Flexibility in Engineering Design

Richard de Neufville and
Stefan Scholtes

ENGINEERING SYSTEMS

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To
Ginger, Julie, and Robert
and
Ingrid, Lukas, Philipp, and Alexander

Contents

Series Foreword

Engineering Systems is an emerging field at the intersection of engineering, management, and the social sciences. Designing complex technological systems requires not only traditional engineering skills, but also knowledge of public policy issues and awareness of societal norms and preferences. In order to meet the challenges of rapid technological change and of scaling systems in size, scope, and complexity, Engineering Systems promotes the development of new approaches, frameworks, and theories to analyze, design, deploy, and manage these systems.

This new academic field seeks to expand the set of problems addressed by engineers, and draws on work in the following fields as well as others:

- Technology and Policy
- Systems Engineering
- System and Decision Analysis, Operations Research
- Engineering Management, Innovation, Entrepreneurship
- Manufacturing, Product Development, Industrial Engineering

The Engineering Systems Series will reflect the dynamism of this emerging field and is intended to provide a unique and effective venue for publication of textbooks and scholarly works that push forward research and education in Engineering Systems.

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Introduction

This book focuses on the challenge of creating best value in large-scale, long-lasting projects. It does this by directly confronting the central problem of design: the difficulty in knowing what to build, at what time. Indeed, to get the best value, we need to have the right facilities in place, when we need them. However, we cannot know what will happen in the future. No matter how hard we try to predict long-term requirements, the forecast is "always wrong." Trends change, surprises occur.

To achieve the best results, we need to adapt to circumstances as they arise. We need to have designs that we can modify easily to take advantage of new opportunities—or to mitigate adversities. The future is uncertain. Design that does not account for a range of possibilities that may occur over a long lifetime runs the risk of leaving significant value untapped—or incurring major losses. An uncertain future provides a range of opportunities and risks. We can deal best with these eventualities and maximize our expected value if we build flexibility into design.

This book helps developers of major projects create value by using the power of design flexibility to exploit uncertainties in technological systems. We can increase the expected value of our projects significantly by designing them cleverly to deal with future eventualities. Flexible design greatly increases our opportunities for success, as this book illustrates throughout. Designs we can adapt to new circumstances enable us to avoid downside risks and exploit opportunities. We can use flexible design to improve our ability to manage financial and social risks and opportunities. Technical professionals who can plan and execute a project to adapt to new circumstances can substantially increase the value obtained.

This book is for all current and future leaders of the development, operation, and use of large-scale, long-lasting engineering systems. Your current or prospective responsibilities may include, but are not limited to, projects implementing:

- *Communication networks* Fiber-optic cables, cellular devices, and fleets of satellites;
- *Energy production, transmission, and distribution* Thermal and nuclear generators, hydroelectric plants, wind farms, and other renewable energy sources;
- *Manufacturing* The production of aircraft, automobiles, computers, and other products;
- *Real estate* Residential and commercial high-rise buildings, hospitals, and schools;
- *Resource extraction* Oil exploitation and refining, mining, and smelting;
- *Transport* Airports, highways, metro lines, high-speed rail, ports, and supply chains; and
- *Defense systems* Aircraft, ships, and armaments of all kinds.

The common feature of these long-lasting engineering projects is that they are all subject to great uncertainties. It is impossible to know circumstances and needs 10, 20, or more years ahead. Moreover, technology changes rapidly and disrupts previous assumptions and forecasts. New technologies both create new opportunities and make previous investments obsolete.

This book is for the entire project team, including current or prospective:

- *Designers* The engineers and architects who create the physical implementations;
- *Financial analysts* The estimators of the value of different designs and so shape them;
- *Clients* The owners, public officials, and program managers accountable for the projects;
- *Investors and lenders* The shareholders, banks, pension funds, and others providing the capital for the investments;
- *Managers* The controllers of the facilities as they evolve over their useful life;
- *Users* The operators over the system, such as airlines benefiting from air traffic control facilities, or the medical staff of a hospital; and
- *Regulators* The authorities responsible for safeguarding the public interest in these projects.

