HANDBOOK OF INTEGRATED RISK MANAGEMENT IN GLOBAL SUPPLY CHAINS

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CHAPTER 1

RISK MANAGEMENT AND OPERATIONAL HEDGING: AN OVERVIEW

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1.1 INTRODUCTION

This chapter, which is based on Chapter 9 in (18), aims to give an introduction and overview of risk management and of the techniques that operations managers can use to mitigate risks. We start the next section by describing the concept of risk management and viewing it as an ongoing 4-step process and integral part of operations strategy. We distinguish operational from financial risk. In section 3, we identify the various operational risks that companies are exposed to. Then we review methodologies to assess and value those risks both qualitatively (using subjective risk maps) and quantitatively (using risk preference functions and risk metrics). The goal of risk assessment is to improve how we react to risk and to proactively reduce our exposure to

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it. In section 5, we review tactical risk decisions, including risk discovery and risk recovery. The remaining sections of the chapter illustrates strategic risk mitigation, i.e., how operations can be structured to mitigate specific risks.

Hedging refers to any action taken to mitigate a particular risk exposure; operational hedging uses operational instruments. Section 7 posits that there are four generic strategies to mitigate risk using operational instruments: 1) reserves and redundancy; 2) diversification and pooling; 3) risk sharing and transfer; and 4) reducing or eliminating root causes of risk. Section 8 reviews financial hedging of operational risk using options and derivatives. Section 9 illustrates how operational hedging can be tailored to the specific operations strategy of the firm using techniques such as: tailored redundancy, dynamic pooling with allocation flexibility, chaining, and multi-sourcing. Section 10 finishes the chapter by summarizing some guidelines for operational risk management.

1.2 RISK MANAGEMENT: CONCEPT AND PROCESS

1.2.1 Defining hazards and risk

Before we can describe the concept of risk management, we must first define some terms. *Hazards* are potential sources of danger. In a business setting, danger can mean anything that may have a negative impact on the firm's net present value. Hazards have a harmful impact, but they may or may not occur.

In everyday language, *risk* refers to an exposure to a chance of loss or damage. ("We risked losing a lot of money in this venture"; "Why risk your life?") Risk thus arises from hazards *and* exposure: it does not exist if exposure to a hazard does not or will not occur (e.g., if you live on top of a mountain, you are not at risk of flooding). The interpretation of risk as *an undesirable possible consequence of uncertainty* suggests that risk is a combination of two factors:

1. The probability that an adverse event or hazard will occur.
2. The consequences of the adverse event.

1.2.2 Financial versus operational risk

While it is intuitive to associate risk with a probability and an undesired outcome, there are other interpretations of risk. The 1997 Presidential-Congressional Commission on Risk Management defined risk as the probability that a substance or situation will produce harm under specified conditions. In economics, "risk refers to situations in which we can list all possible outcomes and we know the likelihood that each outcome occurs."(11)

In finance, risk is "the possibility that the actual outcome is likely to diverge [or deviate] from the expected value." (12) In finance, risk is equated with uncertainty in payoffs, which we will refer to as *profit variability risk*. Risk then implies the existence of some random variable whose standard deviation or variance can be used as a measure of risk. Notice that this view calls any uncertainty in outcomes, whether favorable or not, risk. The key distinction from the common interpretation of risk is the absence of "danger" or an "adverse event." For instance, people don't typically say that they are at risk of winning the lottery.

Operational risks are risks that stem from operations, i.e. from activities and resources. Any potential source that generates a negative impact on the flow of information, goods, and cash in our operations is an operational risk. The inclusion of cash flowing through the operation implies that financial and operational risks are not mutually exclusive. But the goal of operations is to maximize expected firm value by matching supply with demand. Any possible mismatch between supply and demand, excess or shortage, is undesirable and is called *mismatch risk*.

1.2.3 Risk management: concept and examples

In general, *risk management* is the broad activity of planning and decision-making designed to deal with the occurrence of hazards or risks. Risks include both unlikely but high-impact disruption risks, as well as more common volatility in demand, internal processing, and supply.

Procter & Gamble provides an example of managing disruption risk. On Sunday May 4, 2003, 1,200 workers at the company's Pringles plant in Jackson, Tennessee, heard warning sirens and rushed to evacuation areas. About 18 minutes later, tornados hit and badly damaged the plant's roof, while subsequent rain damaged truck loads of potato chips. The south end of the building was demolished and required reconstruction. With the sole Pringles plant in the Americas shut down, P&G had no choice but to suspend all U.S. distribution, armed with only a six-week supply of Pringles already in stores or en-route. It was estimated that it would take at least one month before shipments could resume, causing a huge blow to one of P&G's biggest brands. (According to the company, people eat 275 million chips per day, generating annual sales above $1 billion.) But the company was prepared: by 3a.m., the brand contingency team and an entire recovery process (described in Example 1.1) was set in motion. We shall return to the importance of tactical risk management through fast risk discovery and recovery.

■ **EXAMPLE 1.1**

Risk Management by Procter & Gamble

Only hours after a tornado hit P&G's Pringles plant in Jackson, Tennessee on Sunday May 4, 2003, the brand contingency team started the recovery processes. Employees from the only other Pringles plant in Mechelen, just outside of Brussels, were flown in to help reconstruction. By Wednesday, P&G

determined that its major equipment would be fine, and put its major U.S. customers on allocation. By Saturday, a temporary roof had been installed; on Monday, May 12, a limited production of its most popular flavors was resumed.

Meanwhile, production in Belgium was maximized and re-routed to supply some of the Jackson plant's Latin American and Asian customers. According to the Mechelen plant:

> "Already in the second week of May, first Raw & Pack Material orders were placed at our suppliers with stretched leadtimes which enabled Mechelen to switch its production schedule by the end of the third week (the 2 lines with the capability to run Asian product–14 case count versus 18 case count–started to run the Asian brand codes).
>
> "First, shipments to the Asian market left Mechelen by the end of May! In total Mechelen delivered 11,100,000 200g cans and 7,500,000 50g cans! On top of this achievement, Mechelen produced specific flavors for Japan that were never ran before (a special Operations-QA-PD team was formed to qualify our lines for these specific flavors).
>
> "As a consequence of this massive support, the inventories in Mechelen for the Western European market were heavily eroded. Due to this low inventory the Mechelen organization was further stretched to provide good service levels for Western Europe. We discovered some opportunities in our supply chain (which would be more difficult to find when they were hidden under stock).
>
> "Net: Mechelen protected the Asian business with huge flexibility and strengthened its own supply chain by doing that" (16).

Strategic risk mitigation involves the structuring of global networks with sufficient flexibility to mitigate the impact of hazards. For example, BMW enjoys demand risk mitigation through its global operations network by building cars in Germany, Britain, the U.S., and South-Africa. Out of the annual 160,000 Z4 roadsters and X5 sport "activity" vehicles built in 2003 in its Spartanburg, South Carolina plant, about 100,000 were exported, mostly to Europe. At the same time, BMW imported about 217,000 cars from Europe to reach annual U.S. sales of about 277,000 cars.

Partial balancing of flows through global manufacturing networks (such as those of BMW or DaimlerChrysler'sor service networks (such as large consulting and accounting companies) can also mitigate currency exchange risk. For example, Michelin,the world's biggest tire maker, drew 35% of its 2003 annual sales from North America. While this would normally expose the French company to dollar-euro currency exchange risk, Michelin was not worried about exchange rates. They compensated for the loss caused by translating American revenues into euros by purchasing raw materials that are priced in dollars.

In contrast, companies like Porschewhich builds cars mostly in Germany, must raise local prices to make up for currency changes (a dangerous approach that almost wiped Porsche out in the U.S. in the early 1990s). Otherwise, it

Figure 1.1 Risk management as an ongoing process with four steps.

must absorb the changes in the form of lower profits, or may resort to financial hedging instruments that we will describe below.

1.2.4 Risk management as a process and integral part of operations strategy

Now that we know what is meant by risk, we can proceed with the topic of this chapter: managing risk through operations. It is useful to think of risk management as a four-step process, as illustrated in Figure 1.1:

1. Identification of hazards: the first step in any risk management program is to identify the key potential sources of risk in the operation.
2. Risk assessment: the second step is to assess the degree of risk associated with each hazard. Then we must prioritize hazards and summarize their total impact into an overall risk level of the operation.
3. Tactical risk decisions: this step describes the appropriate decisions to be taken when a hazard is likely to occur soon, or when it has already occurred. For high risk levels, these decisions are also called "crisis management."
4. Implement strategic risk mitigation or hedging, which involves structuring the operational system to reduce future risk exposure.

To adapt to change and to incorporate learning and improvement, risk management must be approached as a process; these four steps must be executed and updated recurrently.

It is useful to make a distinction between tactical and strategic risk management. Tactical risk management uses mechanisms to detect whether a specific hazard is likely to occur soon. Then, it executes contingency plans.

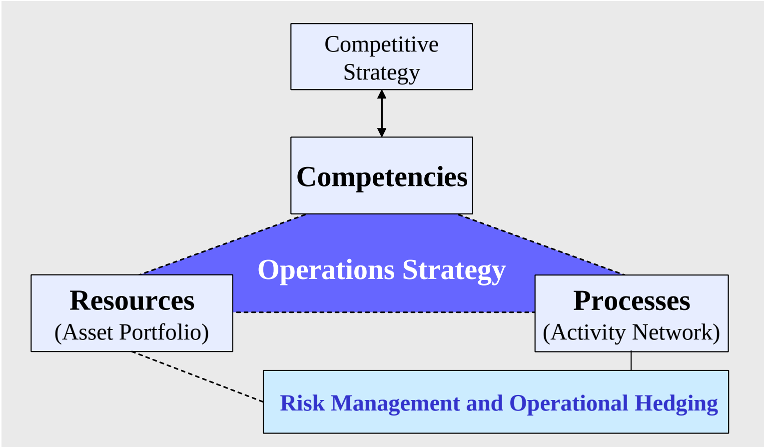


Figure 1.2 Operational hedging is a process of strategic risk mitigation. It involves structuring resources and processes to reduce future risk exposure. Therefore, operational hedging is an integral part of operations strategy.

