our objective is to study cash flows at MBPF in order to determine how long it takes for a cost dollar to be converted into recovered revenue. For that, we need a picture of process-wide cash flows. (Later, to identify more specific areas of improvement within