Contributions to Management Science

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Executive Decision Synthesis

A Sociotechnical Systems Paradigm

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A Sociotechnical Systems Paradigm

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To
My Father and Mother,
Sisters and Brother
Victor Tang

Preface

What This Book Is About

This book is about a new **prescriptive** paradigm for executive-management decisions under uncontrollable uncertainty conditions. *Prescriptive* means that we present actionable methods and procedures to prepare executives to design their decisions so that the choices they make will produce their intended outcomes. Without sacrificing theory, we concentrate on efficacy and usefulness. We define *executive* as one who has been appointed as responsible and accountable for an organizational mission of a depth of control that is at least three layers deep. MIT Institute Professor Joel Moses describes this as the "middle, up, and down" management, simultaneously top-down and bottom-up. An executive is the one single individual who has been empowered to commit resources to implement and execute a decision. This is the executive as a decision-maker. In every organization, decision-making is a *power reserved.* The authority to take a decision and the right to commit resources for implementation are delegated by a more senior executive, to whom the decision-maker must answer to. This reserved power, once granted, is a right, an obligation, and a privilege. It marks the executive as someone who can be trusted with people and resources. In the military, this is the power to *command.* It follows that our prescriptive paradigm and its methods do **not** make decisions. It is the executive who makes decisions. Our paradigm informs executive management who must then make thoughtful and meaningful judgments in their exercise of their executive powers. And for the consequences of their actions, the executive alone is both responsible and accountable. Their impact on the economy, organizations, and individuals is hard to underestimate. Their decisions, although rich in opportunities, are also fraught with uncertainties and difficulties. These challenges are especially acute in today's global economic environment made difficult and complicated by geopolitical uncertainty and instability.

Executive decisions are more than the **events** of decision-making. Executive decision synthesis and management are a life-cycle process. We concentrate on the *decision synthesis* nexus of the life cycle, without neglecting other stages of the life cycle. Decision synthesis is the creative act of design, requiring judicious choice of existing sociotechnical elements to create new and novel solutions to situations that demand resolution. Synthesis is the theory and praxis that engineers use to design *physical* artifacts. We extend the engineering design synthesis paradigm to executive decisions. Unlike engineering of physical products, decision synthesis deals with nonphysical artifacts. A decision is an intellectual artifact. Nevertheless, as in the engineering of physical products, decision synthesis yields a *specification*. A specification is a blueprint for action, a declaration of intent. Hence, *we consider an executive decision, as a specification*. Synthesis, by definition, assumes that existence of elemental parts from which a new whole can be embodied. In our paradigm, the elemental parts are the managerially controllable variables and the managerially uncontrollable variables. Scholars call these the *essential variable*s. The set of managerially uncontrollable variables create uncertainty conditions that impacts every decision. By defining a range of *uncertainty regimes*, *viz*., articulated configurations of the uncontrollable variables, we render the uncertainty space tractable for analysis. Using controllable and uncontrollable variables, we can represent any decision alternative under any uncertainty condition. The construct for the solution space is defined in this way.

Design and synthesis of physical products have the luxury of the laws of physics to inform and guide their design. This luxury does not exist with sociotechnical systems. Physical products and systems are guided and informed by *working principles* grounded on physics, geometry, material characteristics, and the like. These working principles must eventually be combined into a working structure that embody a product. In engineering design, these working structures are specified a priori, from which performance can be deduced and analyzed. This is the luxury of the *ex ante* analytic modeling approach. In contrast, for executive decisions, which are generally complex, messy, and wicked, an *ex ante* analytic model is often not feasible, except for *tame* problems. Therefore, we adopt a *phenomenological* strategy and determine the behavior of the sociotechnical system using ***gedanken experiments***. From experimental data, we obtain, by induction, a phenomenological representation of the sociotechnical system. This is an *ex post* strategy. Executives do not make decisions void of information; rather, they rely on input from trusted advisors, technical experts in the subject matter, and their working staff. Using parsimonious sampling data from a group of experts, we can infer the behavior of the sociotechnical system under a range of uncertainty regimes. Moreover, statistical data will reveal to us whether the variables selected are good predictors of outcomes and whether they satisfactorily explain the outcomes. We use the engineering discipline of Design of Experiments (DOE) to uncover the phenomenological behavior of a sociotechnical system. The experimentation is performed using *gedanken* experiments. The sampling efficiency can be enormous. In our example in Chap. 9, for a complex and complicated problem, the sampling efficiency is 99.9931%. Using this sampling data, we can predict the outcome and its associated standard deviation, for **any** decision alternative, under **any** uncertainty regime. *Our application of DOE for this class of problems is among the first of its kind.*

Nobel Prize work on behavioral economics reveals that people have biases that systematically distort judgments. To address this exposure, we formulate our unique *debiasing procedure* for the collection of our sampling data. The goal of debiasing is not to drive consensus, which can lead to *group think, risky shifts, herding*, and other dysfunctional group behaviors. Rather, the goal is to reduce information asymmetry by presenting complementary reasoning to a group and supporting logic so that persons can expand their problem understanding, reduce gaps of their mental models, and correct distorted judgments. The emphasis is on the semantics and pragmatics of the data rather than the lexical value of the data.

Armed with debiased data, we can design alternatives that can address and predict outcomes and standard deviations any region *anywhere* in the solution space and *anywhere* in the uncertainty space. This is an unprecedented capability that enables *unconstrained* exploration of any variety of decision alternatives. It enables analysis of an *unconstrained* number of hypothetical *what-if* questions under any desired uncertainty regime. Moreover, decisions can be designed to be **robust**. This means that their performance **satisfices** even when the causal negative conditions are **not** eliminated. This kind of immunity to uncertainty is a highly desirable property for executive-management decisions because it reduces downside risk while still being able to sufficiently capture upside opportunities.

Our prescriptive methodology consists of systematically actionable processes. We consider executive decisions as ***engineered intellectual artifacts*** that are deliberately planned, designed, and enacted to produce intended outcomes. *We consider the organization that must implement the decision specification as a production system, a manufacturing factory.* The organization and its sociotechnical processes are part of a decision factory, ***and a production facility***. It is this sociotechnical composite that generates the intended outcomes. The quality of the input data, of the output, and of the production system all need to be measured and evaluated. We call our measurement schema the ***4-R*** system. The ***4-R***s are robustness, repeatability, reproducibility, and reflection. We use the Gage R&R method to measure reproducibility and repeatability, the ability to arrive at the same subjective assessment no matter the expert advisor and no matter what point in time the information is generated.

To address all the above systematically, this book is comprised of four parts. Part I— Motivation and Foundations, Part II—Verifying Functionality, Part III—Verifying Efficacy, and Part IV—Summary and New Research Findings. The creation and development of our paradigm is like the demanding development of a new pharmaceutical medication. The drug must first be shown to be effective in the development laboratories. Then it must be shown to work in clinical trials with people, in the field. Only then is the drug **ready for** use and **ready to** use. To demonstrate readiness, we develop a metrology and a systematic ***readiness-level*** measurement scale and system. *This decision readiness-level assessment is a first in the field of decision theory and practice.*

Part I—Motivation and Foundations presents our fundamental premise for the ***sociotechnical synthesis*** paradigm and ***gedanken experimental*** strategy for executive management decisions. We take a life-cycle approach of the process and argue that the sociotechnical processes, which implement the decision, are a production system. We argue that uncertainty and complexity are the key issues that need to be addressed. Therefore, processes to address uncertainty effectively are key areas we emphasize.

Part II—Verifying Functionality is to show that our paradigm and its methodology are actionable and effective in our internal development environment. Namely under a controlled environment, they are ***ready-to-work*** by an executive's organization. We show how to systematically test and calibrate the r*eadiness level* of our paradigm. Verifying that a prescriptive paradigm is *ready*-***to***-*work* is the responsibility of the creators of the methodology.

Part III—Verifying Efficacy *in situ* shows that that our paradigm and its methodology will work in a customer environment. Namely our prescriptive paradigm is ***ready-for-work*** for an executive's specific real-world decision situation. Readiness ***for work*** must be systematically tested and measured. Verifying that a prescriptive paradigm is ***ready-for-work*** is the responsibility of the perspective client *in situ*. To that end, we tested with three organizations of global scale and scope—a high-technology contract manufacturer, a Japanese service company, and the US Navy. With these cases, we cover three key industry sectors— high-tech manufacturing, high-tech services, and national defense.