Members of the project team all share the common challenge of creating and implementing flexibility in design. To succeed, they need to work together over time. A clever design that can adapt to new opportunities will prove fruitless unless the system managers understand the design and can organize to use it. Conversely, the best system managers may have little scope to cope with unforeseen circumstances if the designers have not configured the project with the flexibility to adapt. Thus, even though team members may participate in the development and operation of the system at different times, and may not deal with each other directly, they all need to work together to achieve the best results for the system.

Flexibility in design maximizes the expected value of a system over time. It enables owners and operators to adapt the system for optimal performance as its requirements and opportunities evolve over its useful life. Project team members will thus be most effective when they work together to integrate planning, design, and management activities from conception to eventual shutdown of the project. Creating best value in large-scale, long-lasting projects requires a sustained team effort. Success involves more than applying special techniques; it entails a way of thinking about systems and implementing them. Flexibility is a fundamental approach to systems design.

Organization of This Book

This book is intended to suit a range of readers interested in using flexibility to improve the value of complex engineering systems. It has three parts.

Part I provides a high-level overview of the concepts and methods of flexibility, why it is necessary, and how it delivers value. It gives sufficient information to senior leaders who want to understand the general issues around flexibility. It also motivates the later chapters, which examine elements of the overview in greater detail.

Part II presents the methods needed to identify, select, and implement the kinds of flexibility that provide the best value. This section is for designers and analysts who need to justify and implement flexible design. It covers the range of necessary techniques: procedures to forecast and anticipate a range of uncertainties; methods to identify the most promising kinds of flexibility to use; tools for evaluating and choosing the best flexible designs; and ways to implement flexible designs successfully over the life of the project.

The appendices in the last part of the book provide more detailed supporting explanations of the analytic tools and concepts used to identify and justify flexibility in design. Readers may benefit from one or more of these appendices depending on their interests and needs. The appendices present brief but comprehensive presentations of the mechanics of economic evaluation and discounted cash flows, the economic rationale for phased development, the mechanics of statistical analysis used in forecasting, the process of Monte Carlo simulation to explore complex scenarios, and the basic financial concepts of options analysis. Importantly, they provide a detailed discussion of the "flaw of averages," the conceptual pitfall that traps so many designs in underperformance.

I

HIGH-LEVEL OVERVIEW

1

Flexible Design: Its Need and Value

> We don't even know what skills may be needed in the years ahead. That is why we must train our young people in the fundamental fields of knowledge, and equip them to understand and cope with change. That is why we must give them the critical qualities of mind and durable qualities of character that will serve them in circumstances we cannot now even predict.
> —John Gardner (1984)

The Future Is Uncertain

Technological systems can quickly become obsolete. New developments continually arise to displace established technologies. What was state-of-the-art yesterday may be out of date tomorrow. We see this in our everyday lives. Consider the distribution of music, for example: In a few decades, it has gone from vinyl records, to tapes, to CDs, to downloading tunes wirelessly onto miniature portable devices.

What happens to consumers also happens to large industries. The recent development of global communications offers several examples of unexpected rapid change. Much to the surprise of their developers, the Iridium and Globalstar satellite telephone systems were obsolete the moment they came into being—ground-based cell phones had become universal (see box 1.1). The examples continue: Wireless is substituting for landlines; satellite broadcasting is eliminating the need for local stations. Disruptive technologies pervade our lives.

Unexpected changes can create both gains and losses. System designers often equate uncertainties with risks—and therefore with bad things. However, uncertainties can also create new opportunities. As the Internet has shown us, unexpected changes can create benefits that the original developers did not imagine. The future is as much about opportunities as risks. The examples in box 1.1 indicate that when thinking about uncertainties, we should not simply worry about downside risks—we need to keep upside potential in mind.

Box 1.1
Technological surprises

The Iridium Fleet of Communication Satellites

This case illustrates the sensitivity of technological projects to rapid changes in context. The Iridium fleet of communication satellites was a superb technical development—but a miserable financial failure.

