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Design Rules, Volume 2: How Technology Shapes Organizations

Chapter 8 Rationalizing Flow Processes

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Note to Readers: This is a draft of Chapter 8 of *Design Rules, Volume 2: How Technology Shapes Organizations*. It builds on prior chapters, but I believe it is possible to read this chapter on a stand-alone basis. The chapter may be cited as:

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I would be most grateful for your comments on any aspect of this chapter! Thank you in advance, Carliss.

Abstract

The purpose of this chapter is to examine the value structure of flow production processes and to explain why it is necessary to rationalize flow processes using the tools of systematic management. I first explain the problems facing managers of multi-step flow production processes at the end of the 19^{th} Century. I introduce a model of the value structure of a production process made up of interdependent steps and define the *production bottleneck* of the process.

I use the mathematical definition of a bottleneck to derive two general properties of stochastic multi-step flow processes with bottlenecks. These properties imply a need for ongoing managerial oversight and intervention using a set of tools that went by the label *systematic management*. Without active systematic management to address production bottlenecks, large-scale flow processes can easily collapse into chaos.

I then argue that that the use of automated machinery, larger (or growing) markets, and systematic management are supermodular complements: each attribute makes the other two more valuable. The next chapter will explore how the technological requirements of multi-step flow production processes affect the optimal design of organizations implementing these technologies.

Introduction

From 1750 to 1970 approximately, the movement of industrial organization was towards higher levels of centralization supporting ever-higher levels of output. First, production tasks became collocated as factories replaced the former putting out system (where jobbers distributed raw materials to households and picked up finished products at a later date). In factories, steps were subdivided and increasingly depended on powered machinery. Even though Adam Smith praised the productivity gains of a simple division of labor, the need to be near a central source of power seems to have been the decisive factor behind the rise of factories in the English Midlands in the 18th Century.[1]

In the decades following 1750, machines got better, and sources of power, including water and steam engines, became more efficient. Larger and more powerful machines were inserted into production processes that were divided into finer steps. Around 1850, the baton of industrial innovation passed from Great Britain to the United States.[2] The American railroad system made the Midwest and far West accessible to Eastern producers. Transportation costs and shipment times dropped precipitously so that separate local markets could be served by geographically distant companies. The so-called American system of manufacturing, which was based on very fine divisions of labor and specialized machinery, permitted single factories to produce goods at low cost in volumes never seen before.

However as the tasks became more subdivided and the intermediate steps more numerous, multi-step production systems, like that at the Singer Sewing Machine Co., spun out of control.

> The problem was a gradual breakdown of the integration of work flow at the lower levels of the company and a concordant deterioration in the ability of top executives to control work lower in the company hierarchy.[3]

The response was a movement towards *systematic management* aimed at rationalizing production within factories.[4] The systematizers, including Slater Lewis, Henry Metcalf, Alexander Church, H.M. Norris, and John Tregoing, invented production control systems, inventory control systems, and cost accounting systems and implemented them at a number of firms.[5] Frederick W. Taylor's work on *scientific management* extended their work by incorporating detailed time studies of work procedures. (Taylor was the most visible proponent of scientific management techniques, but the systematizing movement started well before his career began.)

These organizational innovations, aimed at controlling and coordinating the flow of production through a factory, increased output, but also took away the workers' and foremens' autonomy. Rather than the foreman or worker deciding what to make and what supplies to use, control and scheduling functions were performed by specialized staff, including stock clerks (to control inventory), production control clerks (to keep track of orders) and time keepers (to measure work flow through various tasks).[6] The methods and principles worked out by the systematizers allowed complex factory systems to operate at ever higher levels of output with ever lower unit costs.

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[1] Landes (1998) p. 209.

[2] Hounshell (1985) pp. 17-25.

[3] Litterer (1963) p. 373.

[4] Kendall (1912).

[5] Litterer (1963) p. 370.

[6] Ibid. p. 387.

A flow of tasks and transfers is a necessary corollary of the division of labor. With a division of labor, what was previously undivided work performed by one person becomes a set of tasks performed by different people and a series of transfers between them.

The purpose of this chapter is to examine the value structure of multi-step flow production processes and to explain why it is necessary to rationalize flow processes using the tools of systematic management. I begin by defining systematic management. I then introduce a model of the value structure of a production process made up of interdependent steps and define the *production bottleneck* of the process. I show how production bottlenecks give rise to recurring technical problems, which must be solved in a timely way if the process is to work.

I use the mathematical definition of a bottleneck to derive two general properties of stochastic multi-step flow processes. These properties in turn imply a need for ongoing managerial oversight and intervention using the tools of systematic management. Without active systematic management to address production bottlenecks, large-scale flow processes can easily collapse into chaos.

I then argue that that the use of automated machinery, larger (or growing) markets, and systematic management are supermodular complements: each attribute makes the other two more valuable.[7] The next chapter will explore how the technological requirements of multi-step flow production processes affect the optimal design of organizations implementing these technologies.

8.1 What is Systematic Management?

Systematic management was and is a group of practices aimed at bringing method and system to multi-step flow production processes, including transportation, manufacturing, distribution, and marketing systems.[8] Articles describing these practices first appeared in engineering publications in the 1870s then in management journals in the 1900s. Today the principles of systematic management are taught in courses in Operations Management, Supply Chain Management and Managerial Accounting.

The term "systematized management" was first used by Henry Kendall, who located it between "unsystematized management" and Frederick W. Taylor's "scientific management."[9] Kendall described plants subject to systematized management as "well organized and managed" and stated that in "many such plants the efficiency is exceedingly good," (though not as good as in plants using scientific management).[10] Such plants generally had good cost accounting systems, a single purchasing department, and used written orders to control the flow of work. They did not have a centralized planning

[7] See Chapter 5.

[8] Kendall (1912); Litterer (1961; 1963); Yates (1993).

[9] Kendall (1912).

[10] Kendall (1912) pp. 119-120.

or scheduling department nor did they exercise centralized control over how workers performed their work.

The business historian Joseph Litterer described systematic management as spanning two sets of practices:

> [The first] is a careful definition of duties and responsibilities coupled with standardized ways of performing these duties. The second is a specific way of gathering, handling, analyzing, and transmitting information.[11]

The goal of the systematizers was to "transcend dependence up the skills, memory, or capacity of any single individual," whether the person was a skilled workman or the manager in charge of an entire factory.[12]

Systematic management was a broad movement with many contributors. It lasted over four decades and influenced a range of industries. Frederick W. Taylor's *scientific management* was a unified theory of how to achieve efficiency within a factory. It involved specific practices such as time-and-motion studies, a splitting of the job of foreman into functional components, and differential piece rates.