Part IV—Summary and New Research Findings. We summarize our systematic executive-decision paradigm and make a case for the reasons why it is functional, effective, and useful as a prescriptive paradigm. We discuss new areas of research opportunities that our work has uncovered.

Intended Audience

This book is intended for four groups. The first consists of executives and practitioners. Executives can profitably read chapters for understanding, especially introductory material, chapter summaries, and Part IV. Those more technically inclined can read to master the methods and procedures. Executive staffs and functional executives, who report to senior executives, will profit from detailed understanding gained by hands-on applications of the methodology. No more than elementary statistics and algebra are required to gain proficiency in the methods. The material is best understood by actual application to real problems, in a hands-on team effort, rather than reading as if it were a textbook. We recommend learning-by-doing. Although the material may look arcane, the doing is simpler. The idea is no different than baking a cake. Reading the recipe is always more challenging than just following the recipe. There is no substitute for the satisfaction of baking a cake.

Second, the book is also intended for MBA students who are motivated to master a new, novel, and distinct methodology—one that addresses a problem with a fresh paradigm. Part I should be read as a prerequisite. The book's case studies, Part III, can be selectively read. The case studies are amply illustrated, and every step of all calculations is explained in detail. All data that are used are attached in appendices to enable reproducing all calculations but more importantly to facilitate new research. The material assumes no more than elementary statistics and algebra. As most MBA material, it is most effective when studied, discussed, and especially practiced in groups.

Third, this book can also serve as a complementary textbook for a graduate course in Design of Experiments (DOE). Traditional DOE texts are overwhelmingly dominated by examples devoted to physical products. This book takes DOE into the new domain of nonphysical products, executive decisions, which are intellectual artifacts in the Sciences of the Artificial. To facilitate the book's use as a textbook, all chapters are purposely written to be as self-contained as possible, especially the case studies in Chaps. 5, 6, 7, 8, and 9.

Finally, this book is also intended for researchers investigating executive decisions. We have presented a new prescriptive paradigm grounded on some new ideas—*gedanken* experiments, Design of Experiments, sciences of the artificial, and sociotechnical systems as manufacturing production systems of decision specifications. We have also developed an executive decision metrology and measurement instrument. Executive decision synthesis as a sociotechnical systems paradigm is a worthy new field for research and practice.

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Warren Seering, director of the CIPD, guided the work. His fine guiding hand and penetrating insight were essential in the research. I am very thankful to Warren for his encouragement for me to tackle this topic, which must have seemed very risky. He taught me how to think systematically about product synthesis in the context of the Sciences of the Artificial. This learning and years of technical work in IBM have made this book possible. Kevin Otto was my teacher from whom I learned more about product design and technology readiness than I thought was possible. He introduced me to systems, the importance of creative use of working principles in product design, and how to critically cull the literature. His discussions on Design of Experiments inspired this work. In addition, I am in debt to MIT professors Tom Allen, Gabriel Bitran, Dan Braha, Bruce Cameron, Paul Carlile, Ike Colbert, Ed Crawley, Missy Cummings (professor and the first woman F-18 fighter pilot on duty in an aircraft carrier), Ollie de Weck, Woodie Flowers, Dan Frey, Dave Mindell, Debbie Nightingale, Janet Rankin, Eric Rebentisch, Nelson Repenning, Jesper Sorensen, Dave Wallace, and many others in the MIT community whose research spirit, respect for excellence, and supportive environment enabled this work. Of course, I take complete responsibility for errors of omissions and commissions.

I must express my gratitude to business colleagues and friends who have generously given me invaluable advice and business insight and made sure my feet were grounded in the real world during the *in situ* client case studies. Roy Bauer, my respected colleague and friend, taught me about high-tech outsourcing and manufacturing and, by example, what decisiveness means. Everything I know about quality management I learned from him through years of implementation of

the award-winning Malcolm Baldrige quality management methodology in IBM. Hans Huang is another respected colleague. He has the unique capability to cut through the most messy systems and management problems and identify the core of a predicament. He gave me what is the equivalent of a graduate course in triage of troubled projects. Chapter 9 would have been impossible without the partnership of John Dickmann, friend and MIT classmate. He is coauthor of Chap. 9, which deals with the question of the US Navy's fleet structure for the year 2037. John served as a US Navy Commander in US attack and ballistic-missile nuclear submarines and also as a staff officer in the Pentagon, in the Office of the CNO (Chief of Naval Operations). He provided the nuanced expertise and textured domain knowledge necessary for the analyses and syntheses work in Chapter 9. He patiently tutored me through this difficult domain. Bill Glenney, Director of The US Navy War College's Strategic Studies Group (SSG), first stimulated the problem, and we are in his debt for very direct, no nonsense, suggestions for improvement.

Hardly anyone becomes a manager or an executive without the help of sponsors. It is axiomatic that one cannot "push against a rope"; someone must be at the other end "pulling you up." Jack Higbee was first. He plucked a green Chinese engineer from the ranks and made me a manager. At that time, it must have seemed a strange choice. He gave me excellent advice, one that has worked for me throughout my career. He told me—"Take care of your people. Pay attention to detail. Then just run with it." Mike Quinlan appointed me to a very selective staff function of about seven whose mission was technical oversight of IBM's entire product lines. I was the greenest among seasoned and experienced managers. IBM was then a $70 billion dollar company and the job was daunting. From him I learned to trust senior executives, spot and anticipate big problems, and direct their resolution. Mike trusted us to identify problems, articulate the issues, make an executive judgment, and prescribe a course of action. I don't recall his second-guessing his staff. However, trivial issues, playing it safe, and being wishy-washy were anathema to him. From him I learned (though imperfectly) to focus on important issues and to communicate unambiguous executive instructions. Tom Furey gave me my first assignment as a line executive. He is the embodiment of decisiveness, whose mantra is: "I rather be wrong than indecisive." He is known as a straight talker of good news and bad news, especially to senior executives. He tells them what they need to hear, frequently what is inconvenient and not politic. When an IBM executive vice president opined that the IBM PC was just "serendipity," he retorted, "No, it is a profound industry change." He gave me the opportunity to learn how to lead missions, not just projects. I was also lucky to have many generous tutors, mentors, and supporters. Many other very senior corporate executives taught by example and by the way I was grilled and put through the paces in briefings and reviews. Others were comrades of many shared successes and now forgotten setbacks. Herb Addison, Ned Barnholt, George Conrades, Susan Curtis, Dan Cease, Ralph Clark, Emilio Collar, Bob Cooper, Bob Evans, FAN Yu, Chet Fennel, Jay Holland, Neil Horner, Pat Houston, Craig Kaplan, Phil Kotler, Terry Lautenbach, Bill Margopolous, Jim McConnell, Frank Metz, Joe Nadan, Sam Palmisano, Bill Rich, Rody Salas, K. Sugino, LI Kuo-Ting, General KUO Yun, Wilson Wang, John Woolfolk III, YANG Tian-Xing, Bob Williams, and numerous others from whom I learned the métier of management.

There comes a time when one must integrate what one has learned, by doing and praxis, into a coherent systemic whole, properly framed by first principles. Failing to do so, one risks turning into a managerial mechanic. IBM helped me escape this fate by sending me to Columbia University's Business School. Our cohort was designed for F100 senior managers and executive aspirants. Thora Easton and I were study partners. She was IBM's first woman sales manager, responsible for a territory, which included the Federal Reserve Bank. Whereas I was intensely interested in academic theories, she cut through the mumble-jumble and made everything practical and common sense. I learned the difference between complexity and complicatedness from her. Complexity is an inherent technical property of an artifact; complicatedness is the degree to which people make complexity cognitively unmanageable. To this day, she is one of my most trusted advisors.

Christian Rauscher my editor from Springer cannot be thanked enough for his support and encouragement throughout this endeavor. His immediate grasp of the meaning of this work was very uplifting to us who had been toiling on this work for some time.

Finally, I am most grateful to my parents. My father wrote a four-volume textbook, of 34 chapters on international law, all the while serving as ambassador and plenipotentiary in troubled foreign postings. He set an example for me to internalize and follow. Having lost all material possessions in a civil war, a brutal and remorseless world war, and yet another civil war, I am grateful my mother, a classics professor, insisted that learning and knowledge are more lasting and fulfilling than money. Her passion to pass on learning is an indelible influence in my life. In Taiwan, she and her college classmates founded a high school, for girls, based on traditional Chinese and Christian values, to nurture leaders of the future. I was a guest at the fortieth anniversary of the school's founding and I was astonished to find a lively student body of two thousand in a modern campus of five-story buildings. My wife is an alum of that school.