Iridium originally consisted of more than 60 satellites that communicated with one another and any point on earth. It provided consumers with wireless telephone service from any location to any other, provided they took the three-pound satellite phone outdoors. Motorola designed Iridium in the late 1980s and deployed it a decade later. By that time, it was commercially obsolete—cell phone technology had swept the market.

Iridium went bankrupt and sold for $25 million, about 1/2 percent of the $4 billion investment.[1]

Global Positioning System (GPS)

The U.S. military originally developed GPS to control long-range missiles. The heart of GPS is a fleet of satellites constantly beaming signals, like lighthouses in the sky. Receivers can automatically triangulate these beams to locate themselves very precisely. Such chips are now commonplace in civilian applications. For example, aircraft can position themselves accurately when no radar is available. Cell phones have GPS. Drivers and hikers use GPS to find their way in remote areas.

GPS has created tremendous opportunities and value in ways unsuspected by the original designers. Because they did not anticipate this tremendous commercial success, they did not build the original GPS with any capability to benefit from it—they did not incorporate any way to charge a fee for the service.

New technology affects the value of investments directly and indirectly because of the way it changes patterns of demand. Advances may have complicated, unanticipated ripple effects. Improved health care, for example, has increased life expectancy, which in turn has contributed to a greater population of older patients with chronic diseases and complex co-morbidities. In general, the ultimate impacts of technological developments are complex and uncertain.

The potential benefits of any venture also depend on the vagaries of markets and many other factors. A copper mine may be lucrative if the price of copper is high but not worthwhile if demand changes and prices drop. The benefits of any process also depend on its productivity; the skill, experience, and commitment of staff; the success of marketing campaigns; the speed of diffusion of use; and many other factors.

As this chapter shows, the bottom line is that we cannot count on accurately forecasting the long-term benefits and costs of technological systems. In general, the future value of these investments is highly uncertain. This is the reality that confronts designers, analysts, clients, investors, managers, users, and regulators.

Standard Methods Are Inadequate

Unfortunately, design methods do not deal with the reality of rapid change. Standard practice proceeds from a set of deterministic objectives and constraints that define what designers must accomplish. These mandates go by various names: Systems engineers think of them as "requirements," architects refer to "programs," and property developers and others think in terms of "master plans." By whatever name, these restrictions channel designers toward a fixed, static view of the problem. In the case of the Iridium communications satellites, for example, the designers sized the fleet for worldwide use assuming 1 million customers in the first year of operation—they made no provision for the possibility of far fewer customers or a narrower service area. Likewise, in the extractive industries, it is usual to base design on an assumed long-term price of the commodity despite the fact that the prices of raw materials fluctuate widely. In practice, we "design to specification" when we should "design for variation."

In the same way, standard procedures for selecting designs generally do not deal with the possibility of change. The standard methods for ranking possible choices refer to the "cash flow" of an investment, that is, to the stream of benefits and costs that would occur in each period of the project if the conditions assumed were to exist. In practice, the evaluation process usually discounts this unique flow and brings it back to a reference time to create measures such as the net present value (NPV), the internal rate of return (IRR), or the benefit/cost ratio (see appendix B for details). None of these approaches recognizes two routine features of large projects:

- The assumed conditions, such as demand and price, constantly change; and
- Management might—and it generally does—eventually decide to change the system in response to new circumstances.

Therefore, the initial business case analysis used to select design solutions often falls apart later on in the project. Consequently, the path chosen for the project may be less than optimal.

The Standard Methods Are Passive

Standard methods do routinely explore how designs might react to new circumstances and how these might change future benefits and costs. Analysts calculate how various important factors—prices, market share, and rate of innovation—affect the cash flows and overall value of the projects configured to satisfy stated requirements.

The standard process designs projects based on a limited set of assumptions and then considers uncertainties. The focus is on creating robust designs that will perform satisfactorily under various uncertainties and possible stresses. This reflects a bunker mentality: Will we be able to survive adverse futures? Will we be able to sustain risks?