For instance, P&G used warning sirens and followed a contingency plan to deal with the tornado strike on May 4, 2003, in Jackson, Tennessee (Example 1.1).

In contrast to dealing with the occurrence of a specific hazard, strategic risk management is concerned with mitigating future risk exposure. Operational hedging, a subset of strategic risk management, refers to the adjustment of strategies and the structuring of resources and processes to proactively reduce, if not eliminate, future risk exposure. For instance, P&G's Pringles operations comprise two manufacturing plants with sufficiently flexible processes enabling them to partially take over each other's work. This operational system provides a form of insurance that resulted in the tornado strike having limited financial impact.

In summary, operational hedging is an integral part of operations strategy (Fig. 1.2) for two reasons: it is a necessary process in each operation, and it involves structuring the entire operational system. The remainder of this chapter will illustrate the four-step process of risk management, meanwhile describing how risk management interacts with the operational system's resources and other processes.

1.3 IDENTIFICATION OF OPERATIONAL HAZARDS

The first step in any risk management program is to identify any potential sources of danger. According to one manager who participated in many risk assessment processes: "One lesson I learned is that hazard identification is one of the most difficult steps in the process. Without a clear and robust

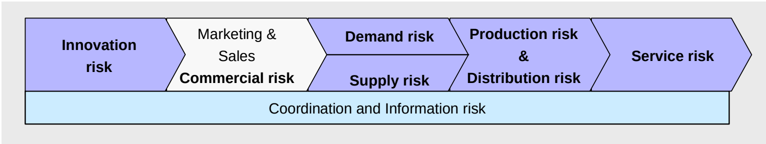


Figure 1.3 Identifying operational risks using the value chain.

framework, it is nearly impossible to identify all critical hazards." Now, we will describe one approach to help this identification process.

An organization is most affected when a danger affects its ability to serve the customer's needs. Although a danger might impact an operation, the effects on the organization and its future are limited if the customer does not suffer from that impact. To identify important risks, it is useful to adopt the customer's perspective by asking: what is my customer's worst nightmare?

The answer then can be linked to operational risks that stem from our activities and assets. As described in (18), any operation can be viewed from three perspectives: as a bundle of competencies, processes, or resources. Adopting these three views directly suggests three approaches that should be combined to identify operational hazards.

1.3.1 Identifying operational risks using the competency view

Linking competency failures to customer nightmares is probably the most direct way to focus the mind on important operational risks. What is the impact of a failure in the firm's key competencies such as quality, flexibility, timeliness, cost, or quantity? If operations strategy is well aligned, this importance should correspond to the priority ranking of the competencies in the customer value proposition. While this link is direct, it is not directly actionable. Therefore, the competency risks must be linked to processes or resources so we can restructure processes and resources to mitigate the competency risks.

1.3.2 Identifying operational risks using the process view

Potential hazards can be identified and categorized by considering each activity in the value chain, as shown in Figure 1.3. Depending on the stage in the value chain where the negative impact may happen, we have:

1. *Innovation risk* represents any exposure to hazards that originate during research and development. The pharmaceutical industry provides a good example: a new drug or compound may turn out to not have sufficient efficacy, potency, or safety to be approved by the relevant governmental agency. Another example is Intel, which recently pulled the

plug on the development of a 3Ghz Pentium chip, its fastest microprocessor for personal computers, because it proved to be too difficult to manufacture.

2. *Commercial risk* represents any exposure to hazards that originate in marketing and sales and negatively impacts revenues. It includes the risk that new products or services are not adopted, cash risks (e.g., lower sales prices than expected), or receivables risks (when customers don't pay).

3. Closely related are *demand and supply risks*, which refer to any uncertainty in quantities demanded or supplied for a given product or service at a given time. Typical examples include retail risks, in which case we may have leftover stock that must be discounted, or insufficient supply (stockouts, underages). Supply risks may also refer to *sourcing risk* , which stems from interaction with suppliers. It may include risks in information (the wrong order was communicated or the order was not received), risks in goods (the wrong quantity or quality of goods was received), or risks in cash (the supply ends up being more expensive than expected). For example, a supplier may claim not to have received an order, or may have sent the wrong amount or type of supply. The shipment may have been lost or stolen. A supplier may have a capacity or yield problem, or may even undergo a catastrophic event such as terrorism, sabotage, or financial bankruptcy.

4. *Production and distribution risks* include any exposure to hazards that originate in our internal processing and distribution networks. There may be labor issues, worker safety hazards and non-ergonomically designed work environments, or maintenance failures that affect capacity availability. Inventory may be at risk of spoilage, damage, or loss. Unexpected operator errors, yield problems, accidental damage, and delays may increase cost above expectations. Distribution channels may be at risk of logistics provider failure, route or transportation mode disruptions, and other hazards (similar to sourcing risks).

5. *Service risk* refers to the exposure to hazards during after-sale service interactions. This may include lack of procedures to deal with product returns, problems, and service inquiries.

6. *Coordination and information risks* refer to uncertainty in coordination and information. They may stem from internal miscommunication and often result in internal demand-supply mismatches. Examples include information technology system failures in hardware, software, local, and wide area networks. Other information risks include forecasting risks, computer virus risks, and errors during order-taking and receiving.

Some industries, such as the pharmaceutical industry, also use the term *technical risk* to refer to the innovation risk of launching a new technology or drug. It is distinct from ongoing operational risk and commercial risk: while a drug may be approved and be no longer at technical risk, it still remains to be seen whether it will have sufficient demand at reasonable prices for it.

1.3.3 Identifying operational risks using the resource view

One can also consider each asset in the operational system and identify associated potential hazards. In practice, one would investigate the key assets in the operation. We can classify assets, and corresponding risks, into three types:

1. *Capital asset risks* are exposures to hazards originating from property, plants, and equipment. These include exposures to property and environmental liability, equipment unreliability, as well as financial risks related to maintenance and perhaps future resale. They can also include working capital such as inventory and receivables risk.

2. *People risks* include safety, health, operational dependence, operator and management errors, resignations, turnover, absenteeism, sabotage, stealing, and more.

3. *Intangible asset risks* include policy risks, intellectual property risks, reputation, culture, and more.

1.3.4 Surrounding background risks

No organization operates in a vacuum. Aside from operational risk, the operating system is subject to various hazards that originate from its surroundings. Depending on the source, we can categorize types of background risks as:

1. *Natural risk*: In addition to operation-specific hazards, nature is capricious and can expose organizations to natural hazards such as earthquakes, heavy rains, lightning, hail storms, fires, and tornados. The exposure typically depends on the location of the organization. For example, coastal properties are exposed to coastal storm hazards such as hurricane storm surges, flooding, erosion, and wind.

2. *Political risk*: This risk includes any negative, unexpected change in laws and regulations (political stability is typically preferred). Examples include a breach in business contracts without recourse to legal action, unexpected strengthening in environmental or labor laws, unexpected currency devaluations, or an outbreak of war.

3. *Competitive and strategic risk* refers to the potential negative impact of competitors' actions, or environmental and technological changes that reduce the effectiveness of the company's strategy.

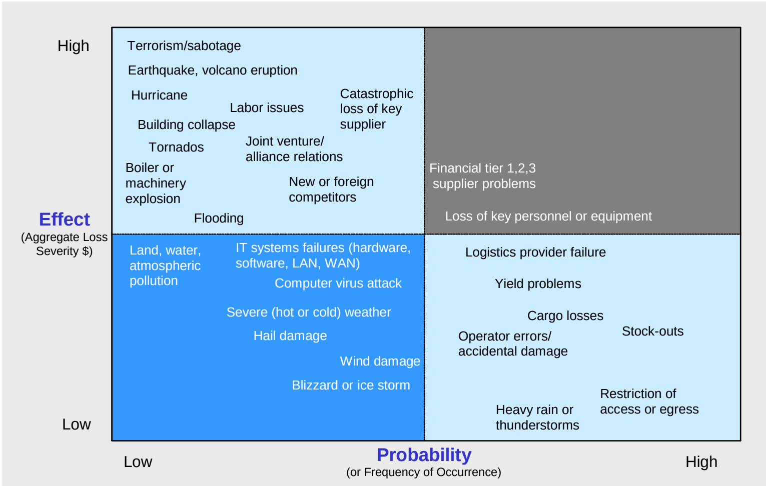


Figure 1.4 A subjective risk map is a graphical representation of the risk assessment for a specific organization done with the help of expert opinions. It shows the impact versus the likelihood of occurrence for each hazard.

1.3.5 Who should identify potential hazards?

Everyone involved in the operation should be able to identify potential hazards. Naturally, people closest to the activities or assets often have the best knowledge. For example, account managers, service representatives and technicians are most knowledgeable in identifying service risk. In contrast, supplier relationship and purchasing managers are the natural parties to identify sourcing risk. This means that risk identification requires a multi-functional team that can interact with functional specialists.

1.4 RISK ASSESSMENT AND VALUATION

The second step in any risk management program is to analyze the degree of risk associated with each hazard. The goal of risk assessment is to indicate which areas and activities in the value chain are most susceptible to hazards.