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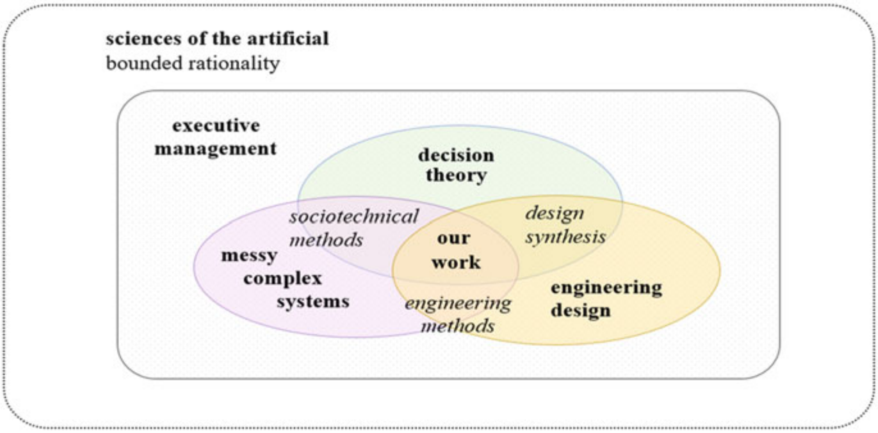
Chapter 1—Introducing Executive Management Decisions
Chapter 2—Decision Theories and Methodologies
Chapter 3—Operations: Foundations and Processes

Chapter 1
Introducing Executive-Management Decisions

> *Most high officials…learn how to make decisions, but not what decisions to make.*
> *Kissinger*

Abstract This chapter introduces the motivations of executive-decision synthesis and narrates our systematic prescriptive paradigm for their robust design. The locus of our prescriptive paradigm is at the intersection of messy complex systems, engineering design and executive decisions. Synthesis of robust executive decisions draws from these three fields and their sociotechnical methods as illustrated by the Figure below. Our domain of interest is executive management decisions in organizations. Our prescriptive paradigm is grounded on The Sciences of the Artificial.



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1.1 Examples of Executive Management Decisions

1.1.1 Motivation

To appreciate the nature, texture and resultant implications of executive-management decisions, we present four examples for which we have first-hand experience. We were active participants and observed in detail the context, conditions, and management processes. Each example is a vignette embodying a lesson. We begin each narrative with a brief sketch of the situational context, the decisions taken, and their outcomes. This is followed by a brief commentary in the spirit of lessons-learned. The lessons anticipate many of the issues and managerial implications that will be discussed in this book. The case commentaries are not intended as criticisms. As a participant and a colleague of the principals involved, and with the benefit of 20–20 hindsight, the lessons learned are reflections of those experiences, subsequent research, and increased understanding of executive-management decisions. Our motivations are to learn and improve the science and the practice of executive decisions management.

1.1.2 Four Examples

1. Sam Palmisano is a former CEO of IBM. The first time I saw him action was when he disclosed to a politely irritated group of important customers that IBM had made a serious technical error. As specified, the system did not meet performance specifications. The audience was attentive, but irritated. Sam made no excuses, dodged no questions, and explained the technical reasons for the problem in language that everyone understood. Then he wraps up the meeting by saying that IBM was doubling system memory to all customers, for free. A potentially hostile meeting was transformed into a constructive and reassuring one. That was an impressive performance, no nonsense, and direct to the point. Beyond the ability to work with customers, Palmisano has a keen sense of industry cycles and the technology shifts that drive them. For example, he drove the transformation of IBM into a services company. He sold the disc storage and PC businesses before they became commodities. In an interview, Palmisano makes no excuses and says: "We invented the PC but viewed it incorrectly. We saw it as a gadget, a personal productivity tool. Unlike Intel and Microsoft, we didn't see it as a platform. We missed the shift. So the lesson to me is you cannot miss the shifts. You have to move to the future" (Karlgaard 2011). IBM's business model didn't include uncertainties in how the PC would or would not expand the market.

This example highlights the importance of *mental models* in designing decisions. A mental model is the cognitive framework, intellectual machinery, and assumptions that problem solvers bring to bear on a problem or opportunity. Problem solvers form, invoke, or create mental models by selectively identifying situational cues, ignoring irrelevant and noisy ones, identifying explanatory variables, and making implicit or explicit assumptions for decision analysis and decision-making (e.g. Kim and Mauborgne 2015). We all use mental models to cope with complexity and uncertainty. It is part of our *sense making* process (Weick 1993, 2001; Weick et al. 2005); *viz.* attaching meaning to what is experienced. It is a precursor to action. Forming a correct mental model is a vital cognitive process to avoid solving a wrong problem. This PC example shows that the "gadget" mental model was adopted instead of the more competitive and useful *platform* in an industry ecosystem. For a company, like IBM, whose strength is grounded on design, manufacturing and selling of large main-frames and super-computers, a PC does indeed look very much like a gadget. This perception illustrates the cognitive biases of availability and saliency (Tversky and Kahneman 2000). The availability bias refers to the fact that in decision making, people tend to use the information that is most familiar, readily and easily available to them. And by recalling distinctive experiences and factors from memory, those aspects dominate the development of a judgement. Saliency bias refers to the phenomenon that distinctive factors or features catch the excessive attention of decision makers, which cause them to overweigh those factors when trying to understand behaviors or situations.[1] It is a cognitive least-energy approach.

2. One of my assignments was to lead the strategy, marketing, and advanced systems development functions for the IBM AS/400 product-family in Rochester, Minnesota. The product-family was positioned between the mainframes and the PC products. Seeking advice, I went to my mentor, a corporate senior executive. He said: "Your product is being simultaneously ***squeezed*** from the top and the bottom. Our mainframes' price-performance is coming down, and our PC's are moving up that curve. The future of your product may be limited." I was to infer that no one will be left to buy AS/400s. Sincere advice, but this prediction did not prove correct. He was thinking of the technical specifications only. Variables IBM can control, but not other controllable and much less the uncontrollable variables. He failed to understand how to design a robust family of products.

Several uncertainties on the dynamics about mainframes are overlooked in this argument. Mainframes are high-priced capital-assets. And because they are also high-technology systems, every purchase also implies a continuous series of down-stream investments in upgrades, applications development, and services. At that time, the rule-of-thumb was that every purchase dollar implied something like 60 cents of life-time expenditures in hardware and software upgrades, and services. As a result, the buying decisions are necessarily made by DMU's comprised of senior executives and executive financial officers. To protect their investment and abide to complex tax laws, companies impose complicated rules, processes and contracts, which must be followed by their organizations, and especially by sellers.

Also overlooked were uncertainties in markets and customer needs. The mental model did not include the existence of medium and small establishments like hotels,

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[1] I must confess that I was grievously guilty of these biases. As an engineer, I did not think that working on PC's was "serious engineering" or "high-tech enough" and, to my regret, avoided appointments in that business unit. (v tang).

retail businesses, medical and health clinics, and the like. Unnoticed were the very large number of autonomous functional units in large businesses like sales, accounting, personnel, and manufacturing. Notably unaddressed were the affordable prices and vast repertoire of ready-to-use applications, a combination that made the AS/400 very attractive to medium/small businesses and by heads of functional units like sales, accounting, personnel, and manufacturing executives. To them, the AS/400, unlike mainframe computers, was an off-the-shelf, ready-to-use system. Price and affordability made approval by corporate finance unnecessary. Ready-to-use applications made applications development unnecessary. Our research revealed that, in every geography around the world, the number of medium/small businesses and functional units overwhelms the number of main-frame DMU financial officers. Moreover, the analysis revealed that the number of medium and small businesses and functional units was growing significantly faster than the main-frame based establishments. Armed with this analyses, we argued to senior corporate executives that the *squeeze* model was a *supply-side* argument, and that our mental model for the AS/400 was a *demand-side* model. We persuaded senior IBM executives that for the AS/400, this was the more fitting and more appropriate way to think of this business opportunity. The AS/400 investments provided a much less risky path to returns, it would make a robust choice. As a result, The IBM Corporate Management Board made the decision to invest more intensely in r&d and sales programs for the AS/400. History proved us right (Bauer et al. 1991). Pundits wrote: "The AS/400, one of IBM's greatest success stories, is widely installed in large enterprises at the department level, in small corporations, in government agencies, and in almost every industry segment.[2]" The next generation of the AS/400 product, the IBM iSeries "is the world's largest-selling computer family... if the Rochester, Minnesota facility that produces the machine were independent, it would be the third largest computer company in the world." (Atlantic 2007).