As Joanne Yates observed, scientific management "was written and talked about far more than it was implemented."[13] In contrast, the broader, less dogmatic systematic management movement reshaped communication and decision-making in essentially all enterprises implementing flow production technologies. Today, Frederick Taylor's theories are seen as anachronistic and demeaning in their treatment of workers.[14] In contrast, the principles of systematic management, which support a wide variety of workplace practices, continue to be important in companies of all sizes around the world today.

8.2 A Model of Flow Production

The goal of systematic management is to make a flow production process more efficient. Let me model flow production as a series of steps that begins by taking in raw materials, fabricates intermediate components, combines components into a finished product, and then transports and sells the product to the final customer.[15] The steps take place in a sequence, although not always a strict sequence.

A strict sequence exists in many "continuous flow" processes, including paper-

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[11] Litterer (1963) pp. 372-373.

[12] Jelinek (1980) p. 69

[13] Yates (1989) p. 10.

[14] Braverman (1998).

[15] Flow processes arise not only in production but in transportation, logistics, and service businesses as well. To make the analysis concrete, I will use factories as a paradigmatic example, but the results generalize to any technology that requires a set of consistent, interdependent steps.

making, the production of iron and steel, and textile manufacturing. However, before and after the strictly sequential steps, other steps can take place in parallel. For example, intermediate components can be produced in different parts of a factory and then assembled. Ingots of metal may be formed in the same furnace, then sent to different rolling mills to be fabricated into different products. Often, the sequence of steps will vary from job to job, depending on the specifications of the order. Steps are essential to the model, sequence is not.

In multi-step production processes making many products, scheduling the flow of production is very difficult. When many steps are involved, it becomes impossible to keep all machinery and workers fully utilized at all times. Thus it is not surprising that as the use of expensive machinery increased, many firms reduced the breadth of their product lines.

> At one time a metal working factory would be willing to make pumps, steam engines, farm implements, tools, locomotives, in brief, just about anything in metal their craftsmen could handle. By the end of the Civil War a number of specialized manufacturers emerged who made just pumps, or locomotives or machine tools.[16]

The critical property of a series of steps aimed at making a particular thing is that all must take place in strict proportion. Using the notation of chapter 6, let us think of the productive steps as a set of functional complements:[17]

$$s_1 \square s_2 \square \ldots s_i \square s_j \ldots \square s_{N-1} \square s_N = S \qquad (1)$$

Here s_i denotes a single step in the production process and S the finished good, which might be a sewing machine. Note that this is a more fine-grained representation of a technology than in the needle-thread-scissors example given in Chapter 6. In effect we are zooming in on a specific part of the technical architecture, whose recipe entails an inter-related set of sequential and parallel steps.

Within each step, a particular technical procedure is carried out and the intermediate good is then passed to the next step. Each step is performed by an operator in conjunction with appropriate materials and machinery. The steps should be strict functional complements: if any one can be omitted without harming the final product, it should be eliminated from the lineup.

The steps are tied together by more than functional complementarity, however. Each has a certain *capacity*, that is, a maximum number of units that can be processed per

[16] Litterer (1961) p. 467.

[17] Even steps that take place in parallel are functional complements. Thus the index may not correspond to the timing or order of steps. For example steps *1 through i* make take place in one line, and steps *j through N-1* may take place simultaneously in another line with the output of both lines coming together only in the final step, *N*. For examples of different process flows, see Gray and Leonard (2016). For an example of parallel steps converging in an automobile assembly plant, see Mishina and Takeda (1992).

unit of time. Because all steps are necessary to make the final good, the *production capacity of the entire system* equals the minimum of the capacities of the separate steps:

$$Q_{\min} = \min(q_1, ..., q_i, q_j, ..., q_N) \tag{2}$$

where $Q_{\min}$ denotes the capacity of the system; and

q_i denotes the capacity of step s_i.

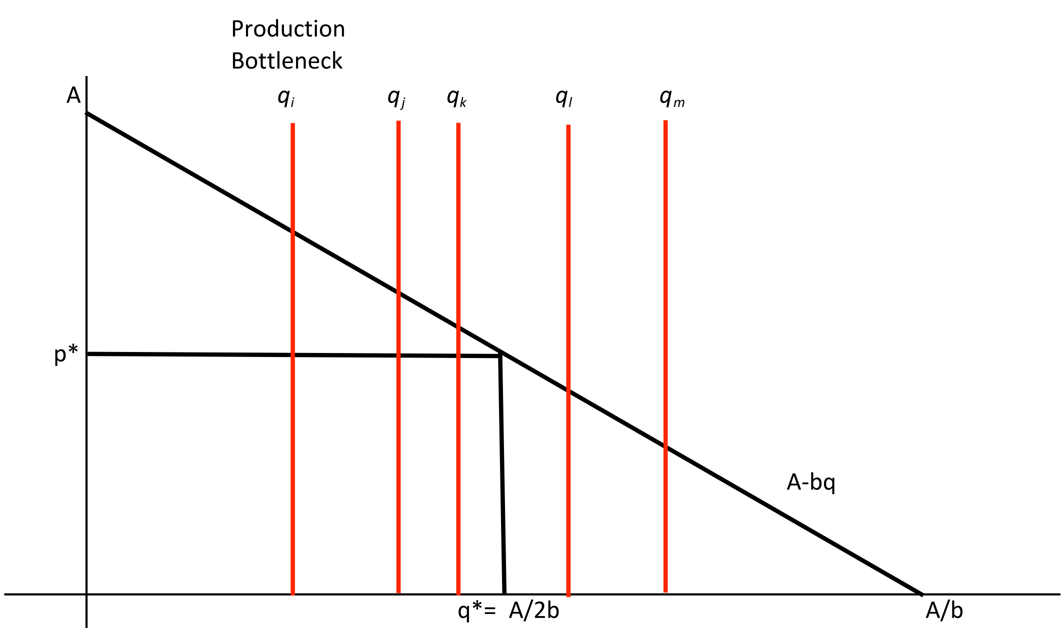
The step with the least capacity is known as the *production bottleneck*:

$$\text{Production Bottleneck} \equiv \text{step such that } q_B = \min(q_1, \ldots, q_N) \quad . \tag{3}$$

Production bottlenecks are a special type of technical bottleneck caused by the interdependence of capacity across steps. The technical problem to be solved is to increase the capacity of the bottleneck. If the capacity of every step can be costlessly adjusted as needed, no production bottleneck will exist. However, as discussed below, real technologies are subject to material constraints that limit their capacity and require readjustment.