The standard process does not design with the uncertainties in mind. System designers do not generally explore how changes in specifications and market factors might change the design itself. The examples in box 1.2 illustrate what happens. In short, the usual design and evaluation procedures focus on an unrealistically narrow description of the possibilities.

Box 1.2
Standard design based on fixed assumptions: Oil platforms

Deep-water platforms for extracting oil and gas from sub-sea reservoirs, as in the Gulf of Mexico or offshore of Angola, can cost several billion dollars each.

The usual practice is to mandate designers to choose projects using a fixed price of oil, even though it varies widely and events have proven trends to be unreliable, as figures 1.1 and 1.2 show.[2] (The price assumed is a closely guarded corporate secret because of its importance in contract negotiations. It represents assumptions about longer-term prices and thus differs from immediate spot prices. It also varies by company and over time.)

The effect of assuming a fixed price is to ignore oil fields that would be profitable at higher prices. This means that when prices are high and exploiting secondary fields might be worthwhile, the platforms do not have easy access to these valuable reservoirs. Their exploitation would require a completely new project, which may not be economically feasible. The owners thus miss opportunities that a flexible, easily adjustable design would exploit.

Box 1.2
(continued)

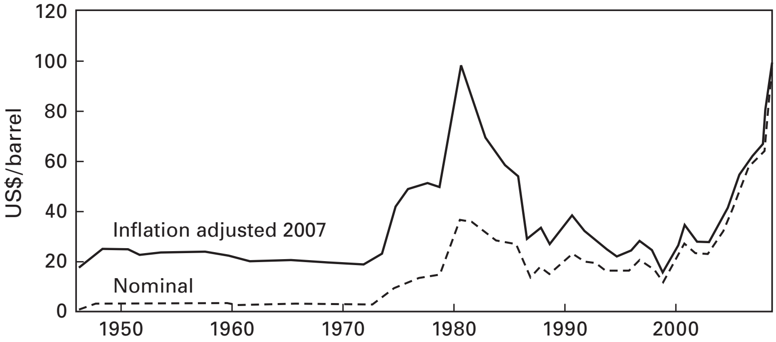

Figure 1.1
Historical prices of crude oil, both in nominal and constant value dollars. Notice how the "trends" have frequently changed direction substantially: constant prices until 1973, a sharp run-up over the next decade, followed by a decade of falling prices and the more recent reversal.
Source: US Energy Information Agency, 2010.

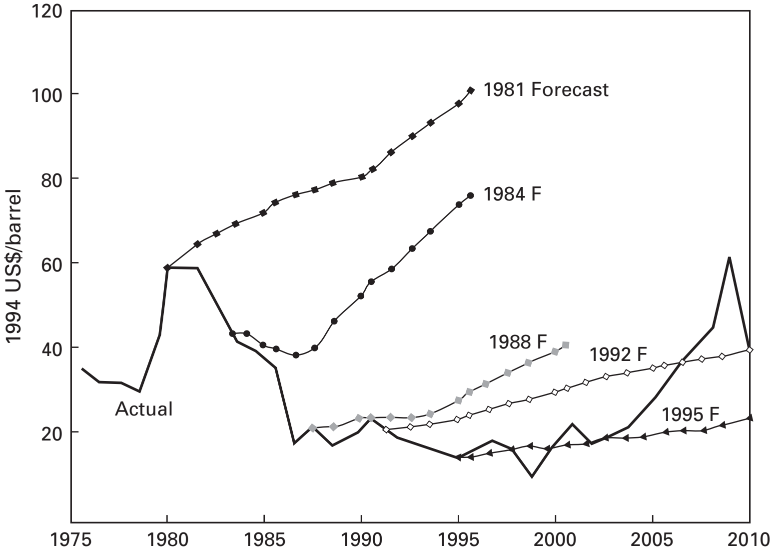

Figure 1.2
Forecasts of oil prices compared with actual prices. Notice how expert estimates failed to anticipate reality, even in the short run.
Source: U.S. Department of Energy, compiled by M. Lynch.