The *squeeze* mental model was incorrect. It improperly perceived and specified the situation as a product exposure rather than a business opportunity, as a narrow supply-side problem rather than a demand-side market-expansion opportunity. The mental model was biased to technology and pricing, variables IBM has strong competence and effective control. The *squeeze* model's boundaries omitted the IBM external world, its market demographics and dynamics. In that mental model, key essential factors that IBM does not control, but which needed to be understood and acted upon, were regrettably not considered.

3. During my initial stay at corporate headquarters, it was explained to me that IBM's strategy was to "exceed industry growth by growing faster in every industry business segment". Pithy, but flawed. To our surprise, years later, we learned that even growing faster in every industry segment did not mean that IBM would necessarily grow faster than the industry. The IBM data are too complicated to show, but Table 1.1 makes the case using a hypothetical case.

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[2] http://search400.techtarget.com/definition/AS-400. Downloaded November 20, 2015.

Table 1.1 Flaw of "exceed industry growth by growing faster in every segment"

	Year 1			Year 6	
Segment	Revenue $M	% of industry	CGR(%)	Revenue $M	% of industry
Industry					
A	$400.0	400/480 = 83	4	$486.7	487/700 = 70
B	$80.0	80/480 = 17	20	$199.1	199.1/700 = 28
C	$0.0	0.0	0.0	$14.3	14.3/700 = 2.0
Total	$480.0	480/480 = 100	–	$700.0	700/700 = 100
Geschäft					
A	$350.0	350/480 = 72.9	5	$446.7	447/700 = 63.8
B	$40.0	40/480 = 8.3	21	$103.5	104/700 = 14.8
C	–	–	–	–	–
Total	$390.0	390/480 = 81.3	–	$550.2	550/700 = 78.6
				$550.2	550/686 = 80.2

Note: *industry denominator is $686 M without segment C*

> This example illustrates a situation in which only the variables IBM can control were considered, overlooking those it could not control. The strategy failed as a robust strategy.

In year-1, the industry is comprised of two segments, *A* and *B*. New segment *C* appears in year-6. Geschäft has products in *A* and *B*. However Geschäft has an adverse product mix. It has only 8.3% market share in the fast growing segment, *B*; and a 72.9% in the slow growing segment *A*. Geschäft grows faster than the industry in both segments. But by year 6, it has experienced a total market share decline, from 81.3 to 78.6%. Even without segment *C*, its market share declines to 80.2%. The problem was Geschäft had inadequate total base in the faster growing segment which allowed others with larger base in these fast growing segments to overcome Geschäft. Simply growing each segments's base faster than the current segment grew was inadequate. It turns out that in some segments Geschäft needed to grow much faster, even as the segment grew fast.

What lessons can we learn from this example? The sum of optimal solutions of the piece parts does not necessarily mean an optimal solution of the whole. The relationship of each of the elemental problems and how they interact individually, under an uncertain external environment, has a strong influence on the intended and unintended outcomes. The goal of "exceeding industry growth" was appropriate, but the strategy was incorrectly prescribed. The "what" of exceeding industry growth was right, but "how" was not. The "how" ignored the external growth dynamics of different segments and its adverse effect on IBM's total market share. External industry dynamics do not remain static. They were uncertain, uncontrollable and remained unaddressed as a blind spot in IBM's strategic field of vision. Consideration of alternative use scenarios for its subsystems could have avoided the loss of market share. The mental model of the "what" to address the solution was appropriate, but the "how" was flawed. Thinking of IBM together with the rest of industry as an interacting *system*, with an external environment, was absent in the strategy.

4. A F100 high-technology company requested an evaluation of their strategy. (The firm wishes to remain anonymous. It is has >$5 B in revenues). To overcome deficiencies of conventional senior-management practices, I decided to use scenario analysis (Bradfield et al. 2005; van der Heijden 2000; Goodwin and Wright 2001). My IBM experiences with this methodology made me optimistic about its use. A work product of this process, from the IBM Research Division, was "IBM's Ten-Year Outlook", a thoughtful document that was widely discussed among IBM senior executives. Typical conclusions from that study were, for example, the decline in the demand for mainframes, restructure of the industry favoring new entrants, and the pervasive emergence of computer networks.

In contrast to incremental extrapolations, scenarios are internally consistent narratives of out-of-the-box plausible futures projected from current uncertainties. Scenarios are designed to challenge the conventional wisdom and inspire "imaginative leaps" (e.g. van der Heijden 2000; Collyns 1994) by stimulating fresh thinking (Martelli 2001). A kind of qualitative simulated annealing approach (Kirkpatrick et al. 1983). Scholars are recognizing that though useful, scenario analysis is not without some shortcomings. Research and practice show that more than five scenarios stress the cognitive ability of the analysts and decision-makers that make the process unmanageable (e.g. Amer et al. 2013). Five scenarios, while more useful than one or two, still severely limits the exploratory capabilities of decision alternatives. The number of hypothetical "what-if" questions that can be analyzed is very greatly limited. This limitation exposes the process to the false "belief in the law of small numbers" (Tversky and Kahneman 1971), which cautions drawing inferences from small samples. In addition, quantitative analysis is limited to ordinal numbers in scenario analyses, e.g. A is better than B is better than C type analysis. Although this is perhaps more useful than pure qualitative and subjective analyses, it remains as a limiting factor. The ability to explore only a handful of conditions, in the uncertainty space, combined with the limited quantitative analyses made our scenario planning incomplete.

The capability for a significantly larger set of scenarios and comprehensive decision alternatives remained an important an unsolvable problem. Although we were able to specify "trigger points" for responding to certain uncontrollable conditions, they could not be systematically identified. The ability to extensively explore and predict outcomes of "what-if" questions in the uncertainty space remained as an unsatisfied and desirable capability. Nevertheless, the F100 client found our scenario planning work valuable and effective. The scenarios did achieve the out-of-the-box thinking that drove productive staff analyses for executive debates. The company now has over $200 B in yearly revenues.

5. As the fourth example, we consider IBM China in the late 1990s. China had recently declared its national policy to transform itself from a central-command economy into a one that is market-oriented. The information industry (IT) and market were designated as strategic. China's national policy, which continues today, was to *informalize* its macro and micro economy. IT products and services were to be deployed in every industry sector to improve productivity and to generate high technology jobs and exports. Unprecedented incentives were

> created to make sure this took place. New companies, governmental bodies, laws, regulations, standards, processes, and practices were being created at a pace that was hard to keep up. To IBM, this was truly an ill-structured and messy opportunity. Faced with these extraordinary developments, it was necessary to explain this historic transformation to IBM senior executives, some of whom judged the conditions in China to be not ready. I sketched a schematic of China's industry and market formation system designed by the Chinese government to jump start the IT industry sector (Fig. 1.1).

The transformation into a market economy was designed to evolve through four phases—policy, initiatives, market formation, and market demand. The goal of the policy phase was direction setting, to formulate and promulgate policies. This required the mobilization of political organs, as well as, the participation and support of diverse subject matter experts. During the initiative phase, designated strategic projects were to be launched, and funded. Simultaneously, rules, controls, regulations, and standards were published. During the market formation phase, new companies, foreign ventures with targeted foreign companies and government authorities were to be established; r&d, manufacturing, sales and service enterprises are formed and permitted to compete. Many of these companies were privatized from established state owned enterprises (SOE). Whereas in industrialized countries this process evolves sequentially over many years, the Chinese government proceeded concurrently in its rush to industrialize into a market economy. These are indicated by dash lines (Fig. 1.1). Without a complete understanding of these dynamics, many foreign companies simply rushed in to just sell products and services, without a full appreciation of the key players, the industry and its market formation dynamics. Many reaped short term benefits but discovered that to develop and sustain a strong position was becoming harder and harder. Meanwhile IBM was learning-by-doing and integrating itself into the sociotechnical economic infrastructure.