1.4.1 Qualitative risk assessment: the theory

Recall that risk is an undesirable consequence of uncertainty. Risk assessment thus involves, for each hazard identified in step 1, the estimation of:

1. the impact (vulnerability) on the organization if the hazard were to occur

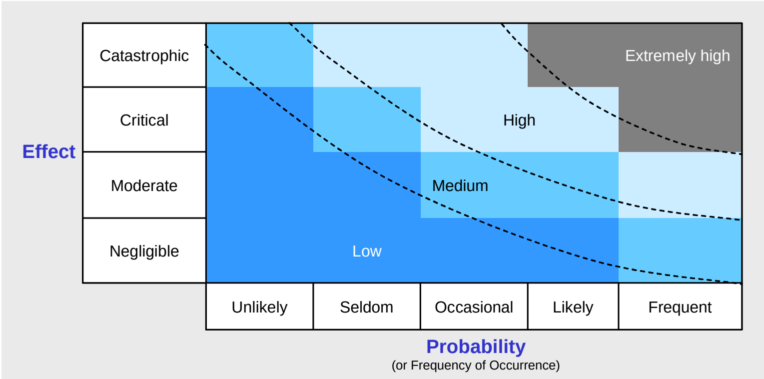


Figure 1.5 Qualitative risk assessment assigns an overall risk level to each hazard, depending on its probability and its impact.

2. and its probability of occurring during the operation.

The result can be displayed in a *subjective risk map*, an example of which is shown in Figure 1.4. The word "subjective" reminds us that this risk map is based on expert opinion only and not on statistical analysis. Obviously, the risk map is company-specific: the risks carry different weights depending on the competitive strategy and the industry. For example, for a commercial bank, IT systems failure would have a much greater impact than would a hurricane.

Risk assessment is completed by ranking hazards to locate the highest-risk activities. This can be done qualitatively by combining the impact and probability for each hazard into an overall risk level. The risk map in Figure 1.4 classifies hazards into three risk levels. High risk hazards occupy the upper right quadrant and create high damage with a high probability. Medium risks are unlikely hazards with high impact (also called *disruptions*) or frequent, low impact hazards (recurrent risks). Low risks stem from unlikely hazards with low impact, and occupy the lower left quadrant.

1.4.2 Qualitative risk assessment: examples from practice

Smart operations managers periodically assess risks. For example, Figure 1.5 shows how the National Interagency Fire Center (10) assigns risk levels (extremely high, high, medium, or low) for helicopter operations depending on the hazard's probability or frequency (unlikely, seldom, occasional, likely, or frequent) and impact (negligible, moderate, critical, or catastrophic).

Debit card companies and other financial companies conduct risk assessment programs periodically. According to one debit card product manager:

> "We had to go through *every* possible operational risk to our business annually, provide an estimate of impact of a hazardous event (on a scale of 1 to 5, covering a range of dollar values) as well as the likelihood of the event happening (also on a scale of 1-5). If you provided a top-two score high impact and high probability event, you were asked to present to the bank's risk management committee, which consisted of senior and executive managers and was headed by the bank's newly formed enterprise risk manager. They would expect to see your action plans if the event occurred, as well as the steps you've taken to mitigate the risk."
>
> "As part of the BASEL II requirements, all banks must conduct this type of thorough assessment for all areas of their business. Failure to meet the BASEL standards can result in sanctions by banking oversight committees (Fed, OCC, etc.) that could affect a bank's abilities to lend, to lend at good rates, to get approval for M&A, etc. It is quite an exhaustive accounting of operational risks. Admittedly, many estimates were just educated guesses by line managers and, of course, it also took a lot of time out of managers' days to focus on events that most likely weren't going to happen... In the end, though, the risk assessment process helped everyone realize where we were vulnerable. It also helps bank management have a much broader understanding of the entire risk exposure and brought operational risk management to the executive board level."

Some risks, such as political risks, are difficult to assess, compared to calculating the technical risk of product approval or the statistical risk of poor forecasting. Yet, where there is a will, there is a way. According to one risk assessment team, "one way to help dimension political risk is to compare the political risks of one country relatively to the risks faced in other countries the firm operates in. One team member found research that provided political risk indexes for various countries throughout the world. Other resources to help quantify what seemed to be a rather nebulous topic include the World Bank's Multilateral Investment Guarantee Agency and numerous consulting firms and insurance providers."

1.4.3 Quantitative risk assessment: risk metrics

The qualitative approach can be quantified by estimating the financial impact and probability of each hazard from past data and experience. A hazard's "risk level" can then be quantified by its expected impact, which is equal to the financial impact multiplied by the probability of occurrence. Constant risk levels are then represented by hyperbolic curves in risk maps, as illustrated by the dotted lines in Figure 1.5.

Besides the methods that assess the expected value of a hazard, there are many other ways of quantifying risk. These are most easily described by letting X denote the (financial) effect of a hazard or random event (i.e., X is a random variable) and $\overline{X}$ its mean or expected value $\mathbb{E}X$. Recall that financially, risk is considered to be the possibility that actual outcomes deviate from expected ones.A basic risk metric is *variance* (or its square root, the standard deviation), the expected squared deviation around the mean:

$$\text{variance} = \mathbb{E}(\overline{X} - X)^2 = \sigma^2.$$

Variance and standard deviationtreat positive deviations from the mean ("the upside") symmetrically with negative deviations ("the downside"). Statistical measures that exclude upside deviations are arguably more natural metrics of risk, because they only capture the undesirable consequences of uncertainty. A popular downside risk measure is *Value-at-Risk* (VaR). It measures the worst expected loss at a given confidence level by answering the question: how much can I lose with $x\%$ probability over a pre-set horizon? Example 1.2illustrates how to calculate VaR. Other examples of downside risk metrics are:

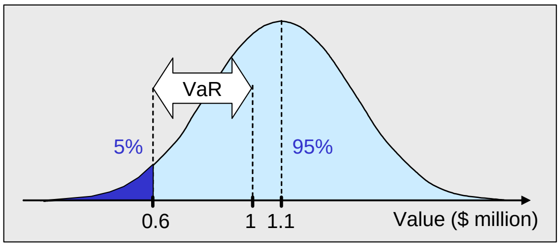
$$\begin{aligned} \text{below-mean semivariance} &= \mathbb{E}(\left(\overline{X} - X\right)^+)^2, \\ \text{below-target } t \text{ semivariance} &= \mathbb{E}((t - X)^+)^2, \\ \text{expected below-target } t \text{ risk} &= \mathbb{E}\,(t - X)^+\,, \end{aligned}$$

where the notation X^+means the positive part of X, i.e., $X^+ = \max(0, X)$.

■ **EXAMPLE 1.2**

How to calculate Value-at-Risk (VaR)

Value-at-Risk at $x\%$ is the answer to the question: how much can be lost with $x\%$ probability over a pre-set horizon? Suppose you currently have a portfolio worth \$1 million, and its annual return is normally distributed with mean 10% and standard deviation 30%. What is your value-at-risk at 5%?



Calculating value-at-risk at 5%.

Your value-at-risk at 5% can be calculated in two steps, as illustrated in the figure above:

1. Find the 5% quantile of next year's value. In our example, Excel gives us that number as `norminv(.05,1.1,.3)`= \$0.6 million.
2. Find the VaR as the difference between the 5% quantile of future value and the current value. In our example, the VaR is $1 - 0.6 =$ \$.4 million.

This means that there is only a 5% chance that you will lose more than \$400,000.

1.4.4 Valuing risk with preferences and utility functions

Measuring risk directly in terms of the downside volatility of outcomes is certainly informative, but such raw risk metrics do not allow us to easily compare risks. For example, do you prefer a risky project with a value variance of \$1 to another with a variance of \$100? Surely, you would want to know the expected value before answering! As a matter of fact, if your preferences depend on expected values *only*, you are said to be *risk-neutral*.

Most people, however, are *risk-sensitive*, which means that their preferences do not depend only on expected value. Deciding between two risky projects then requires trading off risk with expected return. Making this trade-off is difficult in general, but under standard rationality assumptions we can use a utility function to summarize risk preferences. A utility function u simply maps outcomes into a decision-maker's utility. A risky outcome X_1 then is preferred over outcome X_2 if and only if the expected utility of the first exceeds that of the second.

It directly follows that a risk-neutral manager would have a linear utility function, so that only expected outcomes matter. For example, consider choosing between two projects: the first project has a payoff of \$100 for sure, while the second's payoff has an expected value of \$100, but is normally distributed around that mean with standard deviation σ. A risk-neutral manager derives equal expected utility from both projects and is indifferent between them.

In contrast, risk-averse managers have concave utility functions, which reflect their higher sensitivity to downside than upside. To see this, consider a concave function such as the negative exponential

$$u(x) = 1 - e^{-\gamma x},$$

shown in Figure 1.6. The parameter $\gamma > 0$represents the manager's sensitivity to risk and is called the *coefficient of absolute risk aversion*. As the coefficient of risk aversion γ increases, the utility function becomes more concave and more sensitive to downside variations. Notice that the upside has a maximal utility of 1, while the downside is unlimited. The marginal utility of \$1 above the mean is less than that of \$1 below the mean. In other words, a risk-averse manager gets *more* utility from reducing the downside by one unit than from increasing the upside by one unit. It follows that downside variation is not offset by equal upside variation, and that the expected utility from a random outcome with mean 100 is strictly less than a certain outcome of 100. A risk-averse manager dislikes volatility.

1.4.5 Mean-variance frontiers

Risk-averse valuation with expected utilities typically requires calculus, but there is one useful exception. When payoffs are normally distributed, their expected exponential utility can be expressed by the simpler *mean-variance*

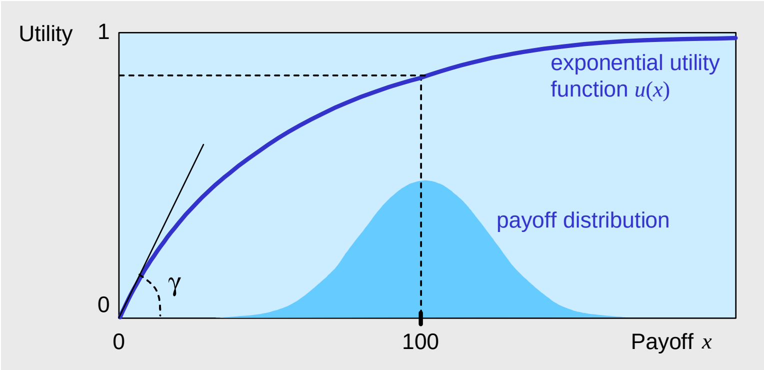


Figure 1.6 Risk-averse managers have concave utility functions, thus preferring a unit reduction of the downside to a unit increase of the upside.

preference:

$$\text{Mean-Variance preference } MV = \mu - \frac{\gamma}{2}\sigma^2,$$

where μ is the expected payoff and σ^2 is its variance. Expected utility increases with the mean payoff, but decreases if the actual outcome is more likely to deviate from its expected value (as indicated by a greater variance) or if the manager is more risk-averse (as indicated by a greater coefficient of risk-aversion).