The Standard Process Ignores Intelligent Management

The standard sensitivity analysis of a fixed design to alternate scenarios does not go far enough. It leaves out a crucial reality: The owners and operators of a project are intelligent. They will alter the design to suit the situations that actually develop, they may cut their losses by exiting from a project, and they may increase their profits by taking advantage of new opportunities. They will in any case respond actively to new circumstances rather than submitting to them passively, as standard evaluation procedures assume.

There is thus a great mismatch between what actually happens to a project over the span of its existence, as the system owners attempt to maximize its value, and standard ways of valuing and choosing between alternative designs. The reality is that future benefits and costs are uncertain, future adaptation to evolving circumstances is commonplace, and designers face a broad range of possible circumstances. Yet the standard valuation procedures assume that designers can design adequately around a single concept of future benefits and costs—and that users will not deviate from such a plan.

This mismatch matters. In general, there is a great difference between the value associated with the reality of many possible futures and the value calculated on the assumption of a single future. This gap exists because equal up-or-down variations in the imagined futures do not translate into equal variations in values. All the possible futures do not average out happily to the most likely cash flow. It is a fundamental mistake to assume that the average project value can be calculated on the basis of cash flow derived from average project conditions: This is when we fall victim to the "flaw of averages" (see chapter 2 and appendix A). It is imperative for designers to deal with the broad range of possible futures. Failure to recognize this leads to incorrect valuations of proposed projects and erroneous project selection. The design that appears best under standard analysis may be second rate.

Intelligent Management Anticipates Many Futures

Once we recognize that the future is uncertain, the intelligent thing to do is to prepare for its various possibilities. For example, if it looks like rain when we go out, the commonsense approach is to take an umbrella. "Be prepared" applies not only to our personal life but also to our professional practice.

Intelligent management anticipates and plans for a range of possible futures. It recognizes that it will react to circumstances as they change and so will prepare the way for this reality. Rather than react passively to what may come, it facilitates proactively the possibility of effective, timely responses to eventualities. It recognizes the possibility of risks and prepares exit strategies or other forms of insurance against their consequences. It also recognizes that advantageous opportunities may arise and anticipates ways of enabling the system to seize these benefits easily.

Intelligent Management Needs Design Flexibility

Flexible designs enable systems owners and managers to respond easily and cost-effectively to changing circumstances. Flexible designs come in many forms, each enabling different kinds of responses. In general, the system should incorporate several kinds of flexibility to protect against the range of different hazards and to exploit any opportunities that develop.

For example, the design of a car routinely incorporates many different flexible elements. It will have some kind of spare tire and jack in case there is a flat. It will have air bags to protect the occupants in case of a collision. It may have collapsible or removable seats in case the owner needs to carry oversize equipment. It might have a trailer hitch to enable users to attach things they might want to tow. In short, the modern automobile incorporates a range of flexibilities, enabling owners to mitigate downside risks and take advantage of upside opportunities.

Flexible designs fall into three major categories: those that enable the system to change its size, those that enable changes in function or capability, and those that protect against particular failures or accidents. For example:

- *Changes in size* A design might be modular to permit the easy addition of capacity. A modular design might also facilitate contraction in capacity; for example, closing areas of an airport terminal during off-peak seasons when the capacity is not needed.
- *Changes in function* The system might permit users to remove or add function. The design of a computer system is flexible with regard to both its hardware and software. Its USB ports enable users to upgrade from simple printers to multifunction devices, including scanners and fax

machines. Its open software enables users to install voice over the Internet and transform their machine into a telephone.

- *Protection against accidents* Systems normally feature a range of ways to protect against risks. These include protective systems, such as seat belts and airbags in cars. Redundant devices to back up a possible failure of key components are routine, such as second (and third) computers on aircraft.

In general, flexible designs include features that enable the system to respond to a range of possible circumstances, either automatically or under the direction of system managers.