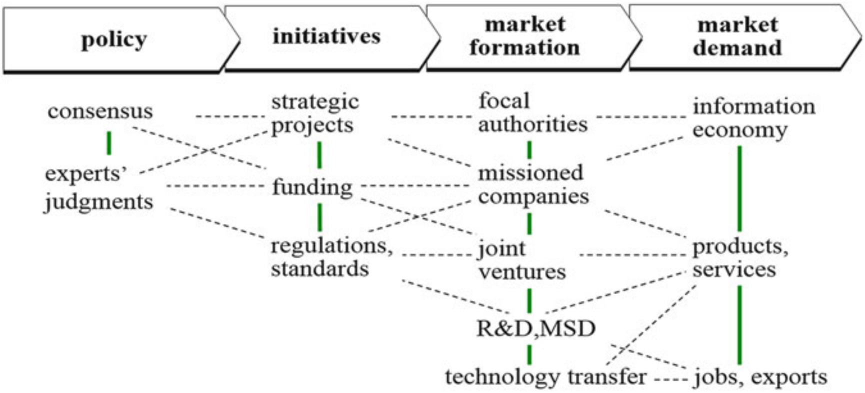

Fig. 1.1 Phases in China's market development process

IBM was playing for the long haul. Its strategy was not merely to compete in the market, but stake out enduring positions. Its approach to this unprecedented opportunity was to participate thoughtfully at pivotal points in market creation process and the technology value-chain with joint ventures and important projects. Cooperating with the Chinese government, IBM created targeted strategic programs. For example, IBM worked with the Chinese Academy of Sciences on technology standards, procured electronic parts from local manufacturers and partnered with former state owned enterprises (SOE's) to learn about supply chains, built factories to learn about business practices, and so on. Each program played a pivotal role as part of an overall long range plan to expand IBM participation throughout the sociotechnical-economic infrastructure. These programs were systemically linked vertically, horizontally, and diagonally (Fig. 1.1). The governmental bodies welcomed IBM's coherent and coordinated system strategy. Years later, many other American and European companies began to emulate IBM's approach.

This example strengthens our conviction that executive-management decisions need to be addressed with systems thinking and consideration of risk, uncertainty and robustness during sense making, problem solving, and implementation. Sustainable participation in the China market required multidisciplinary initiatives within the economic ecosystem created by the Chinese government. The wicked nature, in Rittel and Webber's sense (Rittel and Webber 1973) of our work was evident by internal bickering, petty jealousies, and unproductive intramural obstructions in both IBM and the Chinese government. But the IBM China efforts persisted, mostly because Gerstner, the IBM CEO, was so determined to be the key IT player in China. This case highlights the importance of a multidisciplinary system view of a complex problem/opportunity and the need to present an uncomplicated system image (Fig. 1.1) of complex decision situations for senior executives' mental model building.

1.1.3 Remarks

These examples illustrate typical senior-management situations and decisions. With the benefit of hindsight, they may not appear particularly formidable. But they were all multi-billion dollar decision situations, affecting thousands of people, and influencing the industry and competitors in nontrivial ways. A significant common theme in these cases was that they were complex multidisciplinary problems under uncertainty conditions. They were one-of-a-kind problems which cannot be addressed with predefined off-the-shelf solutions. Another common feature was that the decision situations were deliberated by seasoned executives with their direct reports. They all had the benefit of experienced personal staffs to do specialized work. An important lesson is that the practice, the intellectual machinery, the composition of the executive management DMU, and the sociotechnical processes must rise to the level of unprecedented problems and opportunities; an asymmetry invites a lack of control and organizational instability at many levels and in many dimensions. This is Ashby's Law of Requisite Variety (Ashby 1957), which states that the variety of a controller must exceed that of the system it seeks to control. We need to rethink:

- what exactly is a decision? How to represent them?
- what is a high performance decision? Especially under uncertainties?
- what is the right mix of hard and soft sciences?
- what is a systematic decision process?
- what makes us overlook crucial issues? How to reduce blind spots?
- what is "DMU capability" so that the problem's solution is in control?
- what is a quality sociotechnical system for executive decision-making and execution?

We will argue that fresh actionable methods to supplement current practices and problems facing executive management are necessary. This the purpose of this chapter.

1.2 Chapter Introduction

This chapter is an introduction to a new paradigm for executive-management decision making, one that does not focus on just point returns, but rather on *success* as high immunity to unpredictable uncontrollable conditions of returns. That is—robust returns. We define *executive* as one who has been appointed as responsible and accountable for an organizational mission with a depth of control that is at least three-layers deep. An executive is the one single individual who has been empowered to commit resources to implement and execute a decision. MIT Institute Professor Joel Moses describes this as the "middle, up and down" management, simultaneously top-down and bottom-up. As such, executive-management decisions are in a class of their own. Their impact on the economy, organizations, and individuals is hard to underestimate. The US Bureau of Labor Statistics reports that there are about 250,000 executives in the US. This is a small number, when put in context of a $16.3 trillion American economy and a labor force that exceeds 157 million people. The scale and scope of executive-management decisions are non-trivial. These decisions, although rich in opportunities, are also fraught with uncertainties, and difficulties. These challenges are especially acute in today's global economic environment in which capital, labor, technologies, production, and knowledge move at unprecedented speeds.

To address these challenges, we present a new prescriptive paradigm to help executives make better decisions in concert with their staffs and direct reports. We call this organizational composite, a *decision-making unit* (DMU) (e.g. Phillips 2007; Kotler and Armstrong 2010). It is not realistic to assume that an executive working alone, can, or will, single handedly perform every single task or personally implement every process during the decision life-cycle. Therefore, much of the analyses are delegated, key deliberations are performed as a team, and implementation is executed by groups. Only **one** person is ultimately responsible and accountable for results. This person is the executive as a decision-maker. In every organization, decision-making is a *reserved power*. This means that the authority to take a decision and the right to commit resources for implementation are delegated from a more senior executive to whom the decision-maker must answer to. This reserved power, once granted, is both a right, an obligation, and a privilege. It marks one as someone who can be trusted with people and resources. And unless granted, this power remains exclusively reserved for higher authorities to bestow. In the military this is the power to *command* (e.g. Blumenson and Stokesbury 1990). It follows that our prescriptive paradigm and its methods do **not** make decisions. People make decisions. Our paradigm can inform executive management who then must make thoughtful and meaningful judgements in their exercise of reserved powers. And for the consequences, the executive alone is responsible and accountable.

A hallmark of executive decision making is uncertainty, not knowing whether a choice made will result in the desired success. Such decisions are not solvable by logical deduction, there are unknowns which must be clarified and secondary effects to be considered. Typically, choices which maximize returns are also the riskiest. Consideration must also focus on the risky conditions of whether the success desired will occur despite a host of possible uncertainties. We seek a decision making process that will generate such decision outcomes, the choices that are most likely to provide success despite uncertain possibilities.

Our paradigm is distinctive. It proposes a set of actionable processes to systematically generate and consider new decision alternatives, perhaps not appreciated of their significance or overlooked. We can design alternatives that can address a region *anywhere* in the solution space and anywhere in the uncertainty space. This unique and unprecedented capability enables *unrestricted* exploration of very dissimilar choices for a decision. It enables decision-makers, the DMU and their staffs to think broadly and analyze an *unconstrained* number of hypothetical *what-if* questions. Moreover our paradigm allows decisions to be designed so that desirable outcomes can be made highly insensitive to the harmful effects of uncontrollable conditions, even when these conditions cannot be eliminated. This capability makes decisions significantly less vulnerable to uncontrollable uncertainties and makes success more assured. This kind of immunity to uncertainties, *robustness*, is a highly desirable property for executive-management decisions because it can help make decisions that reduce downside risk while still being able to capture upside opportunities. The ability, to formulate these kind of decisions, is a major indicator of managerial expertise (e.g. Shapira 1995; Clemen 2008). Our methodology also includes structured social processes to improve data quality, as well as, sociotechnical-process integrity (Tushman and Nadler 1978). The rigor of our prescriptive paradigm is grounded on the works of others from a variety fields, including proven engineering methods (e.g. Pahl and Beitz 1999; Phadke 1995; Taguchi et al. 2000; Otto and Wood 2001), axioms and principles of decision theory and practice (e.g. von Neumann and Morgenstern 1964; Howard 2007; Keeney 1992; Leleur 2012), research findings in cognitive psychology (e.g. Lu et al. 2012; Kahneman and Tversky 2000; Weick 1993; Eisenführ et al. 2010), and organizational management (e.g. Wright and Rowe 2011; Achterbergh and Vriens 2009;

Mathieu et al. 2008; Simon 1997a). Our paradigm is also a sociotechnical methodology (e.g. Brodbeck et al. 2007; Erden et al. 2008; Clegg 2000; Cherns 1976; Bucciarelli 1994) for complex systems (e.g. Sterman 2000; Bar-Yam 1997; Luhmann 2013; Mobus and Kalton 2015) to address complex and difficult interdisciplinary composite problems (e.g. Levin 2006; Ackoff et al. 2007; Ackoff 1974; Rittel and Webber 1973).