We can represent the capacity of each step relative to market demand and the firm's desired level of production using the graph shown in Figure 8-1. Here the horizontal axis represents the quantity of goods produced and the vertical axis represents contribution, defined as price less variable cost. The line $A - bq$ indicates the contribution per unit corresponding to different levels of output. If the firm is a monopolist, this is an (inverse) demand curve. However, functions like this arise in oligopolistic and monopolistic competition as well.

Figure 8-1 Capacity of Various Steps Relative to Demand and Desired Level of Output



The rectangular area defined by $pq \equiv (A - bq) \cdot q$ indicates the profits of the firm for each feasible combination of price and output. As it raises production levels, profits will first increase and then decrease. The profit-maximizing combination of price and quantity is given by the points p^* and q^* indicated on the graph. If the firm overshoots q^*, it will want to reduce production in order to increase its profits.

My concern, however, is not with oversupply but undersupply. Specifically, given a target level of production, q^*, *what are the technological impediments to achieving that level of output?* Recall that the technological process consists of a series of subdivided tasks (steps), all of which are necessary to obtain the final good. The vertical lines in the graph represent the maximum capacity of the factory to perform a specific step in a given period of time (a day or a week).

I have drawn only a few representative vertical lines. A reasonably complex production process (to make a sewing machine or a harvester or a plate of steel) might have several hundred steps arranged in a rough order within the factory. Thus in most real production systems there exists a veritable thicket of capacities. In the absence of a detailed and systematic analysis of the process, these capacities would be known roughly, but not precisely. The production bottleneck is the step with the least capacity, here shown as step *i*. Steps with capacities above the profit-maximizing quantity (steps *l* and *m*) do not constrain the production process.

This technology presents its managers with several immediate problems, whose solutions affect the optimal design of organizations seeking to implement the technological process.

8.2 Technical problem # 1: Find the production bottleneck.

As I've drawn the graph, the production bottleneck's capacity q_l is below the ideal quanity, q^*. Managers would thus like to relax the constraint and increase production. This condition corresponds to that of companies like Singer Sewing Machine Co. throughout much of the late 19th Century, where factory production could not keep up with orders coming in from the field.[18]

At a conference held at Dartmouth University in 1911, Henry Kendall, the manager of a printing business, vividly described the nature of production bottlenecks at plants subject to what he called "unsystematized management." His best guess was that approximately 70% of all plants in the country were of this type.[19] Most unsystematized establishments made multiple products, generally to order. Thus their problems were compounded by the fact that, at any given time, they had to manage several step processes simultaneously.

In these factories, said Kendall:

[18] Hounshell (1984) p. 96, 109.

[19] Kendall (1912) p. 114.

> [W]ork progress[es] to a certain extent through the shop until it is stopped … waiting for some material.
>
> [W]ork which should go through the manufacturing departments rapidly is held up at different places … . [There is] loss of space … because work in process does not pass promptly through the workrooms ... [and] loss of capital, because more money is tied up in [inventory] and in the jobs which represent labor and material sidetracked throughout the plant.
>
> Orders are transmitted verbally by the salesman … to the superintendent [who gives them] to the foreman. …[The foreman] gives work to each workman … . As questions arise …, the workman goes to the foreman who in turn goes to the office for instructions. *Meanwhile progress on the work stops.* [Emphasis added.]
>
> This lack of planning the work at the start, of complete instructions, of coordinating the departments and routing work throughout each operation, results in congestion of unfinished work at many points [as well as] frequent mistakes at rush times and shortages that must later be made up … .[20]

A critical characteristic of flow processes based on interdependent steps is that *solving any one obstruction may have no immediate effect on overall output*. Work may be visibly halted in some places in the factory, but if it has also halted at other points, then remedying one shortage will do nothing unless it is *the* production bottleneck. (In Figure 8-1, increasing the capacity of step j will not increase production unless the capacity of step i has already increased.)[21]

Production bottlenecks that cause work to stop can be found in two ways. The direct method involves looking for buildups of inventory. Steps ahead of the bottleneck will have excess output, steps behind it will be starved for inputs. However, this method only works if the *sequence of steps* is clearly delineated, which, as I have indicated, is often not the case. It also requires that upstream operators are not scaling back their rate of work, which is a common response to excess inventory levels.

A more indirect method of finding the bottleneck is to construct an ideal or representative sequence of steps and then conduct studies that rate the capacity of each step by calculating the time needed to make a certain volume of intermediate products. Such time studies were advocated by most proponents of systematic management. However, getting such information was not easy. Foremen had other tasks that needed their attention and operators were generally averse to self-reporting. Thus the job of conducting time studies was given to specialized employees, who were clerks not factory workers.[22]

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[20] Ibid. pp. 116-118.

[21] For a vivid description of the detective work needed to find *the real* production bottleneck, see Eliyahuh Goldratt's *The Goal*: *A Process of Ongoing Improvement* (Goldratt and Cox, 2016).

[22] Litterer (1963) p. 382.

Two other facts are worth noting. First, the constraining production bottleneck cannot be found reliably unless *all* candidate steps are within the information-gathering scope of the production analyst. Second, eliminating recurring bottlenecks requires the ability to change the design of any part of the system. The changes needed in turn may be local, affecting adjacent steps, or global, affecting the entire organization.