Mean-variance preferences are at the core of modern financial *portfolio management* and provide a good inspiration for operations strategies for risk mitigation. The original idea was first formulated in 1952 by Nobel laureate Harry Markowitz,who employed mean-variance preferences. He started by observing that individual investors are not interested in the expected value of their portfolio only. If that were the case, portfolios would consist of one asset only: that with the highest expected return.

Most investors hold diversified portfolios because they are concerned with risk as well as expected value. Markowitz used the variance of portfolio value as a measure of risk. Not only are mean-variance preferences reasonable models to describe the decisions of a risk-averse investor, but variances of a portfolio are also easily computed as a function of the covariances between any pair of assets in the portfolio. Markowitz thus presented a mathematical approach to optimal portfolio selection depending on the investor's risk-aversion, represented by the coefficient of risk aversion γ.

Optimal portfolio selection can be illustrated graphically as follows. Imagine that you calculated the expected value (return) and variance (risk) of all possible portfolios that can be bought with a given budget. Now represent each portfolio by one point on a risk-return graph, as shown in Figure 1.7. Then, the optimal portfolio can be derived in two steps:

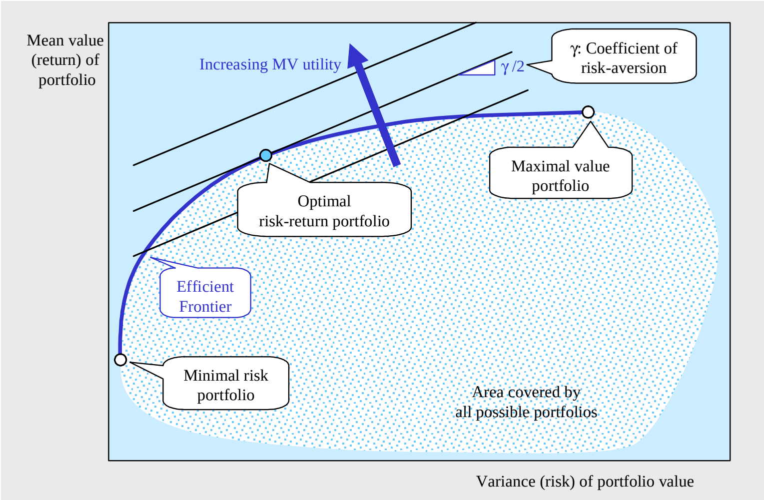


Figure 1.7 Graphical representation of Markowitz's optimal portfolio selection. The optimal risk-return trade-off for a manager with coefficient of risk aversion γ is the point on the efficient frontier with a tangent of $\gamma/2$.

1. Only portfolios that lie on the northwestern frontier, called the *mean-variance frontier*, should be selected; these are called *efficient* portfolios (any other portfolio is dominated by an efficient one with the same expected return but less risk, or the reverse).

2. Once the frontier is known, the final step is to estimate the investor's coefficient of risk-aversion γ, in order to identify the optimal portfolio with the point on the frontier with tangent $\gamma/2$. Indeed, the investor maximizes his expected utility by maximizing his mean-value preferences, which are straight lines in the risk-return graph.

Before we use this approach for strategic risk mitigation and operational hedging, we must consider step 3 of the risk management process.

1.5 TACTICAL RISK DECISIONS AND CRISIS MANAGEMENT

The third step of the risk management process is to let our risk assessment guide us in developing a plan of appropriate tactical decisions to be taken when a specific hazard is likely to occur, or when it has already occurred. For high risk levels, these decisions are also called "crisis management." Tactical risk management involves three activities: risk preparation, risk discovery, and risk recovery.

1.5.1 Risk preparation

To be successful in later risk recovery, organizational risk preparedness is key. This means that companies have formulated proactive and reactive plans: what to do if risk levels are elevated, and contingent actions to take after the hazard occurs. In addition to making plans, they also practice the plans with fire drills, backup routines for power losses, and so on.

1.5.2 Risk discovery

In order to execute proactive plans, one must monitor risks and have a fast system of hazard detection or discovery. Reconsider the P&G Pringles plant example (Example 1.1 on p. 3). When it became likely that the plant was in the path of an oncoming tornado, management decided that the risk level was sufficiently high to evacuate the plant. The anticipatory risk decision was to turn on the sirens as a signal to everyone that the earlier-designed evacuation procedure was in effect.

■ **EXAMPLE 1.3**

Risk discovery and recovery: Nokia v. Ericsson

At 8pm on Friday, March 17th, 2000, a lightning bolt hit an electric line in New Mexico and, somehow, resulted in a fire at the Philips NV's semiconductor plant in Albuquerque. While the sprinkler system extinguished the fire in less than 10 minutes, it also destroyed the clean room during that process, and with it, millions of cell phone chips that were destined for its two largest customers, Nokia and Ericsson. But how the two companies responded to the crisis couldn't have been more different.

At Nokia, computer screens indicated delays of shipments from some Philips chips even before Philips called Nokia's chief component-purchasing manager Tapio Markki on Monday, March 20th. Philips said the fire impacted some 4 million handsets and that there would be a one week delay. Given that it was about to introduce a new generation of cell phones based on the Philips chips, Nokia decided to further look into the issue and offered to fly two Nokia engineers to Albuquerque to help with the recovery. Philips declined the offer and said on March 31, two weeks after the fire, that they would need more weeks to repair the plant, and that several months worth of chip supplies could be disrupted.

Nokia went into textbook crisis management mode. Of the five parts, two were indispensable: one was made by various suppliers around the globe, while the other one was an application specific integrated circuit (ASIC) made only by Philips. A Nokia team, headed by current chairman Ollila flew to Philips' headquarters in Amsterdam and spoke directly with Philips' CEO, Cor Boonstra in an attempt to find alternate supply. Nokia demanded capacity information about all Philips plants and insisted on rerouting the capacity. "The goal was simple: For a little period of time, Philips and Nokia would operate as one company regarding these components," said Nokia's Korhonen. As a solution, Philips used its plants in Eindhoven to produce more than

10 million units of the ASIC chip, and also freed up a Shanghai plant for Nokia. Meanwhile, Nokia engineers redesigned some of their chips so they could be produced elsewhere, and they worked further with Albuquerque to boost production.

Ericsson, in contrast, treated the initial call from Philips as "one technician talking to another." When Ericsson's top management finally learned about the problem several weeks later, it was too late. Philips had no more spare capacity left and no other suppliers were capable of providing the parts Ericsson needed. Thus, Ericsson came up millions of chips short in a rapidly moving cell phone market. The company said they lost at least $400 million in potential revenue. At the end of 2000, its mobile phone division announced a staggering $1.7 billion loss and vowed that it would never be exposed like this again. In January 2001, Ericsson exited the handset production business completely. *Source: (9)*

1.5.3 Risk recovery

Once disaster has struck, risk recovery executes contingency actions such as finding other supplies, temporarily changing prices to ease demand, providing substitutes when actual demand significantly differs from plan, or using backup suppliers or processes. For example, when Grainger,which supplies maintenance and operating parts, had its East Cost facilities hit by electricity blackouts or hurricanes in Florida, they switched to internal power generators; by using this quick backup strategy, Grainger did not miss a single order fulfillment. Similarly, once a tornado struck at P&G, managers immediately started a recovery operation by calling the corporate brand contingency team.

Fast risk discovery and recovery is paramount to containing the negative impact of a disruption. The differential reaction to the unforeseen problems at a Philips semiconductor plant by two of its customers, Nokia and Ericsson, provides a case in point (Example 1.3). Nokia quickly switched sourcing to other back-up facilities and suppliers with little impact to ongoing operations, while Ericsson's slow response along with its unhedged single sourcing strategy is reported to have cost it $400 million in lost sales.

In summary, in good tactical risk management, companies are prepared, use risk discovery mechanisms, and have quick risk recovery plans (Figure 1.8). By the very nature of a crisis, however, there still is a fair amount of unforeseen decision making to be done. The first step is to examine options for addressing the risks. Then, make decisions about which options to implement. Finally, take actions to implement the decisions. Naturally, the appropriate decision maker for these contingent decisions is more senior the higher the risk level.

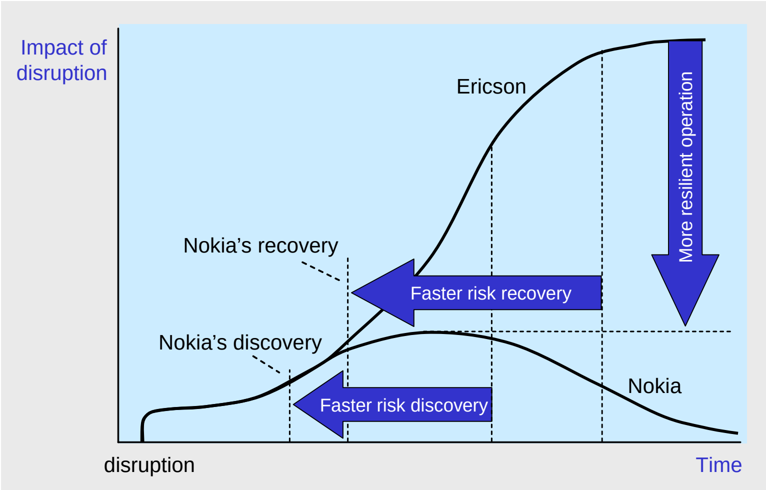


Figure 1.8 Faster risk discovery and recovery, along with a more resilient operation, is paramount in mitigating the impact of disruptions (adapted from 13).