There are many reasons why executive management decisions are challenging. The decision situations that executives face are not simple. Simple problems do not come to the attention of executive managers. They can be solved at lower levels in the organization. Executive management problems are necessarily difficult, laden with more risk and uncertainties. Moreover, they require coordinated efforts from different organizations, a variety of specialized expertise, and strong interpersonal skills. The problems are complex sociotechnical problems. They are rarely well-structured. A well-structured problem is one which has a readily (but not necessarily easily) definable problem statement, in a domain that has established solution strategies. Rittel and Webber (1973) call these problems *tame*. Tame does not mean easy. On the contrary, they can be very demanding. Operations research (OR) problems, building a suspension bridge, designing a super-computer, constructing a deep-water oil-drilling platform are well-structured problems; but they are far from being easy.

Unlike tame problems, ill-structured problems defy well-structured conditions. The scale of ill-structured problems is very broad. For example, at a grand scale, terrorism and poverty are ill-structured and *messy*. At a smaller scale, a technology company's loss of competitiveness, safety in a nuclear power plant, and manufacturing quality are also messy problems. They are messy and *wicked* (Simon 1977; Rittel and Webber 1973). They are messy because they are problems of problems, systems of systems, ensembles of problems and opportunities that must be considered together as a coherent whole.

The aggregate of optimal solutions of individual problems is not necessarily an optimal solution to a mess (Ackoff 1974). Moreover, in many cases it is difficult to define, at all, what does optimality means. For example, what is an optimal level of unemployment? What is an optimal rain forest? What is an optimal level of rework? We can only say that is better or worse by some measure. Moreover, messy and wicked problems are *multi-disciplinary*. They require both technical and social solutions (e.g. Brodbeck et al. 2007; Schulz-Hardt et al. 2006; Leleur 2012). Rationality, involves people, social and technical systems, all of which challenges even the most seasoned executive. Moreover, problem definition and solution of messy/wicked problems are very much dependent on the—*Weltanschauung*—of the participants and the DMU. This presents another challenge. People have systematic *biases* (e.g. Kahneman and Tversky 2000; Baron 1998), which distort reality and prejudice rationality. At times, the problem solving constituency and even the beneficiaries become part of the problem. These are yet other non-trivial contributing factors to messy and wicked problems. Moreover, these class of messy and wicked problems, rarely have yes-no, true-false kinds of solutions. More likely, they have a better-or-worse type answers, but for which, only continuous adjustments and improvement are consequential. For example, executives create programs to reduce manufacturing waste, university deans strive to improve the quality of research, and national leaders struggle to preserve peace, and so on. These are situations that can be improved with thoughtful actions; but for which, categorical evaluations are not necessarily meaningful.

Beyond descriptions and characterizations of messy and wicked problems, it is critical to know the fundamental factors that contribute to the formation of messy and wicked conditions. We consider this necessary so that a decision-making unit (DMU) need not be overwhelmed by ill-structured, messy, and wicked problems. And also to ensure that the DMU does not focus only on symptoms, but root causes of problems. By understanding the key contributing factors of these messy and wicked problems, the DMU is better equipped to address the problems and form new opportunities (e.g. Lu et al. 2012; Brodbeck et al. 2007).

We will argue that there are four factors that forcefully contribute to ill-structured messy and wicked problems. They are *complexity, uncertainty, disciplinary,* and *organizational* factors. Individually, collectively, and systemically, they influence decision outcomes. An executive-management decision process must be able to manage these factors and their systemic interactions in order to make *good* and *meaningful* decisions (e.g. Phillips 2007; Banks and Millward 2000; Mohammed et al. 2010). Good and meaningful decisions are, in fact, the central themes of this book.

We will present a prescriptive methodology consisting of systematically actionable processes for resolving executive-management decision situations under uncertainty. We consider executive decisions as **in*tellectual artefacts*** that are deliberately planned, designed, and enacted to produce intended outcomes. Decisions are ***engineered***. It follows that executive-management decisions are not spontaneous reflexes, but the result of actions derived from—mental, physical, and material—team efforts that form the life-cycle of a decision development process. We will use scholars' research about decisions and proven engineering and social methods from the managerial praxis to *systematically* design, analyze and specify decisions that remain satisfactory to managerially intended goals and objectives even when uncontrollable conditions continue to exert their negative influences. We assert that a systematic process for executive-management decisions must satisfy a daunting set of functional requirements:

- Sense making and framing of the decision situation,
- Specifying goals and objectives,
- Clarifying the boundary conditions and constraints,
- Identifying the essential managerially controllable **and** uncontrollable variables,
- Dispelling bias through systematic processes,
- Constructing decision alternatives and predicting their outcomes,
- Exploring alternatives over both the entire solution space and uncertainty space,
- Constructing solutions and predicting outcomes to any hypothetical what-if question,
- Constructing robust solutions,

- Having a high performance sociotechnical team and processes to implement decisions,
- Committing resources to a decision specification and a plan.

These criteria are a composite of Pahl and Beitz's (1999) and Otto and Wood's (2001) systematic engineering-design with the canonical decision-making process (e.g. Baron 1998; Bell et al. 1988) and sciences of the artificial (Simon 1997a, 2001). We will organize these functional requirements into a systemic structure and frame its organizing and operating principles.

The remainder of this chapter is structured as follows. *One*, we began with examples of executive-management decisions to illustrate key concepts and their implications to the practice. They were not stylized textbook examples. They were real world cases for which we have first-hand experience. *Two*, we follow with an overview of the salient features of our new prescriptive paradigm. We discuss the features that make our paradigm different and distinctive. Critically, although decisions are engineered, they are not physical objects. They are content intensive intellectual artefacts. But like products, decisions are also manmade objects. Neither products nor decisions occur in nature without intentionally goal-directed human effort. For decisions, we frame this effort as activities that take place in five spaces—the problem, solution, operations, performance, and commitment spaces. *Three*, we discuss the messy and wicked nature of executive-management decisions. We map the specific expressions of messes and wickedness within the domains of the five spaces. This is followed by a detailed discussion of the social and technical factors that make problems messy and wicked. We discuss in detail how these factors **interact systemically** to reveal the pivotal points that influence the behavior of the implementation and intended outcomes of ill-structured, messy, and wicked problems. From the system dynamics analyses of the factor interactions, we infer fundamental principles and functional requirements for decision design. *Four*, we close with a specification of fundamental functional requirements for a systematic decision development process and a set of principles for good decisions. The specific criteria of a good decision will be discussed in the next chapter in the context of other extant and complementary decision analyses theories and methods.

1.3 A New Prescriptive Paradigm

This book is about a new paradigm for executive-management decisions using engineering methods. Our motivation is to help executives make better decisions and help their staffs perform better analyses and make more thoughtful recommendations that will perform well. We propose a new and fresh *prescriptive methodology* for difficult and risky decision situations under uncontrollable and unpredictable conditions. We present an actionable paradigm that preserves the core axioms and principles of mainstream decision theory and practice, and that also integrates theoretical findings in cognitive psychology and organizational management. We are connecting behavioral research and traditional decision analysis (Clemen 2008) with our paradigm. A paradigm and methodology that takes a decision life-cycle perspective; one that does not omit intermediate steps, nor is truncated at the selection of an alternative; and thereby omits the evaluation of the sociotechnical system as the machinery and mechanism of decision-making.

1.3.1 Decision: A **Compleat** *Definition*

Yates and Tschirhart (2006) use the basketball metaphor to illustrate decisions. It is insightful and useful. The word ‘basketball’ is filled with meaning and distinct ideas. It can refer to the inflated spherical rubber object, the game, free throws, scoring, and many other things. The word “decision” is similarly densely packed with meaning, nuance, and assumptions. We will unpack “decision” and discuss its implications in the remainder of this section.