8.3 Technical Problem # 2: Variation in the skill of operators.

Step *i* might be a bottleneck when performed by an operator unskilled in that particular task, but have more than adequate capacity when performed by another, more skilled operator. Thus the efficient allocation of operators to tasks requires what is called "assortative matching": harder tasks should be allocated to more competent and energetic workers.[23] In theory, one needs to test all operators performing all tasks to figure out the who is best for each job. In practice, one can approximate an optimal allocation by ranking tasks (steps) in terms of difficulty and operators in terms of skill. In fact, this was done, and different skills and skill levels were recognized at most factories.[24]

Henry Kendall described the challenge of matching workers to tasks:

> The different kinds of work demand [workers] selected with special reference to their aptitude for their particular work. In every factory will be found workers in one department who cannot successfully do their work, but who would successfully do work of another kind.[25]

Note, however, that if the step in question is not a production bottleneck, then having it performed by a less skilled, slower operator does not harm the overall system. Thus systematic management of a flow production system permits the deskilling of some steps. It is also possible to redesign the work itself through further subdivision of labor. This leads to:

8.4 Technical Problem # 3: Variation in skill needed in subparts of a job

In the European factory system it was customary for a skilled operator, upon receiving a production order, to personally assemble the materials necessary to do the job. In the case of a highly skilled person operating an expensive machine this setup time detracted from the efficiency of both the operator and the machine. A notable feature in the American system of manufacturing was the splitting of tasks and jobs between sourcing and carrying away (low skill) and running the machine (higher skill).[26] Even

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[23] This statement rests on the assumption that the skilled operator's proportional impact on the capacity of a difficult step is greater than his or her impact on an easy step. In this case assortative matching will cause a great improvement in the difficult step at the cost of only a small decline in the easy step. However, if the easy step happens to be the current production bottleneck, then placing a skilled operator on the job may be the best thing to do, at least in the short run.

[24] Litterer (1961) p. 464; Nelson (1974) p. 499.

[25] Kendall (1912) p. 123.

[26] Nelson (1974) p. 499.

further specialization was possible, for example, skilled workers would be used to set up a machine for a given job, and the most skilled workers would make production equipment that was then set up and operated by those of lesser skill.[27]

Kendall describes the advantages of splitting the sourcing of materials from the operating of machines:

> [T]he workman who is to use them should not be delayed or give a thought to the materials which he needs for his next job. They are moved … to the point where he can use them to the best advantage. The *time* a workman spends looking for … his materials can be better spent in effective work.
>
> A detailed schedule of the average workman's day in an *unsystematized* shop … will show a surprisingly small proportion of effective time.[28]

The matching of task to skill and the redesign of work to split jobs into high-skill and low-skill tasks requires not only specific information but also control over task content and task assignment. The analyst, who by definition must be outside the process in order to observe its many parts, must first obtain the requisite information about productivity and task content, and then be able to redesign work, divide tasks in new ways, create new jobs, and assign specific people to specific jobs. These numerous microscopic interventions would generally require extensive bargaining if they took place across the boundaries of independent firms.[29] We will return to this issue in the next chapter.

However, we are not finished with the technical problems inherent in multi-step production processes. Indeed the last problem is in many ways the most significant.

8.5 Technical Problem # 4: Bottlenecks move around.

Although I have represented the capacity of a step as a fixed number, in fact such capacities are subject to random perturbations. A part breaks and must be repaired. A key input is temporarily unavailable. The operator has a bad day (or a good day). Such variation is present in all productive establishments. It is especially prevalent when the underlying technology is new and the output of particular steps is not well-controlled. As a result, production bottlenecks move around within the process.

The case described in Chapter 3 where the chief mold-maker found a flaw in the mold and then saved it is a good example of a stochastic production bottleneck. In that factory, usually the work of making molds would flow normally, but every once in a while something would go wrong. Then actions were no longer predictable and programmable. Transfers of material, energy and information in the task network became

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[27] Litterer (1963) p. 371.

[28] Kendall (1912) pp. 130 and 118.

[29] Baldwin (2008). See Chapter 2 on the location of transactions.

more complex, and the network itself changed in real time.

We can represent stochastic step capacities by converting the individual q_i s in equation (2) into random variables, each with an underlying probability distribution:

$$\tilde{Q}_{\min} = \min(\tilde{q}_1, ..., \tilde{q}_i, \tilde{q}_j, ..., \tilde{q}_N) \qquad (4)$$

In Figure 8-1, each vertical line would be expanded into a probability density function—a small bell curve. Overlapping bell curves indicate that at a given time, step *i* might have less capacity than step *j* while at other times the relationship would be reversed.[30]

Unfortunately, beyond recognizing the fact that random events can change the location of bottlenecks, formal probability theory is of little use in actual production settings because the underlying probability distributions are generally unknown. However, randomly occuring production bottlenecks can be identified and addressed using empirical methods. By studying the process systematically, managers can determine which step is the production bottleneck during any one time interval. Over many time periods, they can simply count the number of times step *i* is the bottleneck.

For example, let's say that over *T* time periods, step *i* is the constraining bottleneck a_i times. Then if step *i* is redesigned to increase its capacity, that action should increase the capacity of the whole system a_i/T *percent* of the time. Clearly one should make a special effort to redesign steps that appear as bottlenecks most frequently. This is known as "making the common case fast."[31]

8.6 Properties of Stochastic Step Processes

Two important properties of stochastic multi-step processes can be shown to hold for any set of underlying probability distributions. They are:

Proposition S-1. *In the absence of systematic management, expected system*

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[30] Formally the probability that step *i* has less capacity than *j* in a given time interval can be written as:

$$P(q_i < q_j) = \int_{q_j=0}^{\infty} \int_{q_i=0}^{q} F_{q_i}(q_i) F_{q_j}(q_j)\, dq_i\, dq_j \qquad (5)$$

where $F_{q_i}(q_i)$ and $F_{q_j}(q_j)$ are the cumulative distribution functions of q_i and q_j respectively. The probability that a given step is the production bottleneck (the global minimum) at any point in time can be calculated via multiple integrations. Consistent with notation in Volume 1, $\tilde{Q}_{\min}$ denotes the random variable, $\hat{Q}_{\min}$ denotes a specific realization of the random variable, and $Q_{\min}$ the expectation of the random variable.

[31] Hennessy and Patterson (1990) p. 8. The so-called 80-20 rule (also known as the Pareto Principle) is an empirical prediction by Joseph Juran which states that 80% of outcomes are produced by 20% of causes. (Juran, 1960). Under this principle, collecting systematic data on actual bottlenecks would reveal a relatively small number of steps that were implicated in most problems. Those steps would then become the focus of rationalization efforts.

capacity decreases with the number of steps in the process. In other words, adding steps by subdividing the work flow without attending to bottlenecks is likely to make overall performance worse.

Proposition S-2. *In the absence of systematic management, expected system capacity decreases with the random variability of any step.* Thus adding random variation to any step is also likely to make overall performance worse.

Proofs are given in Inset Box 8-1.