1.6 STRATEGIC RISK MITIGATION

Fast risk discovery and recovery from actual disruptions is paramount in containing negative impact. The effectiveness of such tactical risk decisions to respond to actual disruptions also greatly depends on the flexibility of the operational system. Crisis management is similar to operating a hospital's emergency room: speed and flexibility are the most important competencies to quickly deal with unforeseen problems. Strategic risk management, the fourth step in risk management, involves configuring the operational system for speed and flexibility so as to mitigate future risk exposure. Its goal is to design what (13) calls a resilient organization.

Typically, it costs money to mitigate risk exposure. Strategic risk mitigation must balance that cost with the benefits of reduced risk exposure. The greatest benefit is typically gained by focusing on the most risky hazards (that were identified in step 2 of the risk management process) first. Let us discuss how to carry out the cost-benefit analysis behind strategic risk mitigation.

1.6.1 The value-maximizing level of risk mitigation (risk-neutral)

Risk mitigation strategies fall on a continuum between risk acceptance and risk elimination. Many hazards have such a small risk that one simply accepts their exposure. For example, passengers and freight forwarders accept the inherent risks of flying. Sometimes, risks can be eliminated. For instance,

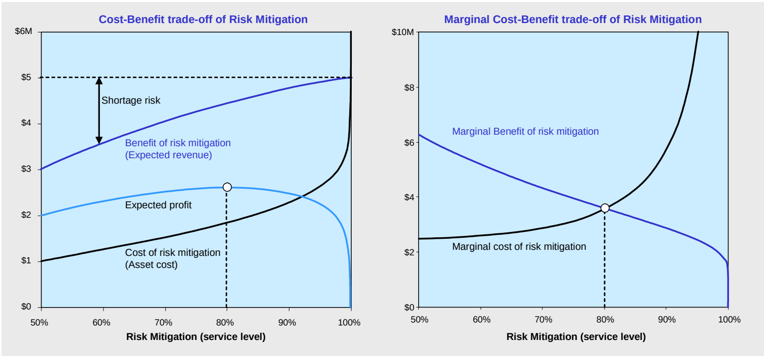


Figure 1.9 Risk-neutral managers determine the optimal level of risk mitigation by trading off costs and benefits. Consider adding safety stock in order to mitigate shortage risk. Initially, the increase in expected revenue outweighs the increase in inventory cost, which in turn increases expected profit (left panel). But beyond a certain level, marginal costs exceed marginal benefits (right panel).

P&G could eliminate tornado risk by relocating its plants to areas where tornados are highly improbable.

Typically, the marginal benefit of risk mitigation decreases while its cost increases, so that the appropriate risk mitigation level falls in between the extreme strategies of risk elimination and risk acceptance. For example, consider mitigating shortage risk by adding safety stock. Figure 1.9 depicts the costs and benefits of reducing shortage risk by adding safety stock for product with a sales price of \$5, a unit cost of \$1, and a normally-distributed demand forecast with mean and standard deviation of 1 million. When stocking the average demand, the shortage probability is 50%. Shortage risk mitigation requires adding safety stock. Complete shortage risk elimination would yield expected revenues of \$5 million, but would require exorbitant safety stock. A risk-neutral manager is better off mitigating 80% shortage risk because that maximizes expected profits, according to the newsvendor model.

1.6.2 Strategic risk-return trade-offs for risk-averse managers

Risk-averse managers care about profit risk as well as expected profits. They are willing to give up some expected profits for a reduction in profit risk.[1]

When managing a single asset such as capacity or stock, profit risk can be decreased by reducing the asset level. Reconsider our earlier example of mitigating shortage risk by adding safety stock. With an abundance of stock,

[1]This is simply a statement of fact, not a prescription. In fact, managers of publicly held companies should maximize expected value, because shareholders can diversify risk on their own by engaging in portfolio management consistent with their own risk-reward preferences.

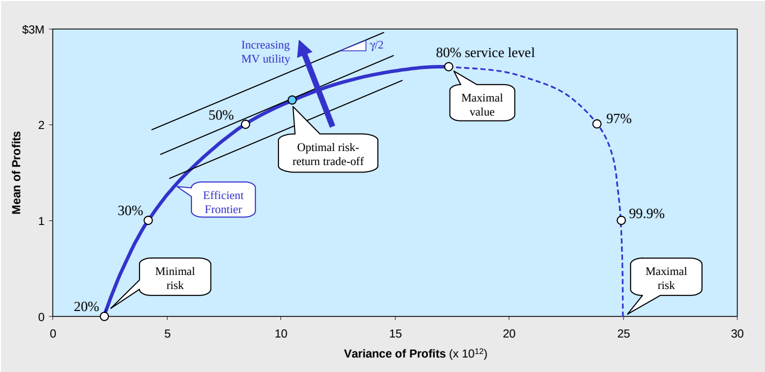


Figure 1.10 Increasing inventory or capacity increases service level and reduces shortage risk, but increases profit variance risk. The optimal risk-return trade-off for a manager with a coefficient of risk aversion γ is the point on the efficient frontier with a tangent of $\gamma/2$.

shortages are eliminated and sales equal demand. The manager then is exposed to total demand risk, and profit standard deviation is maximized (equal to \$5 $\times$ 1 million demand standard deviation). By reducing the stocking (and thus service) level, sales are capped by inventory and profit risk decreases (to \$5 $\times$ the standard deviation of the minimum of demand and stocking level). Figure 1.10 depicts the mean and variance of profits as a function of the service level. Using Markowitz's approach, the appropriate level of risk mitigation for a manager with a coefficient of risk aversion γ is specified by the point on the frontier with a tangent of $\gamma/2$. By moving southwest along the frontier, we give up some expected profit and thus decrease profit variance risk.

1.6.3 Periodic updating and continuous risk management

Strategic risk mitigation includes a procedure to keep risk assessment up to date. Business risks continually change over time and risk management must evolve accordingly. Just like periodic financial portfolio rebalancing and health checkups, periodic updating of risk management is a smart preventative move. Grainger, for instance, reviews each risk plan every six months and updates if there is a business change. It also performs real tests, as well as "desktop exercises" of its risk plans on an annual basis.

In the remainder of this chapter, we will turn our attention to various strategies that can be used to mitigate operational risk.

1.7 FOUR OPERATIONAL HEDGING STRATEGIES

Hedging refers to any action taken to mitigate a particular risk exposure. It often involves counterbalancing acts that take on one risk to offset another. Most businesses hedge or insure to reduce risk, not to make money. In theory, a perfect hedge eliminates risk without impacting mean value. In practice, however, hedging impacts both risk and value. Using Markowitz's visualization, hedging becomes more effective as the frontier becomes flatter, so that risk reduction only comes with a small value loss.

The insurance industry uses three means to mitigate its risk: it builds reserves to meet claims, pools risks over many clients (this diversification reduces its total risk), and transfers remaining risks to reinsurers using contracts. Operations can also use these three generic risk mitigation strategies; in addition, there are also an arsenal of operations management techniques to reduce risk.

These four generic strategies to mitigate risk using operational instruments, i.e. *operational hedging*, are summarized in Example 1.4. Let us review these four strategies qualitatively; the remainder of this chapter will quantify and tailor them to a particular situation.

■ EXAMPLE 1.4

Four generic operational hedging strategies

1. Reserves & Redundancy

- safety capacity, safety inventory, safety time, warranties (reserves)
- multi-sourcing, multiple locations and transportation modes, back-up assets and processes (redundancy)

2. Diversification & Pooling

- operating in diverse markets (diversification)
- serving diverse markets with one resource (demand pooling)
- using diverse suppliers for one resource (supply pooling)
- allocation flexibility of suppliers, designs, resources, activities, and outputs

3. Risk-Sharing & Transfer

- alliances and partnerships
- outsourcing with structured supply contracts
- entering financial hedging contracts with third parties

4. Reducing or Eliminating Root Causes of Risk

- postponement with quick response (decrease risk exposure)
- supplier collaboration and improvement
- root cause analysis and variance reduction (Six Sigma, total quality management)
- robust product and process design, including process relocation

1.7.1 Reserves and redundancy

A core risk mitigation strategy is to invest in reserves, which are assets held in excess of expected requirements, "just-in-case." Reserves are well-understood and a key tactic in operations management: standard inventory and queueing models directly specify how risk-neutral decision makers should size safety capacity, safety inventory, and safety (lead) time as a buffer against uncertainty.

In general, redundancy refers to an excess over normal requirements or duplication. In engineering, redundancy is the duplication of critical system component to increase system reliability, often through backup assets or processes, such as Grainger's backup power generators. In the normal course of operations, these redundant assets or processes are not needed.

1.7.2 Diversification and pooling

Diversification refers to serving multiple risks (e.g., product demands) from one portfolio or network. This popular risk mitigation strategy is also known as "not holding all eggs in one basket." There are several ways of pooling risks with operations, each with a different impact:

A. *Pure diversification and natural hedging* refers to serving two markets with separate, dedicated resources. This reduces total profit variance risk because variability in one market partially offsets variability in the other (unless both risks are perfectly positively correlated). Supplying countries from local operations is an example of pure diversification that is also known as *natural hedging*. It mitigates profit variance risk arising from local demand risk as well as currency exchange risk. Notice that pure diversification does not impact expected value and differs from reserves and redundancy.