We start with the etymology of the word *decision*. The expression originates from the Latin word *decider*, which means to ‘determine’. In turn, *decider*, is the composite of *de*- ‘off and **caedere**’ (to cut).[3] In other words, a decision eliminates alternative possibilities. Consistent with this concept, scholars define “decision” as making a choice of “what to do and not to do” (Baron 1998, p. 6) with the additional requirement “to produce a satisfactory outcome” (e.g. Baron 1998, p. 6; Yates and Tschirhart 2006, p. 422). Building on these ideas, we propose the following unpacked definition for executive-management decisions.

A **decision** is a commitment made by:

- an executive **who** is responsible and accountable,
- **to** achieve intended outcomes,
- **by** committing resources to its implementation,
- **by** directing sociotechnical infrastructures,
- **while** under uncontrollable uncertainty, and
- learning from good, bad outcomes, and unintended outcomes.

This definition is more precise and complete than traditional definitions that focus on the “how” but not on the “what”. [*This is the equivalent to the bias of concentrating how to free-throw in basketball, while neglecting other key aspects of the game* (Seering 2003).]

Our definition makes several key points explicit:

1. **the requirement of a decisive executive decision-maker**. We define decision-makers as those who are trusted with formal and delegated authority to make decisions, i.e. they have power; they are in command. With power comes the responsibility and accountability for the achievement of intended outcomes or the failure to perform. To use this power and meet these responsibilities, they are given financial, human resources, technical and other physical assets to implement decisions in order to produce intended outcomes. Thus, decisiveness is the *sine qua non* attribute of effective decision-makers. [This is the equivalent of

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[3] http://www.oxforddictionaries.com/us/definition/american english/decide, downloaded June 1, 2015.

having the reflexes and being physically fit to play in a game of basketball, but being hesitant and reluctant to score is not the hallmark of an effective athlete.]

2. ***choice* is making a selection from alternatives**. This is the "what" of Baron's (1998) "what to do". The alternatives are the "what not to do". This step—*selecting an alternative, making a choice*—is what, in the vernacular, is called a decision. This use of "decision" truncates the full meaning of a decision per our compleat definition. [*What the players "do" on the court is only part of the doing. The coach chooses specific game-plans and tactics for competitive situations. This "doing" guides players on what to do and not do. These are all parts of doing.*]
3. **the requirement of committing resources in order to commit to a choice and its execution** (Yates and Tschirhart 2006). There is always a cost associated with a decision. An economic cost and a social cost that the decision-maker must bear. [*This is equivalent to a coach judiciously calling time-outs during a heated game. He must avoid exhausting the limited number that they can use.*]
4. **the requirement of organizations and technical systems to operationalize the chosen alternative**. Any choice, to be meaningful, has to be operationalized. [*This is the equivalent of the live game of basketball. This is the operational side of the game—scoring points, while your opponent is blocking you from doing so.*]
5. **the aleatory nature of every executive decision**. There are uncontrollable conditions that impinge of the implementation and execution, but which must be understood and harnessed. [*This is similar to not having home court advantage in which the physical conditions, such as how the ball bounces on a different floor, emotional energy from home town fans, and so on.*]
6. **the requirement to learn at a personal and organizational level**. An outcome, whether as expected or unexpected, is never certain. To remain as a viable enterprise, it must reflect, learn and adapt from its execution (Achterbergh and Vriens 2009). [*This is why coaches and teams review and discuss films of games. The idea is not entertainment, but pedagogical.*]

1.3.2 What's New and Different?

Our paradigm integrates new themes into a new conceptual architecture, which is framed by Fig. 1.2. This makes our paradigm distinct from tradition (e.g. Buchanan and O'Connnell 2006). The thematic ideas are declared and discussed in the sections that follow.

1.3.2.1 Decision Life-Cycle as a Complex of Five Sociotechnical Spaces

Executive-management decisions are not spontaneous events, or automatic reflexes. The outcomes of executive-management decisions are not like the effects of colliding electrons, which, without any human effort, consistently produce predictable effects. In contrast, the outcomes of an executive-management decision are the result of intentional, goal oriented human activities that are coupled with technical systems

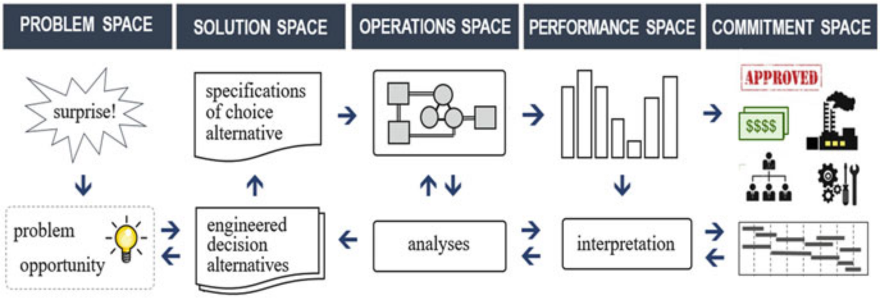

Fig. 1.2 The five-space model of a decision development life-cycle

(e.g. Bazerman 2002). Sociotechnical activities that produce results endowed with meaning and significance in the context of the organizational mission (Achterbergh and Vriens 2009).

The activities to produce these kinds of results are part of a *decision development* process life-cycle, similar to product development process life-cycle. This life-cycle process entails a *complex of five sociotechnical spaces*—the problem, solution, operations, performance and commitment spaces (Fig. 1.2). The life-cycle activities are triggered by *surprises*. A surprise as an event that has rendered a prevailing conceptual model invalid. A surprise also draws attention because it produces a structural dislocation in the sociotechnical system that went beyond the limits of existing control systems (Bredehoeft 2005; Patter Allen et al. 2010). Surprises are stubborn things. They demand executive-management attention. Executives have learned that surprises are disguised problems or opportunities. Surprises reveal new data, flaws, blind spots in executive management operations and qualitative contradictions between observations and expectations (Carpenter and Gunderson 2001; Bredehoeft 2005). Collectively, these triggers create d*ecision situations* in a *problem space*. Surprises require cognitive processes to define problems and opportunities in a meaningful way. Resolving the decision situation requires a design system to create solution alternatives from which a selection of a choice alternative can be made. This design activity is situated in the s*olution space*. The choice is known in the vernacular as a "decision", it specifies a course of action. This is one of the most demanding and creative efforts in the decision life-cycle. The enactment of this specified course of action occurs in the *operations space* by means of a sociotechnical production system. Finally the enactment and control occur of this specified course of action occurs in the Operations Space. Enactment is the operational expression of the chosen alternative. It is an implementation of a decision that consumes organizational resources.

A *decision* specifies *how* an organizations and associated sociotechnical systems must behave so they will generate the intended outcomes in the *performance space*. *Thus, we can consider organizations as production or manufacturing systems*, which must work under a variety of uncontrollable conditions, i.e. uncertainties. *An organization is a factory whose machinery are social and technical systems designed to recognize meaningful opportunities and problems, to analyze, execute,* *and learn from outcomes*. Actual outcomes are evaluated, against the declared intended outcomes' specifications, to make adjustments, improvements, and learn. This requires a measurement system whose attributes and operations can be quantitatively evaluated. But production, execution of decision specifications require scarce and costly resources, funds, equipment, and skilled people. Commitment, of sociotechnical effort toward set goals for specific outcomes on a defined schedule according to an approved and committed plan, is not automatic. Formulation of a plan, obtaining approval for its implementation, allocation of resources and execution the plan form the *commitment space*. A decisive executive must initiate the enactment. By definition there is no decision without a commitment to action or without an allocation irrevocable resources to its implementation. The absence of these commitments reduces executive-decisions to merely an exercise in analyses, executive wishful thinking, and it is an indicator or executive malpractice. The problem, solution, operations, outcomes, commitment, and performance spaces and their interactions form the decision management life-cycle (Fig. 1.2).

In summary, the problem space is where a conundrum comes to the surface as a decision-situation that requires the attention of an executive manager. The solution space is where a decision-making unit (DMU) engineers alternatives, explores their potential outcomes, and choses one as satisfactory. The operations space is the decision factory. It implements the chosen alternative, by following the specifications of the chosen alternative. The performance space evaluates the production quality of the operations space. The commitment space is where the financial, physical and human resources are committed for action. *Ex post* analyses of the results take place in solution space and operations space to improve the performance of the sociotechnical system (e.g. Greve 2003).