Flexibility in Design Increases Expected Value

As both theory and many case studies demonstrate, flexible designs that are "prepared" for future possibilities can add great overall value to a project. Flexible designs enable owners, managers, or operators to adjust the design to new circumstances. When the future is unfavorable, they can avoid bad consequences. When the future offers new opportunities, design flexibility will enable them to take advantage and benefit from those possibilities (see box 1.3).

Flexibility in design can easily lead to significant improvements in overall expected benefits. The case studies we report in this book show increases of up to 80 percent in expected value. Flexibility provides a two-fold advantage: it limits possible losses and increases possible gains. Both actions increase the overall average value of a project. Even relatively small opportunities to make major gains or avoid disastrous losses can cumulate to important gains on average. For major projects costing billions, the combined value of flexibility in design can be worth hundreds of millions (see box 1.4).

Because we necessarily have to deal with an uncertain future, the value of any project is not a fixed number but an expectation over a range of possible futures. We can think of it as an average value over a range of good and bad outcomes. For this reason, design flexibility does not provide the best design under all circumstances. It would be cheaper, for example, to have a car without airbags and a spare tire—and this would be the better solution for the driver who never had an accident or a flat tire. Flexibility in design aims to provide improved solutions overall.

Sometimes a system will not use its flexibility, and its cost might be considered a waste. As for insurance, the value of flexibility has to be

Box 1.3
Flexible design: Tagus River Bridge

The Ponte de 25 Abril, the first bridge over the Tagus River at Lisbon, offers a good example of flexibility in design. The Salazar dictatorship inaugurated it in 1966 with a single deck for automobile traffic but with the strength to add a second deck at some future time. Moreover, they also built a railroad station under the toll plaza to minimize disruption in case Portugal ever decided to build rail connections.

A generation later, Portugal was a democratic member of the European Union, which allocated funds to develop commuter rail services throughout the region, and in 1999 the bridge received a second deck that carried these lines.[3]

When first built, designers of the bridge recognized that its ultimate capacity could be larger. Instead of trying to anticipate specific future requirements, they built for immediate use, with the flexibility to develop in many ways. Even if the original designers had tried to define future requirements, they could hardly have imagined the overthrow of the dictatorship and the development of the European Union.

The flexible design of the bridge saved money by not building too early or building unnecessary highway capacity. It also enabled Portugal to take advantage of the support of the European Union to extend rail traffic across the river.

judged in terms of its contributions over all possible futures. Both insurance and flexibility are justified by the value they bring when relevant events occur, not by their continual use. At the right price, we happily buy life and accident insurance every year and never complain about our failure to claim on these policies. It is the same with flexibility: Its value lies in helping us avoid bad situations or enabling us to benefit from opportunities in the right circumstances, not in whether we use it. Taking the proper overall perspective, flexible designs provide very significant opportunities for major increases in expected value.

What This Book Does

The book gives the leaders of major projects what they need to know to create value in technological systems by using the power of flexibility to deal with uncertainties and take advantage of them. It shows how project leaders can:

- *Recognize uncertainty* by replacing usual point forecasts with projections of realistic ranges of possible future outcomes;

Box 1.4
Flexibility leads to major gains: Satellite fleet

A detailed analysis of alternative ways to deploy geostationary satellites over different regions showed that a flexible system design, which enabled system operators to reposition satellites as demand for broadcast services changed, greatly outperformed the system "optimized" for the specified "most likely" pattern of demand.[4]

As table 1.1 shows, flexible design increases overall expected value. Instead of launching the final fleet right away, systems operators initially launch a smaller fleet, reducing initial capital expenditure, and therefore the amount at risk and potential losses. The flexible design, however, allows the capture of the upside, too, when operators deploy the second module, sized and located according to actual need, thereby obtaining a maximum value if demand exceeds initial capacity.