B. *Demand pooling* refers to serving multiple demands from one resource, such as a centralized warehouse that stocks one product to serve multiple areas, or a single facility that supplies multiple markets. Similarly, *supply pooling* means serving one demand from multiple suppliers; a typical example is multi-sourcing of a single component. (3) and (15) provide several approaches that involve demand and supply pooling.

Demand and supply pooling are special forms of diversification and risk-pooling. By "betting on two horses," they provide the profit variance risk mitigation benefits of pure diversification that are valued by risk-averse investors. In addition, they reduce expected mismatch costs, safety capacity, and safety inventory, while improving service (because resource sizing is driven by the aggregate standard deviation.) Thus, in contrast to pure diversification, demand and supply pooling also brings benefits to risk-neutral managers (but less so as correlation increases or if risks have dissimilar magnitudes).

C. *Allocation flexibility and information updating* refers to pooling *heterogeneous* risks with a *flexible* network. The embedded real options achieve more powerful operational hedging than do static demand or supply pooling. For example, consider serving continental Europe and the United Kingdom from a single process in Belgium. If the process has sufficient flexibility to postpone country allocations, it can first observe actual demands and exchange rates and then maximize revenues by steering the allocation to the more profitable country. It is exactly this type of dynamic pooling that was effective in the Pringles and Nokia examples.

In addition to the embedded risk mitigation of pooling, allocation flexibility and other real options can increase expected profits. called this the revenue maximization option of flexibility, which becomes more valuable as the pooled risks become more heterogeneous. This "active" operational hedging highlights an interesting advantage over financial hedging or pure insurance: operational hedging not only mitigates risk but can also add value by exploiting upside variations. We will illustrate this quantitatively in the next few sections.

Redundancy and diversity through flexible networks are related. For example, consider P&G's network for Pringles production has two plants. Each plant's main mission is to serve its own geography, so that neither plant is redundant, strictly speaking. The flexibility embodied in the network, however, does allow the Belgian plant to serve as a backup for the Jackson plant, illustrating its relationship to redundancy.

1.7.3 Risk sharing and transfer

Instead of bearing all the risk ourselves, we can share it with partners, alliances, or suppliers. A vast supply chain contracting literature studies various structured contracts (e.g., buy-back and revenue sharing contracts) that balance risk between a supplier and buyer. Later in this chapter, we will discuss how a company can share and even transfer risk by entering into financial hedging contracts with third parties. The obvious example of sharing risk is taking on insurance contracts.

1.7.4 Reducing or Eliminating Root Causes of Risk

In addition to these three insurance-like techniques, operations research has also emphasized risk reduction by quick response, supply chain collaboration and continuous improvement. Continuous improvement uses root cause analysis and an entire arsenal of techniques for variance reduction. While reviewing those techniques go beyond the scope of this chapter, it cannot be overemphasized that, in the long run, eliminating problems is better than mitigating their impact. The Toyota Production System exactly tries to achieve this.

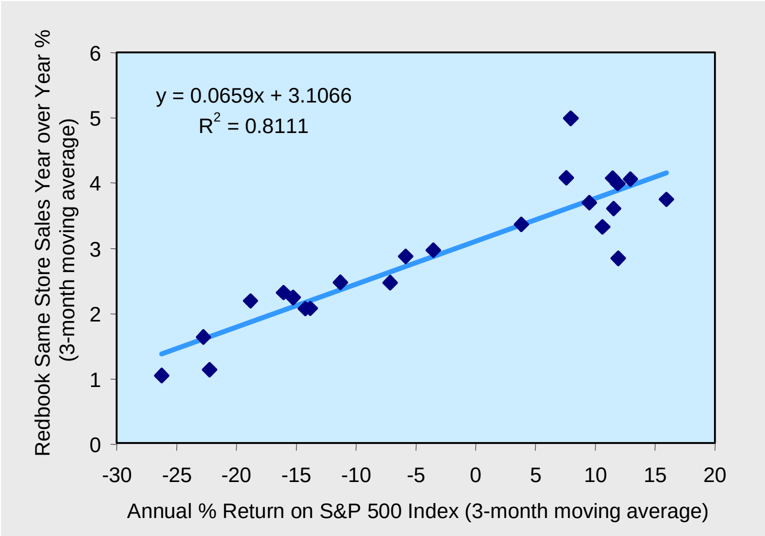


Figure 1.11 Redbook's same-store sales growth rate is highly correlated with the annual return on the S&P 500 Index (7) .

1.8 FINANCIAL HEDGING OF OPERATIONAL RISK

Financial hedging uses financial instruments to mitigate risk. Let us discuss some examples of how financial hedging can mitigate operational risk and how it relates to operational hedging.

1.8.1 Hedging demand risk with options

Demand for discretionary items such as apparel, consumer electronics, and home furnishings is often correlated with economic indicators. (7) present evidence that the correlation can be quite significant. For example, The Redbook Average (a seasonally adjusted average of same-store sales growth in a sample of 60 large U.S. general merchandise retailers representing about 9,000 stores) monthly time-series data from Nov. 1999 to Nov. 2001 had a correlation coefficient of 0.90 with same-period returns on the S&P 500 index ($R^2 = 81\%$, see Figure 1.11). In addition, that value of R^2 is correlated with the fraction of discretionary items sold as a percentage of total sales.

Similar results hold on the firm-level. Figure 1.12 shows that sales per customer transaction and sales per square foot at The Home Depot (a retail chain selling home construction and furnishing products) are both significantly correlated with the S&P 500 index.

Figure 1.12 Quarterly sales per customer transaction (a) and per square foot (b) at Home Depot are correlated with S&P 500 Index (7)

Theoretically, the correlation between sales and a financial instrument can be exploited to mitigate demand risk by buying a (tailored) call option on the financial asset.[2] Consider a retailer who must order inventory today but faces a leadtime of 4 weeks. Assume for simplicity that demand is perfectly correlated with the S&P 500 index. Buying call options on the index with exercise price corresponding to the inventory and exercise date one month from now would provide a perfect hedge, as shown by Figure 1.13.

In reality, the correlation is imperfect and the hedging transactions are more complex (involving a tailored family of different calls) but we can take away the main insights: financial hedging can significantly mitigate profit variability risk. (For this specific example, however, a healthy dose of caution is appropriate, given that Home Depot is part of the S&P 500 ; thus, the correlation is to be expected and may not be a reliable predictor of future performance.)

In well-functioning financial markets, arbitrage arguments show that the options are priced at a level equal to their expected return. Financial hedging then reduces variance risk without impacting the expected return. Risk-averse retailers will then increase their order sizes closer to the risk-neutral (newsvendor) level. In addition, financial market information can be used to update demand forecasts.

1.8.2 Hedging demand risk with (weather) derivatives

When demand is correlated with weather conditions, demand risk can be mitigated using financial weather derivatives. For example, Japanese insurer Mitsui Sumitomo sells derivatives based on the snowfall in a particular loca-

[2] A call option gives its owner the right to buy the asset at a specified exercise price on or before the specified exercise date.

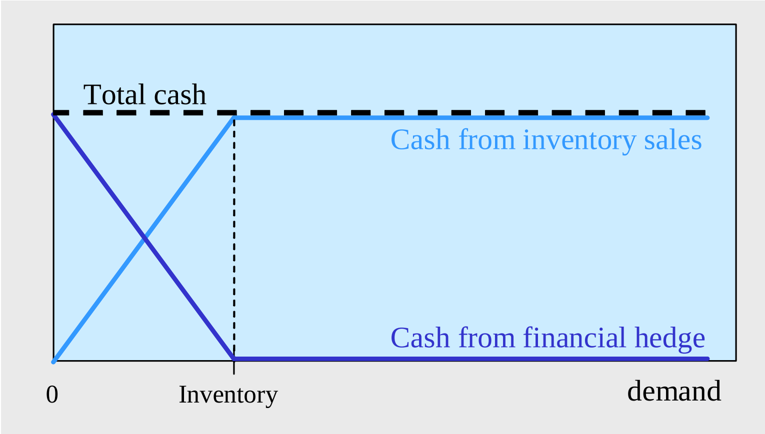


Figure 1.13 When demand is correlated with a financial asset, inventory risk can be mitigated by buying a call option on the financial asset. If the correlation is perfect, a financial option with an exercise price corresponding to the inventory would provide a perfect hedge.

tion. Retail ski shops could use that derivative to hedge against low snowfall that could impact sales. At the same time, Mitsui Sumitomo could sell the opposite derivative to a snow removal company. This example shows how intermediaries such as Mitsui can sometimes improve markets by balancing risks.

In addition to snowfall, weather derivatives can include specifications on rainfall, temperature, and wind. In 2002, Mitsui Sumitomo issued a weather-derivative contract to a soft drink wholesaler based on the number of hours of sunshine. If the number of sunshine hours recorded in the July–September quarter fell below a certain predetermined threshold, Mitsui would pay the company a pre-determined amount.

1.8.3 Hedging currency risk with forward contracts and swaps

Global firms like Michelin, BMW, and Porsche are exposed to currency exchange rate risk. Two popular risk mitigation strategies are natural hedging (produce and sell locally) and financial hedging involving forwards and swaps.

In a *foreign exchange forward market*, you can buy and sell currency for future delivery. If you are going to receive €500,000 next month, you can insure yourself by entering into a one-month *forward contract*. The forward rate on this contract is the price you agree to receive in one month when you deliver the €500,000. Forward contracts specify future customized bilateral transactions. (They can be used to hedge various types of risk. For example, 5) study the equilibrium forward contract on a nonstorable commodity between two firms that have mean-variance preferences over their risky profits and negotiate the forward contract through a Nash bargaining process.)

More generally, you can manage risk by entering into a *swap*, which is a contract between two parties specifying the exchange of a series of payments at specified intervals over a specified period of time.