Inset Box 8-1 Proofs of Propostions S-1 and S-2

Proof of Proposition S-1. Consider one realization of a process with *N* steps. The realization results in a capacity for the system as a whole, $\hat{Q}$, that is the minimum of the realizations of the *N* steps:

$$\hat{Q} = \min(\hat{q}_1, ..., \hat{q}_N) \ .$$

Now consider adding a step to the process. The new step has a cumulative distribution function $F_{N+1}(q_{N+1})$. This function does not have to be known to the analyst. Let the support of F_{N+1} be ($q_{\min}$, $q_{\max}$). If $q_{\min} < \hat{Q}$, then adding step *N+1* diminishes the capacity of the system with probability $F_{N+1}(\hat{Q})$, which is greater than zero. If $\hat{Q} \le q_{\min}$, then adding the step leaves system capacity unchanged. Thus adding a step weakly decreases the expected capacity of the system as a whole. *QED.*

Proof of Proposition S-2. Consistent with Rothschild and Stiglitz (1970), I define increasing variability (risk) as the addition of a mean preserving spread to a given probability distribution. Consider again a process of *N* steps that has a realized capacity of $\hat{Q} = \min(\hat{q}_1, ..., \hat{q}_N)$. The impact of the *N+1* step on the capacity of the system is:

$$P(\tilde{q}_{N+1}) = \begin{cases} \hat{q}_{N+1} - \hat{Q} & \text{if } \hat{q}_{N+1} < \hat{Q} \\ 0 & \text{otherwise} \end{cases} .$$

$P(\cdot)$ is a concave function, thus, as demonstrated by Rothschild and Stiglitz:

$$EP(Y) \le EP(X) \qquad \text{if } Y = X + \text{mean preserving spread.}$$

Therefore increasing the variability of the *N+1st* step, weakly reduces the expected value of system capacity. (The reduction is strong if the lower bound of the support of *Y* is less than $\hat{Q}$. This result holds (1) for any focal step in the process, and (2) for any realization of $\hat{Q}$ for the *N* steps that are not the focal step. *QED.*

8.7 Organizational Implications of Proposition S-1

Proposition S-1 implies that the division of labor is a two-edged sword. On the one hand, the narrowing of tasks combined with special purpose, automated machinery can greatly increase the capacity of an individual step. However, the process as a whole is hostage to the least-efficient step—the production bottleneck. Especially in systems using novel technology and/or experiencing rapid growth, adding more steps to the process has the potential to decrease the capacity of the entire system—at least in the short run.

The solution to this conundrum, of course, is not to take the capacity of any step as a given. Instead managers must pro-actively seek to identify production bottlenecks and increase their capacity. This means first studying the process from start to finish. In the 19th and early 20th Centuries the problem was addressed by men armed with stopwatches, clipboards, and slide rules. Firms began to hire special timekeepers, process engineers, and ultimately planners and schedulers to observe the workers and machines, analyze the data, and implement flow-enhancing changes in the technical architecture of the systems.

These men (for most were men) inserted a new layer of specialized workers between the top managers of a factory and the foremen and workers who handled material and machines. The new layer of staff dealt with information—orders, schedules, inventory, plans. Their role was to eliminate bottlenecks and rationalize flow within and beyond the factory. The hiring of these individuals signaled the emergence of a multi-level, multi-function managerial hierarchy. They were the precursors of a new class of middle managers in what became large corporate bureaucracies.[32]

8.8 Organizational Implications of Proposition S-2

Proposition S-2 implies that uncontrolled variation is "the enemy" in a multi-step process subject to capacity contraints. According to Proposition 1, a random negative draw in any step may turn that step into a bottleneck. Proposition 2 then states that the *wider* the potential variation, the more damage a random bottleneck can do to the performance of system as a whole.

It follows that there is real value to *controlling* each step to reduce its intrinsic variation. In effect, a technical system made up of many interdependent steps with variable capacity creates an environment in which extreme risk aversion pays. (This is the essential insight behind the so-called "six sigma" approach to process improvement: each step in the process delivers the same output 99.99966% of the time.[33])

A set of interdependent steps may extend beyond the boundaries of a given enterprise both upstream and downstream. Consider a multi-step flow production process in which a critical part is sourced from a group of external suppliers. If the suppliers' production systems are subject to random variation, the focal firm's most likely bottleneck may be the *supply* of a critical resource. (Alternatively, it may be able to obtain the resource, but only at an inflated price that threatens its profit margin.)

[32] Litterer (1963) pp. 68-69; Chandler (1977) pp. 381-414.

[33] Harry and Schroeder (2005).

The systematizing firm then has strong incentives to dampen upstream variation, and the most cost-effective way to do this may be to own a source of supply. The steps of the upstream flow process can then be added to the firm's own steps, creating a larger, *more vertically integrated* flow production system. Vertical integration is not the only way to reduce upstream variation in quantities and prices—however, it is *one way* to address those potential bottlenecks.

Similar logic applies to downstream steps, such as transportation and distribution. If their performance is uncertain and a likely bottleneck, that problem may be addressed through vertical integration.

In some markets, the largest source of potential variation is end-user demand. Unexpected downturns in demand can leave the producing firm with large quantities of unsold inventory and attendant losses. Downstream customers then become the bottleneck of the process.

To reduce the impact of variation in demand, the focal firm may elect to invest in forecasting systems and in advertising campaigns and merchandising programs designed to smooth end-user demand. The result of these investments is further vertical integration: even if the focal firm elects to purchase forecasting and advertising services and to share merchandising costs with retailers, it will still need to incorporate additional steps within its own boundaries to oversee these new activities.

If particular steps cannot be controlled beyond certain limits, then there must be buffers between them. If the individual step-capacities in each small time interval are independent, then the variance of the sequence will decrease as the time interval grows longer. In this fashion, buffers can absorb the variability of individual steps and the law of large numbers can work to make the throughput of the system more consistent and predictable. Thus buffering is a way to reduce effective step variability, and increase the overall capacity of the system.

However, buffering comes at a cost. First, there is the direct cost of the inventory itself. Second, the use of buffers makes it difficult to study the contingencies of each step to reduce its variation through better design and control of the actual work flow. If one can reduce step variation directly, then buffering inventories can be eliminated. This is the essential insight behind Toyota's identification of buffers as source of "waste" (muda) in a production system.