Table 1.1
Comparison of value of "optimized" and flexible designs for a satellite fleet

	Present value, $ millions			
Design	Expected	Maximum	Minimum	Fixed cost
"Optimized"	49.9	192	–162	–393
Flexible	95.8	193	68	–275
Which better?	Flexible	Flexible	Flexible	Flexible

The design "optimized" for a single forecast performs poorly on average across the range of possible scenarios.
Source: Hassan et al. (2005)

- *Identify desirable kinds of flexibility* that will enable the system to deal with the kinds of uncertainties it faces;
- *Understand and communicate the way flexibility adds value* to design;
- *Estimate the specific value that flexibility* contributes to their project; and
- *Implement a development strategy* that profitably exploits the advantages of flexibility.

In a nutshell, the book develops critical thinking about flexible design and provides a framework for presenting flexible designs.

The central message is that designing a system with the flexibility to adapt to future needs and opportunities greatly increases its long-term expected value, compared with standard traditional procedures for developing and implementing projects. In this book, we demonstrate this point with a wide range of practical applications.

Our book is pragmatic. It shows how project leaders of technological infrastructure can achieve extraordinary benefits, avoid future downside risks, and profit from upside opportunities by building flexibility into their designs. It provides a four-step process for developing design flexibility:

- *Step 1* Recognize the major uncertainties the project or product is likely to encounter. This step identifies the kinds of situations where flexibility in the system might help.
- *Step 2* Identify the specific parts of the system that provide the kind of flexibility best suited to deal with the uncertainties recognized in step 1.
- *Step 3* Evaluate alternative flexible designs and incorporate the best into the design.
- *Step 4* Plan for eventual implementation of the chosen flexibilities by both making arrangements with the stakeholders in the process and monitoring the conditions that would indicate whether and when to exercise the design flexibility and adapt the system to new circumstances.

Box 1.5 illustrates the process, which we describe in detail in part II.

Box 1.5
Application of the four-step process: High-rise building

Many developers have used "vertical flexibility" in the design of their buildings. The development of the Health Care Service Corporation building in Chicago (figure 1.3) illustrates the process.[5] The original design for this building had the strength, the space for elevator shafts and stairs, and the planning permissions to add 24 more stories to the original 30-story skyscraper built in the 1990s.

The four-step process proceeds as follows:

1. *The architects/developers recognize the client's uncertainty* about the amount of space needed, for example, because it is not possible to be sure about long-term growth or how zoning regulations might change to allow greater height.
2. *They identify that vertical flexibility is the only realistic possibility* because they cannot increase the ground area available for development.

Box 1.5
(continued)

3. *They explore numerous design alternatives*, involving different numbers of floors for the first and subsequent possible additions, estimate how each might perform under the range of future scenarios, and choose the arrangement that provides the best set of metrics overall.

4. *They plan for implementation* by making arrangements with the multiple stakeholders involved in the execution of the vertical flexibility and monitoring developments to determine when (and if) they should use their design flexibility. They obtain planning permission for expansion, operational support from the tenants, financial commitments from the bankers, and so on. They then keep track of their needs for additional space. The owners inaugurated the additional phase in 2010.

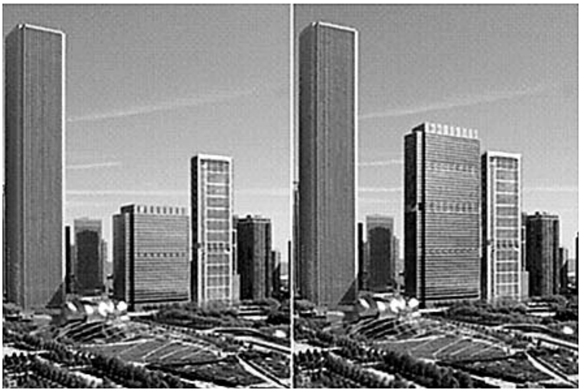

Figure 1.3
Vertical expansion of Health Care Service Corporation Building in Chicago in center of image: phase 1 (left) and phase 2 (right).
Source: Goettsch Partners release to Wittels and Pearson, 2008.

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