For main currencies and specific amounts and delivery dates rates, there are standardized contracts, called *futures*, that are traded on currency future markets. In well-functioning financial markets, arbitrage arguments imply that future rates equal the expected rate so that forwards and futures do not impact expected value (neglecting small transaction costs). Inspired by an example of Professor John R. Birge, Example 1.5 illustrates how a global manufacturer can benefit from natural, operational, and financial hedging. As predicted, natural and financial hedging reduce profit variance without affecting expected profits. In contrast, active operational hedging can use allocation flexibility in the global network to produce and sell at the most advantageous location, thereby increases expected profits (combining that with financial hedging further reduces variance without impacting expected value).

■ **EXAMPLE 1.5**

Should we use financial hedging with futures, or operational hedging?

Consider a global manufacturer with production facilities in Europe and the U.S. that is exposed to demand and currency risk. The firm wonders whether it should hedge financially or operationally.

Suppose that the unit sales price is €20,000 in Europe and $20,000 in the U.S.; similarly, the unit cost is 10k in local currency. Suppose that currencies are correlated with demand and that there are two states of nature, each equally likely:

1. U.S. demand is 100k units, Euro demand is 50k, and the exchange rate is $1/€.
2. U.S. demand is 50k units, Euro demand is 100k, and the exchange rate is $2/€.

Hedge Option 1: a natural hedge produces and sells locally with operating profits per state:

1. $1,000M in U.S. + €500M in Europe at $1/€ = $1,500M
2. $500M in U.S. + €1,000M in Europe at $2/€ = $2,500M

The expected profit is $2,000M, with a variability risk of ± $500M.

Hedge Option 2: a natural hedge combined with a financial hedge that sells 500M future euros for $1.50 per euro (the expected financial return is zero and we neglect small transaction costs). The operating profits per state are:

1. $1,000M (US) + €500M (Europe) + $750M - €500M (future) = $1,750M

2. \$500M (US) + €1,000M (Europe) + \$750M - €500M (future) = \$1, 250M + €500M at \$2/€ = \$2, 250M

The expected profit is again \$2,000M but with a reduced risk of ± \$250M.

Hedge Option 3: an active operational hedge using allocation flexibility: we only produce in the low cost location—in Europe in state 1 and in the U.S. otherwise. The operating profits in each state are:

1. Sales: \$2,000M in U.S. + €1,000M in Europe. Cost: € 1,500M in Europe. Net = \$2,000M - €500 at \$1/€ = \$1,500M
2. Sales: \$1,000M in U.S. + €2,000M in Europe. Cost: \$1,500M in U.S. Net = \$500M + €2,000M at \$2/€ = \$3,500M

The expected profit is \$2,500M, an increase in value of 25% over the passive hedges! Recall that this option should at least require quick response in production (decide where to produce after the exchange rate is observed), which will likely be more costly than Hedge Options 1 and 2.

Hedge Option 4: the active operational hedge of Option 3 combined with a financial hedge would yield an expected profit of \$2,500M with reduced variance.

1.8.4 Differences between financial and operational hedging

A firm can simultaneously use both financial and operational hedging. For example, (4) study integrated operational and financial hedging decisions faced by a global firm who sells to both home and foreign markets. Production occurs either at a single facility located in one of the markets or at two facilities, one in each market. The firm can use financial currency forward contracts to hedge currency risk. To further mitigate currency and demand risk, it can use ex-post operational flexibility.

Sometimes, however, complementing operational hedging with financial hedging may not be possible. For example, the planning horizon for a production facility may exceed 10 years. While operational hedging can be used, it is unlikely that financial hedging is available over that time-horizon. Financial hedging of capacity is also problematic if there is no capacity futures market that can replicate the capacity's cash flows (a swap can always be constructed if a counter party is available).

Whether a company should use both financial and operational hedging is the topic of current academic research. The answer depends on the type of financial contract, the operational system, and the correlation between the underlying financial asset and the operational risk under consideration. With perfect correlation, operational flexibility and financial hedging can complement each other, as Example 1.5 illustrates. Yet the optimal amount of operational flexibility that a firm should invest in depends on whether it engages in financial hedging or not. (2) show that financial hedging with linear contracts increases the desired level of operational flexibility, while option contracts decrease it.

Demand Forecast

Scenario	Afour	Bassat	Probability
1	70	150	5%
2	70	200	10%
3	70	250	15%
4	100	150	10%
5	100	200	20%
6	100	250	10%
7	130	150	15%
8	130	200	10%
9	130	250	5%

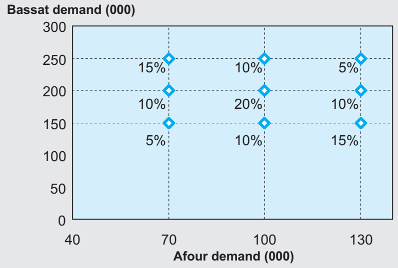


Figure 1.14 The demand forecast for Afours and Bassats. Uncertainty is captured via nine scenarios with associated probabilities. The forecast can be represented in a table (left) or a graph (right).

1.9 TAILORED OPERATIONAL HEDGING

Earlier we said that risk management is an integral part of operations strategy. In this section, we will illustrate how risk management interacts with resource decisions (capacity size and type) and sourcing decisions. Furthermore, we will demonstrate how some generic operational hedging strategies can be tailored to specific situations.

1.9.1 Tailored natural hedging at Auto Co.

To illustrate the concept of tailored hedging, let us analyze how to tailor pure diversification to a particular setting. Consider, for example, a company that faces correlated demand risk, and manufactures two products, each on its own dedicated line. The question is how to size the capacity portfolio to mitigate risk. Mean variance analysis of profits provides an answer.

To illustrate mean variance analysis of a capacity portfolio, consider the stylized Auto Co. example introduced in Chapter 5 in (18) , first in a risk-neutral setting. Auto Co. is introducing two car models, Afour and Bassat. The Afour commands the higher price and unit contribution margin of $2000 versus the Bassat's $1000. Investing in capacity involves a significant fixed cost and a variable cost that increases with the installed capacity size. For simplicity, we will assume that the fixed cost is the same for either product and hence does not impact our technology strategy choice. However, the capacity cost per unit for an Afour dedicated line is $800, slightly greater than the $700 for the Bassat line. The key risk stems from demand uncertainty and Figure 1.14 shows the total demand forecast.

The profit mean and variance for an investment budget of $100 million can be calculated for the demand data using simulation-based optimization. (Easily implemented in a spreadsheet that is downloadable from www.vanmieghem.us). Figure 1.15 plots the results for $100 million investments that vary their allo-

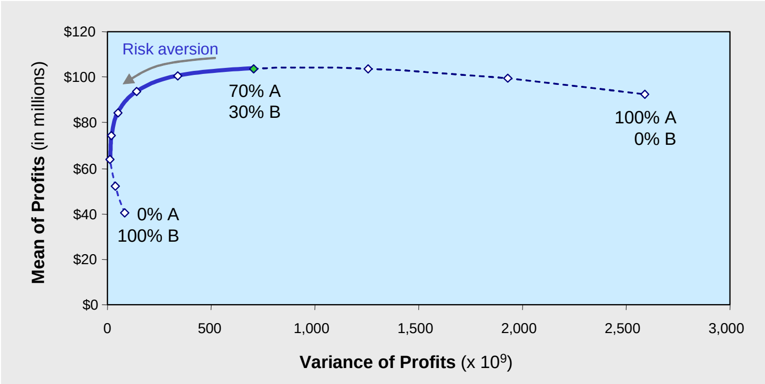


Figure 1.15 Pure diversification results from serving two markets with dedicated resources A and B. The percentages show the relative resource investment for a given budget. A risk-averse manager can operationally hedge by rebalancing towards resource B, which serves the lower profit variance market.

cation to Afour (A) and Bassat (B) capacity. A risk-neutral manager would maximize expected profits by investing $70 million in product line A and the remaining $30 million in B. In contrast, a risk-averse manager should move down the frontier (in bold in Fig. 1.15) and rebalance capacity towards B.

But why B? Given that market A's demand has a standard deviation of $30,000$ with a unit contribution margin of $\$2,000$, the standard deviation of its (budget-unconstrained) contribution is $60 million. Compare this with the $50 million for market B, whose demand has a standard deviation of $50,000$ with a unit contribution margin of $\$1,000$.

The general insight gained here is that firms can tailor their operational hedge by rebalancing dedicated capacities towards the resource that serves the market with lower profit variance. The Auto Co. example shows that this doesn't need to be the market with the lowest demand risk or the highest contribution margin. Rather, it is the product of these two factors that counts. The effectiveness of natural hedging increases as the pooled risks become more similar in magnitude and more negatively correlated. Indeed, a perfect zero-variance hedge would be obtained if both markets had equal profit variances and were perfectly negatively correlated.

1.9.2 Tailored redundancy and dynamic pooling with allocation flexibility at Auto Co.

To illustrate active operational hedging, continue considering the Auto Co. example, enriched with two additional options. First, the firm can borrow investment funds, meaning that it has no budget constraint. Second, the firm

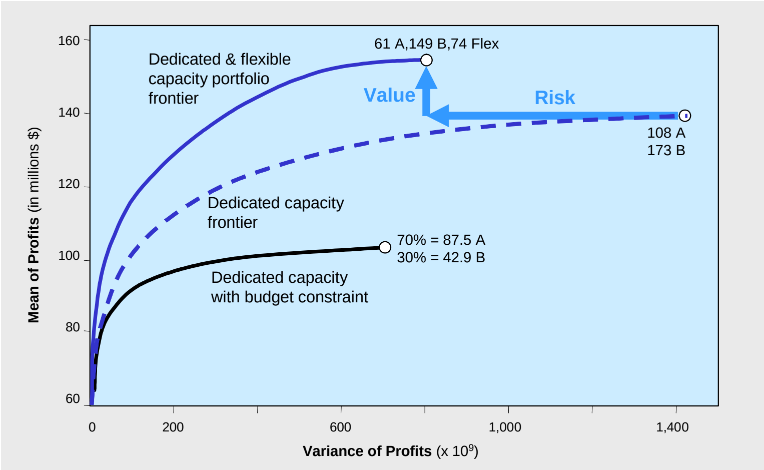


Figure 1.16 Adding flexibility not only mitigates profit variance risk through pooling (frontier is to the left of the dedicated capacity frontier) but also increases value by exploiting upside variations through contingent revenue maximization (frontier is above dedicated capacity frontier).

can not only invest in the two dedicated resources, but also in a product-flexible line. The capacity portfolio now consists of three assets. The flexible line has higher capacity investment costs–the flexible line has the same fixed investment cost as a dedicated line but costs \$900 per unit of annual capacity–but pools *and* exploits demand uncertainty. Given that flexible capacity serves as a substitute to the dedicated resources, it can also be interpreted as a form of adding reserves in the form of adding *redundancy*.