Proposition S-2 shows how variability (in individual steps) detracts from expected performance in a multi-step flow production process. In such processes, *technology operating through the "min" function ties the steps together in a particular way so that any step can constrain the whole system.*

However, Proposition S-2 does not hold for all technical systems. Indeed if we change the "min" to a "max" function, then by a classic theorem of option pricing, variability will increase the value of the whole system. We will investigate systems where the "max" function dominates in Part 3 below.

8.9 Throughput in Large Enterprises

One of the most salient features of the United States in the late 19th Century was the growth of national markets for manufactured goods caused by (1) the expansion of the railroads; (2) the growth of cities and populations close to urban areas; and (3) rising standards of living for many Americans. Market growth created new opportunities for businesses to sell single products in large quantities.

This demand might have been satisfied by building many new factories of the same size as those already in existence.[34] Instead, the most successful enterprises redesigned their production and distribution systems to increase the flow of goods through centrally managed facilities. In some cases, a single factory, like Singer's Elizabethport works or International Harvester's Chicago factory would produce enough goods to supply the entire nation.[35] In other cases, like meatpacking, individual tasks and physical assets were geographically dispersed, but flows of goods were tightly coordinated (via telegraph) from a single central office.[36]

These firms achieved high-volume production by taking the American system of manufacture to new levels, pursuing both the division of labor and the mechanization of individual steps farther than had previously been attempted. Even before the invention of the moving assembly line in 1913, the increases in system-level throughput achieved by these methods were nothing short of amazing.

For example, in oil, the throughput of the largest refineries increased from 500 to 6500 barrels per day between 1866 and 1879, and increases continued through 1900.[37] In steel, the production of large blast furnaces increased from about 6000 tons per year in the 1860s to over 100,000 tons a year in the late 1890s.[38] Rolling mills exhibited an even higher rate of growth in throughput: in 1850 a typical mill might produce 3000 tons a year, while in 1900 a large rolling mill's output was 3000 tons *a day*, or approximately 900,000 tons a year.[39] A single Bonsack machine could roll as many cigarettes as 50 skilled workers at a fraction of the cost: five years after the first Bonsack was introduced by James Duke, there were no hand-rollers employed in his factory.[40] The output of Singer sewing machines was less that 1000 per year in 1856; by 1880, two factories produced 500,000 machines per year.[41]

The list continues. In canning, meat-packing, grain milling, metals, machinery

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[34] Litterer (1963).

[35] Hounshell (1984).

[36] Fields (2004).

[37] Chandler (1985).

[38] Temin (1964) p. 159.

[39] *Ibid.* p. 165; Popplewell (1906) p.103.

[40] http://www.learnnc.org/lp/editions/nchist-newsouth/4705 (accessed June 13, 2016).

[41] Hounshell (1984) p. 89-123.

production, as well as in department stores, wholesale goods distribution, mail order sales, and chain stores—multi-step processes were defined and rationalized. Powered machinery, much of it newly invented, was introduced at key points in each process. The result was an amazing increase in the throughput of goods through a relatively small number of organizations that managed high-volume flow processes in systematic ways.

For the most part, these increases in speed and throughput took place before Frederick Taylor formulated his principles of scientific management and before managers at Ford Motor Company invented the moving assembly line. The improvements in productivity across a wide range of industries in the U.S. in the late 19^{th} and early 20^{th} Century were caused by combining extensive use of automated equipment *with the techniques of systematic management* to address emerging bottlenecks.

8.10 Impact of Systematic Management on Workers

The practices of systematic and scientific management brought greater efficiency and productivity to factories, but they also changed the nature of work in those factories. Writing about the impact of systematic management on labor, Daniel Nelson observed:

> To operate effectively, cost and production control plans required the workers to supply detailed information about their activities, submit to standardized procedures, and surrender traditional functions and prerogatives. A production control scheme, for example, might be introduced to reduce delays and make better use of existing plant and machinery. But, by instructing the workman what to produce at a particular time and perhaps providing him with the necessary materials and tools, it might also reduce his ability to decide what to do and how to do it. The first line supervisor, in particular, lost many of his powers.[42]

The premise behind the methods of Frederick W. Taylor and other systematizers was that men and women could be viewed as machines to be utilized at their own maximum capacities. The overall trend was to devalue craft knowledge, deskill many steps in the process, and make the work of the most skilled laborers more intense and arduous.[43] Relations between managers intent on systematizing flow production and workers deteriorated as a result. Labor resistance and strikes were a common response to managers' attempts to streamline flow processes and introduce systematic management techniques into factories.[44]

Systematic management made flow processes more efficient, increasing the productivity of workers and capital equipment (see the discussion of supermodular complementarity below). However, an increase in labor productivity does not necessarily result in higher wages for workers. For example, in a comprehensive study of wages in

[42] Nelson (1974) p. 481.

[43] Braverman (1998) pp. 77-80.

[44] Montgomery (1976). For example, the famous Homestead steel strike in 1892 was motivated by Carnegie and Frick's desire to control job content and work flow in opposition to the workers who then controlled work rules at the mill. See Chapter 10 below.

the textile mills of Lowell, Massachusetts during the 19th Century, James Bessen showed that higher wages for experienced weavers lagged the introduction of the power loom (which greatly enhanced each weaver's productivity) by almost forty years. The power loom was introduced in the 1830s; weavers' wages did not begin to rise relative to less skilled spinners until the 1870s.[45]

Bessen argues that the lag was caused by two factors that limited workers' mobility. Early in the development of power looms in Lowell, work practices were changing rapidly. New skills were required and old skills became irrelevant. At the same time, every mill was experimenting in its own way (rationalizing its flow process) and no two mills were alike. Thus early on, "workers trained at one mill would not necessarily work proficiently at another." [46]

Later, the technologies in use became more stable, but practices still varied from mill to mill. Experienced workers were more productive than inexperienced ones *at the mills where they were trained*, but their skills were not transferable to other mills that were set up in different ways. Competition among employers based on standardized technology *and portable skills* was eventually what allowed experienced weavers to be paid a premium for their acquired skills.

The process of rationalizing flows in a multi-step production process often fosters technical solutions that are customized to particular establishments. Labor mobility in such systems will be low, and, as a result, owners are more likely than workers to capture productivity gains obtained through the deployment of new technologies. Only when workers' skills are standardized and transferable will their wages rise in conjunction with their technologically-enabled productivity. It follows that when a multi-step flow production process is rationalized in an incremental, *sui generis* fashion, new, productivity-enhancing technologies may bring little or no benefit to workers.

8.11 Supermodular Complementarities in Flow Production

The dynamics of throughput were driven by a set of supermodular complementarities inherent in the underlying technologies. As discussed in Chapter 5, supermodular complementarity is a property of some mathematical functions that measure the value of a particular system of input variables.[47] It exists when an increase in one input variable increases the positive impact of one or more of the others.

In the case of multi-step flow production processes, the inputs affecting value can be mapped onto three different types ("three prongs") of investment in the technical system:

- Investments in mechanized equipment that reduced the per-unit cost of processing;

[45] Bessen (2015) p. 87.

[46] *Ibid.* p. 92.

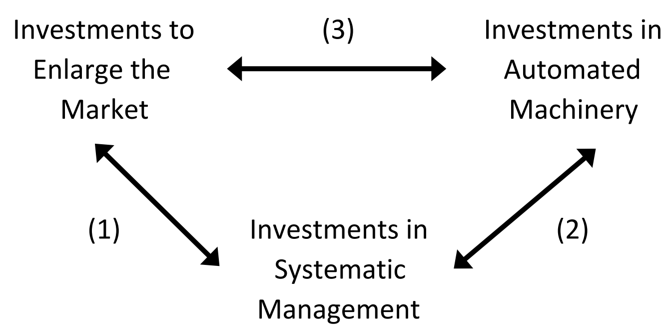
[47] Milgrom and Roberts (1990; 1995); Topkis (1998). See Chapter 5.

- Investments in marketing and distribution to increase the size of the market served by the process; and
- Investments in systematic management to rationalize process flows and reduce variability.

Alfred Chandler argued that these "three pronged investments" were the common characteristic of the large, vertically integrated corporations that arose in early part of the 20th Century in the United States, Great Britain and Germany.[48]

In this section, I shall argue that the three pronged investments are in fact supermodular complements as defined by Paul Milgrom, John Roberts, and Donald Topkis.[49] The relationship is graphically depicted in Figure 8-2. The double headed arrows indicate that each investment increases the returns on the other two. The arguments supporting these relationships are summarized in paragraphs below.

Figure 8-2 Supermodular Complementarity of Three Investments



First, investment in systematic management eliminates bottlenecks, hence makes it possible to increase the capacity of a given flow process. The extra capacity is more valuable in a larger (or growing) market than in a smaller (or shrinking) market. This means that systematic management is a supermodular complement of investments in marketing and distribution. Thus relationship (1) holds.

Second, investments in mechanized equipment reduce the unit cost of products, increasing the profit (contribution) of each unit sold. The extra capacity created by systematic management is more valuable when unit profits are higher. Thus systematic management is a supermodular complement of investments in automated machinery and relationship (2) holds.

Finally, the ability to sell more units in a larger or growing market is more valuable when the profit per unit is higher. Thus investments to enlarge the market are a supermodular complement of investments in automated machinery and relationship (3)

[48] Chandler (1986; 1990).

[49] Milgrom and Roberts (1990; 1994); Topkis (19xx).

holds.

Inset Box 8-2 provides a formal proof of relationship (1) within the framework of a simple microeconomic model with linear demand. The analysis is a simplified version of Paul Milgrom and John Roberts' analysis of the complementarities inherent in flexible manufacturing processes.[50] Relationships (2) and (3) can be proved by simple extensions of the argument.

Inset Box 8-2 Supermodular Complementarity of Investments in Marketing, Capital Equipment and Systematic Management

Supermodular complementarity between investments x and y holds if the following mathematical relationship holds:

$$V(x, y) - V(0, y) > V(x, 0) - V(0, 0) \qquad (8\text{-}1)$$

Here the arguments x and y indicate making the investment x or y, while the argument 0 indicates not making the investment. $V(0, 0)$ corresponds to doing nothing.

Consider a firm facing a linear price-quantity tradeoff as shown in Figure 8-1. Let $p(q)$ be defined as the contribution to profit per unit sold corresponding to the quantity q:

$$p(q) = A - bq.$$

(Defining p as unit contribution simplifies the notation, without affecting the results. The firm charges customers its variable unit cost plus a markup p.)

The firm's profit is simply the unit contribution, $p(q)$ times the quantity sold:

$$\Pi(q) = p(q) \times q = Aq - bq^2 \quad .$$

Given systematic management, the firm will set its quantity and price to maximize its profit, with no bottleneck constraints. Standard calculus yields profit-maximizing price and quantity and the resulting profit. These optimized values are denoted by stars (*):

$$q^* = A/2b$$

$$p^* = A/2$$

$$\Pi^* = A^2/4b \quad . \qquad (8\text{-}2)$$

In the *absence* of systematic management, the firm's output is constrained by the production bottleneck $q_{min} < q^*$. The corresponding price and resulting profit, denoted by apostrophes (′), are as follows:

$$p' = A - b \times q_{min}$$

$$\Pi' = (A - b \times q_{min}) \times q_{min} \quad . \qquad (8\text{-}3)$$

We want to vary parameters A and b to reflect the following treatments: (1) a base case with no marketing or capital investments; (2) a larger market (more demand at each price) resulting from marketing investments; and (3) a higher unit contribution resulting from investments in capital equipment that lower variable costs; (4) both a larger market and a higher unit contribution resulting from both investments.

[50] Milgrom and Roberts (1990).

(a) In the base case, with no investments, let $A = A_0$ and $b = b_0$.

(b) Market growth results in a flatter demand function (more purchasers at every price). In the case of marketing investments, let $A = A_0$ and $b = b_0/m$ where $m > 1$ is a market scaling factor. $(m – 1)$ is the percentage increase in the size of the market.

(c) Higher unit contribution shifts the demand function up in a parallel fashion (higher profit at every level of output). Thus in the case of capital equipment investments, let $A = kA_0$ and $b = b_0$ where $k > 1$ is a profit scaling factor. $(k – 1)$ is the percentage increase unit contribution.

(d) Finally both investments lead both parameters to shift: $A = kA_0$ and $b = b_0/m$.

We can now prove each of the three relatationships by substituting appropriate *A*s and *b*s into the profit functions (8-2) and (8-3), and applying brute force algebra to the resulting expressions. The same approach works in all three cases. I illustrate by proving relationship (1).