Figure 1.16 shows the magnitude of risk mitigation and the value enhancement of hedging with operational flexibility compared to pure diversification with dedicated assets. The system with the \$100 million investment budget is dominated by relaxed budget constraints: mean profits and profit variance risk increase, thus reflecting higher investments (108,000 A and 173,000 B annual car capacity versus 87,500 A and 42,900 B). In contrast, adding the option of investing in an additional flexible line here cuts profit variance risk roughly by 50% while increasing value by more than 10%. This shows that flexibility is attractive even to risk-neutral investors.

Risk-averse investors can further tailor the optimal operational hedge by rebalancing the capacity portfolio in two directions, as suggested by Figure 1.17 and studied by (17): to do so, they must increase the shares of the flexible capacity and of the resources serving the lower profit variance market (B). The latter reflects the pure diversification effect inherent in pooling, while the former demonstrates the profit variance risk mitigation power of flexibility (notice that the operational hedge can be so powerful that a risk-averse

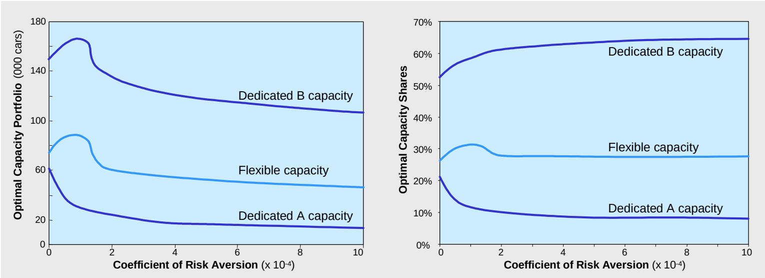


Figure 1.17 Risk-averse managers tailor the operational hedge by rebalancing the capacity portfolio toward (1) more flexibility and (2) resource B, which serves the lower profit variance market.

manager may even increase capacity relative to the risk-neutral levels). The tailored capacity balance depends on the manager's coefficient of risk aversion, as well as on the demand and processing network data.

1.9.3 Tailored operational hedging: base demand, tail-pooling, and chaining

The appropriate capacity mix between flexible and dedicated capacity illustrates another tailoring dimension. Tailored flexibility serves mostly the uncertain part of the demand distribution (also known as tail risk), while most of the predictable "base demand" is allocated to dedicated resources. Benetton provides another example: garment production of its base demand is allocated to a set of efficient subcontractors up to two quarters ahead of the season. Flexible in-house capacity produces garments quickly, thereby minimizing demand risk.

Tailored flexibility also works in service operations. Service representatives may be mostly dedicated to a certain product or region (base demand). As long as the resource-product allocations form a chain, service representatives can help out colleagues who are overloaded. Pooling benefits accrue while specialization benefits are enjoyed the majority of time. (1) show that this "tailored chaining" can outperform the chaining of only bi-flexible resources (first studied by (8)) by balancing specialization (favoring dedicated resources) and pooling (favoring flexible resources) benefits.

Temporal tailoring of scale flexibility allocates quick response capacity to peak demand. Electricity capacity illustrates temporal tailoring in a single product setting: nuclear power serves base demand continuously while various levels of fossil fueled generators (including even jet generators) pick up peak demand.

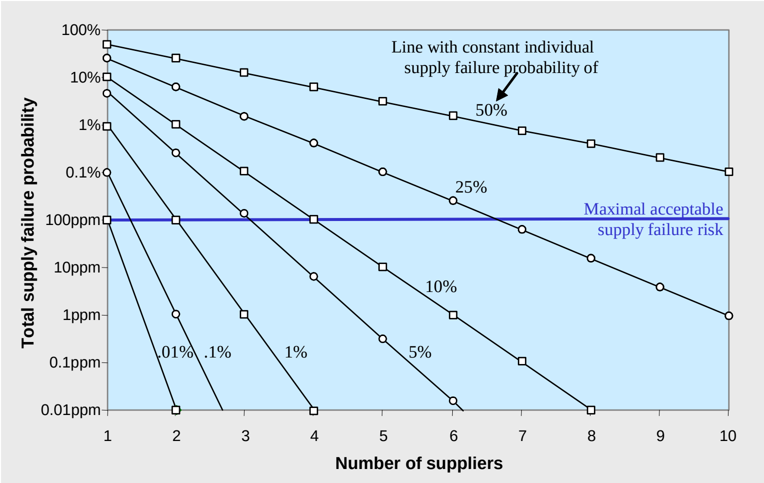


Figure 1.18 Tailored redundancy uses the appropriate number of suppliers depending on the maximal acceptable supply failure risk (100 parts per million here) and the failure probability of an individual supplier.

1.9.4 Tailored redundancy and multi-sourcing for supply and project risk

Multi-sourcing is a powerful strategy to mitigate supply failure risk. Consider the U.S. flu vaccine supply problem in 2004, when a major supplier (Chiron) was forced to close down due to violations of regulatory quality standards. The U.S. had roughly split the majority of its expected need of 100 million flu vaccines over Chiron and one other supplier. Because of the long lead times (about 8 months), it had little recourse; thus, flu vaccines were put on allocation, causing a serious political outcry. This was in marked contrast with the U.K.'s hedged strategy, which uses 6 suppliers for a target demand of only 14 million.

Tailored redundancy selects the appropriate number of suppliers based on the maximal acceptable supply failure risk and the failure risk profiles of individual suppliers. For example, consider the simplest situation where supply risk is all or nothing (similar perhaps to Chiron's flu vaccine problem) and the failure probability p is the same for all suppliers and independent of one another. Supply totally fails only when all suppliers fail. The probability of total supply failure when using N suppliers thus is p^N. Figure 1.18 shows this relationship in a log-linear plot. This determines the minimum number of suppliers needed to diversify supply risk below a maximal tolerable level. Clearly, more suppliers are needed if they are more unreliable or if maximal acceptable risk levels are tighter.

This insight extends to the setting where supply failure is manifested by an uncertain or *random yield* (or probability that a unit ordered is of acceptable quality) and can differ from supplier to supplier. The analysis is much more involved and has only recently been done by (6). They found that total supply should be allocated to a tailored number of suppliers, each supplier's allocation being proportional to the mean-to-variance ratio of that supplier's yield distribution. That allocation scheme also minimizes variable sourcing costs.

Redundancy through common platforms or even parallelism can also mitigate project risk. For example, when Toyota develops a new car, it often produces a large number of prototypes, several of them in parallel (14). It decides which type will eventually be commercialized as close to market introduction as possible, in order to have the product better respond to market needs. While redundancy increases the costs of the R&D stage, it gives Toyota an option to significantly increase project revenues by commercializing the most profitable prototype.

1.10 GUIDELINES FOR OPERATIONAL RISK MANAGEMENT

1.10.1 Implement an operational risk management process

In most companies, risk management is the responsibility of the CFO. In addition to financial risks, companies should also acknowledge, identify, and assess operational risks. Setting up a formal operational risk management process under a senior operations manager is a necessary first step. For example, Grainger has a "business continuity department" of about 15 people that anticipates, evaluates, and mitigates operational risks.

1.10.2 Use a multi-faceted approach tailored to the type of risk and product life cycle

No single size fits all. Risk mitigation should use the right mix of multiple financial and operational hedging strategies, depending on the type of risk. For example, supply risk of short life cycle products is best mitigated with supplier diversification and demand management techniques such as contingent substitution and pricing. For long life cycle products, inventory, contingent supply, and continuous risk monitoring of suppliers may be more appropriate. Make the distinction between intermittent and recurrent supply risks.

Not only the length, but also the stage in the product life cycle determines appropriate tactics. Technical innovation risk in the pharmaceutical industry is mitigated by redundancy (developing several designs in parallel), faster and earlier drug trials (testing), and retaining flexibility so important decisions can be postponed (e.g., by using modular facility construction).

1.10.3 Use a portfolio approach

While each risk needs a tailored response, remember that the organization's total risk exposure enjoys portfolio diversification benefits. Such a portfolio approach often justifies investment in redundant assets or more expensive flexible assets.

1.10.4 Realize that operational hedging may incur additional costs

There is no such thing as a free lunch. The benefits of operational hedging may involve additional hidden costs. For example, multi-location processing incurs a loss of scale, requires procurement from a wider supply base, slows down the learning curve process, and may produce less-consistent quality. Good risk management tries to reduce these costs over time.

1.10.5 Reducing risk is more powerful than mitigating exposure

In the long run, reducing and eliminating sources of risk is often more profitable than mitigating their impact with fences, counterbalancing actions, or band-aids. For example, exposure to demand uncertainty can be mitigated through pooling and reserves like safety inventory or capacity. Yet, initiatives like lead time reduction, postponement, quick response, better forecasting, and information sharing reduce the demand uncertainty (and with it, the need for mitigation).

Operations management has a rich heritage in eliminating the root cause of "problems" as illustrated by the success of the Toyota Production System and continuous improvement programs such as lean operations, Six Sigma, and total quality management. Such operations improvement programs, which we will study in the next chapter, should be an important component of any risk management program.

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