Relationship (1) Larger markets and systematic management are supermodular complements:

$$\Pi(m, s) - \Pi(0, s) > \Pi(m, 0) - \Pi(0, 0) .$$

Substituting appropriate parameter values into equations (8-4) and (8-5), the test for supermodularity becomes:

$$\frac{A_0^2 m}{4b_0} - \frac{A_0^2}{4b_0} > A_0 q_{min} - \frac{b_0}{m} q_{min}^2 - A_0 q_{min} + b_0 q_{min}^2$$

$$\frac{A_0^2}{4b_0} \cdot (m-1) > b_0 q_{min}^2 \frac{(m-1)}{m}$$

Without loss of generality, let $q_{min} \equiv \alpha q^* = \alpha A_0/2b_0$, where the scaling factor α is less than 1. Substituting for q_{min} in the above expression, we have:

$$\frac{A_0^2}{4b_0} \cdot (m-1) > b_0 \left[\frac{\alpha A_0}{2b_0}\right]^2 \frac{(m-1)}{m}$$

Rearranging and canceling terms leads to:

$$1 > \frac{\alpha^2}{m}$$

α is less than one and m is greater than one by definition, thus the inequality is true. Marketing investments and systematic management are thus supermodular complements: the presence of one makes the other more valuable. *QED.*

8.12 Significance of the Complementary Relationships

Why do these relationships matter? And what do they indicate about the optimal design of organizations that seek to implement technologies based on step processes?

Each type of investment has value in its own right, but the three together together are worth more than any one taken alone. Thus the investments are self-reinforcing. This fact can unleash powerful dynamic forces. Each investment enhances the value (rate of return) on the others. An organization that implements all three will outperform organizations that pursue only one or two.

But does the organization in question have to be a single firm? As always, that depends. At one extreme, as we saw in Chapter 5, if the investments are strong complements, i.e. one is worthwhile only in the presence of the other(s), then unified governance or very strong relational contracts are necessary to avoid the threat of hold up. At the other extreme, if the tasks and returns associated with each type of investment are separated via thin crossing points, then armslength transactions and contracts may be sufficient to induce a network of autonomous agents to make complementary investments where each member of the network benefits from the actions of the others.

Returning to the example of the smiths and the cooks (see Chapter 2), some cooks may see opportunities to increase the size of their markets, perhaps by opening food stalls.[51] If their investments are successful, those cooks will need more pothooks and other iron implements. They will then increase their purchases of iron implements (at the prevailing prices), benefiting their suppliers, the smiths. Faced with higher demand, some smiths might invest in automated bellows, increasing their capacity and lowering their unit cost. They might then experiment with lowering their prices. Passing on the lower prices to their customers, the cooks would find their profits and market size increasing still further.

The cooks would thus benefit from the smiths' investments in automated equipment, just as the smiths benefited from the cooks' investments in larger markets. Each side's investment increases the returns to the other side's investments, which is the definition of supermodular complementarity. Each might justify his or her investment based on the current prices and quantities, but if both invest, each will receive a positive "surprise" as a result of the supermodular complementarity of their investments.

In Chapter 5, I derived three necessary and sufficient conditions under which this type of "distributed supermodular complementarity (DSMC) holds as a dynamic equilibrium. If these conditions are satisfied, it is better not to combine separate activities under unified governance. A network of autonomous firm pursuing supermodular investments independently will survive in competition with a single firm pursuing the same set of investments in an integrated fashion.

The question is: do step processes with bottlenecks satisfy the conditions of DSMC? And if not, which conditions are violated and why? These questions will be addressed in the next chapter.

8.13 Conclusion—How Technology Shapes Organizations

Flow production processes are a set of technologies that became economically

[51] I am implicitly assuming some form of competition exists between smiths and between cooks. If there is only one smith and one cook, then they are in a position of bilateral monopoly, where each can hold up the other.

important when work was centralized in factories in the late 18th and early 19th Centuries. The ongoing development of these technologies in turn laid the foundation for the emergence of many new businesses and industries in the U.S. in the late 19th and early 20th Centuries.

Wherever they are used, multi-step flow production processes pose a similar set of technological problems. First, the steps in the technical recipe are functional complements: each is essential to the final good, thus each affects all of the others. Second, multi-step flow production processes do not run seamlessly without interruptions or stoppages. System-level production is constrained by the step with the smallest throughput. This step is known as the production bottleneck. Efficient flow production requires active managerial intervention so that production bottlenecks can be identified and addressed wherever and whenever they arise.

In this chapter, I used the mathematical definition of a production bottleneck to formulate and prove two propositions. First, absent active managerial intervention to address bottlenecks, chaining more steps together in a multi-step process creates new possibilities for production bottlenecks, thus is likely to decrease system-level throughput. Second, again in the absence of active managerial intervention, variability in the throughput of individual steps allows bottlenecks to emerge randomly in different parts of the process. Greater variability in any step also reduces the average throughput of the entire system.

Systematic management was a movement in the late 19th and early 20th Century that sought to address the problems of flow rationalization in multi-step production processes by inventing new tools, policies and practices. The pioneers of systematic management invented factory planning, centralized inventory control, production control systems, and hierachical organizations, as well as careful time studies of individual steps in the production process. Their methods aimed to increase throughput in factories, transportation systems, and other businesses by finding and addressing underlying production bottlenecks, thereby making the flow more efficient.

Rationalizing a flow production process unquestionably makes workers more productive. By reducing delays and idle time the same number of workers can produce more goods in the same amount of time. However higher levels of productivity do not necessarily result in higher wages. The rationalization of a step process at a given site may be achieved in an idiosyncratic way: workers may learn jobs and skills that cannot be transferred to other sites. In such cases, productivity-enhancing technology may bring little or no benefit to workers. This was the case in the New England textile industry in the mid-19th Century.

I then showed that, in a multi-step flow production process, systematic management to address bottlenecks and rationalize flow is a supermodular complement of cost-reducing capital investment and larger markets. More of any of these factors makes the others more valuable. All three factors were very much in evidence across a number of industries in the U.S. between 1870 and 1910.

In the next chapter, I will argue that the technological rationalization of a flow process rewards organizations characterized by unified governance, the exercise of direct authority, and hierarchies to manage information and decision rights. By the property of supermodular complementarity demonstrated in this chapter, rewards to such organizations will be greater in the presence of large or growing markets and opportunities to use automated machinery to reduce the unit costs of production. The success of organizations pursuing and benefiting from these complementarities in turn led to the rise of what Alfred Chandler labeled "modern corporations."

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