1.3.2.2 Decision as a Specification

A decision is a choice, a selection from alternatives. All alternatives are embodied as specifications. A specification is a "blueprint" for action intended for a sociotechnical system to execute in an operations space. It follows that all decisions are specifications. Three mutually reinforcing and dependent rules apply to decision specifications. One is the rule of clarity in the directions for the operations space and in the economic requirements to implement to achieve intended outcomes. Two is simplicity to enable efficient use of resources and cognitive elegance that diminishes the mental load for implementation. Simplicity means *uncomplicated* to those who must interact with the sociotechnical systems. Three, all must make sense to the DMU and those who must implement the sociotechnical system's operations. Decision-making is an event in the operations space that marks the intent to enact a designated blueprint with allocated and irrevocable resources. Decision-making is the equivalent of release-to-manufacturing of a product design.

Decisions without commitment are wishful thinking. Desired outcomes are impossible without commitment of resources. Resources can be physical assets such as plant and equipment; financial assets; organizations, and people. The degree to which the outcomes are consistent with executive-management's intentions is dependent on at least two factors. One is the quality of the implementation of the blueprint in the operations space executed by organizations and technical infrastructures. Two is the impact of uncertainty, i.e. the uncontrollable variables that impinge on the inputs and the sociotechnical systems that are designed to produce intended outcomes. A distinctive feature of our paradigm is that we can design robust decisions—blueprints for action—that are highly insensitive to uncontrollable conditions even when they are not eliminated.

1.3.2.3 Decisions as Intellectual Artifacts

A decision is a specification, the embodiment of a solution concept. As such, it is an **artifact**, an intellectual artifact. What is an artifact? An artifact is a manmade object designed to fulfill a purpose, satisfy goals, and achieve intended outcomes. For example, Michelangelo's *pièta* is a sublime artifact that communicates and evokes many of the most noble values and feelings about the human condition. In engineering, the artifact is a useful physical construction to satisfy a need, e.g. a computer to make large numbers of calculations quickly and accurately, a bridge to move people across otherwise inaccessible places, a plant to make pharmaceuticals. An executive-management decision is a non-physical artifact, an intellectual creation, a recipe intended for action. A specification is a plan to guide implementation. It is a blueprint, a set of instructions intended for execution intended to produce expected outcomes.

An artifact is a human creation. Simon (2001) defined these creations as artificial because they do not appear in nature like a flower, a bird, an electron, or a planet. Artifacts have form, structure, and purpose. For physical artifacts, tangible materials determine the character of the artifact, as in a watch or a sculpture. For nonphysical artifacts, like a decision, intangibles give form and character to the artifact. Whether physical or non-physical, they are intended to fulfill an intended purpose. The parts of the artifact are not random collections of pieces, they have form and they work together to produce an effect through working principles. For example, Gödel's incompleteness theorem is an intellectual artifact. The theorem is comprised of a logical sequence of mathematical arguments that give it form and meaning. Beethoven's fifth symphony is another embodiment of an intellectual artifact. The symphony is a structure of musical notes arranged into movements, which endows it with form intended for orchestral performance. The Brandenburg Gate is built from brick mortar and stone shaped to project an image and make a statement. For decisions, the artefact is a specification intended to be enacted by systems, sociotechnical infrastructures, organizations, so that they respond in such a way that will produce intended outcomes. The specification is the embodied form; goals and objectives give meaning to a decision. Outcomes authenticate or refute the validity or usefulness of the specification.

Artefacts do not always perform as intended; they produce unintended outcomes. Tires blow out on the road, violin strings break during a concert, people sabotage plans and deliberately do not follow directions. External and internal uncontrollable factors introduce uncertainty that impact an artefact's systems behavior and its outputs. Yet, physical systems can be designed to be insensitive to uncontrollable factors. Creating a decision specification so that its implementation results are highly insensitive to uncontrollable factors is the principal challenge of decisions. “Uncertainty places a premium on robust adaptive procedures instead of optimizing strategies that work well only when finely tuned to precisely known environments.” (Simon 2001, p. 35). This is one the major goals of our work in this book.

1.3.2.4 Decisions as Design Synthesis

“Everyone designs who devises courses of action aimed at changing existing situations into preferred ones” (Simon 2001, p. 111). This defines the ethos of design. A decision is a specification, an artifact of the artificial that is the product of engineering design. We define *engineering* as the application of science to design and develop useful artifacts. We define *engineering-design* as the set of tasks of creating new solution concepts, determining the elements of the solution and configuring them into a functioning whole that will produce intended effects when implemented and put in operations (e.g. Pahl and Beitz 1999; Taguchi et al. 2000; Otto and Wood 2001). A design (noun) is a series of cause-and-effect constructs systematically linked through ***variables*** intended to produce a desirable behavior and intended outcomes. The process and decisions to create the artefact is also called design (verb). *Ex ante*, design requires creative and analytic skills to engineer alternative designs and determine their relative merits against competing alternatives. A design is said to produce *robust* results if, *ex post*, the results are highly insensitive to uncontrollable conditions, even when they are not removed. Engineering is a discipline that has well-proven methods to address these kinds of challenges. This motivates us to adopt engineering methods for designing robust decisions.

Executive-management decisions as *robust engineering design* is a new territory in decision theory, decision analysis, the practice, *and* to engineering, as well. We will demonstrate that engineering methods can be effective to systematically design robust decisions in the *solution space* for enactment in the *operations space* to meet intended performance specifications in the *performance space*. We will use the engineering method of Design of Experiments (DOE) to design and evaluate decision alternatives. (e.g. Taguchi et al. 2000; Otto and Wood 2001; Montgomery 2001; Creveling et al. 2002). DOE is a statistical technique to simultaneously study the effects of many variables. Uncontrollable situations cannot be controlled by analyses, but preventative measures that diminish their impact are very useful and can be addressed. Herein lies the power of DOE. We will also use analytic methods from manufacturing technology (MSA 2002) to evaluate the attributes and quality of the performance-space. And as in engineering processes, we will also use key findings and procedures from the social sciences to tackle the complex sociotechnical hurdles in the decision life-cycle (e.g. Kahneman and Tversky 2000; Eisenführ et al. 2010; Janis 1982).

1.3.2.5 Decisions That Have Reduced Bias

Bias is a class of flaws in judgment caused by mental or social motives that distort reality leading people or groups to make incorrect, illogical, or inconsistent inferences about decision situations (e.g. Taylor 1982; Kahneman and Tversky 2000; Ariely 2008). At the group level, Janis (1982) coined the term *groupthink*. Groupthink is the phenomenon wherein people succumb to peer pressure and suspend critical thinking that negatively influences their judgement. He describes Kennedy's meetings to discuss the invasion of the Bay of Pigs during the Cuban missile crisis. This case is the poster child of groupthink. Kennedy and his advisors collectively surrendered to wishful thinking. Esser (1998) reports that groupthink is not uncommon. It is persistent. *Risky Shifts*, is a form of group bias. Risky shifts occur when a group adopts a position, which is more extreme than any one person would choose individually; looting, riots during soccer matches, the dot com bubble are examples of risky shifts. At the individual single-person level, biases are well researched and documented by scholars. Kahneman (2002) was awarded a Nobel award in economics for pioneering research on personal bias. In Sect. 1.2, we presented examples of *framing* bias and *saliency* biases. Baron (1998) discusses over 40 types of bias, and Eisenführ et al. (2010) describe over two dozen. Bias is like noise and friction in the physical world. It is always present and very difficult to eliminate entirely. Bias can be mitigated by reducing information asymmetry dissent, and group discussions (e.g. Brodbeck et al. 2002; Schultz-Hardt et al. 2006).

1.3.2.6 Decisions' Performance as Robustness

Robust, in the engineering sense, is not synonymous with rugged, hardened, strong, or vigorous, in the vernacular. We define robust decision performance as the system outcomes, from the *operations-space*, that are highly insensitive to uncontrollable conditions, even when the uncontrollable factors have not been eliminated. In mathematical terms, the behavior of the system is such that its outcomes exhibit limited variability in spite of volatile uncontrollable variables. An example of robust design is an automobile's suspension system. The vehicle rides smoothly on paved streets, dirt tracks, and rocky roads. The wide variations of road surface conditions is barely experienced by the car's passenger. Restaurant service is designed to be robust. Delays in and waiting for the arrival of a meal order can be made tolerable by serving drinks and putting bread at the table.

Consider the following example to illustrate other important factors to consider in addition to maximizing decision outcomes. The top panel of Fig. 1.3 shows a contour map of maximum-value-of-the-firm (MVF) at a time marked by

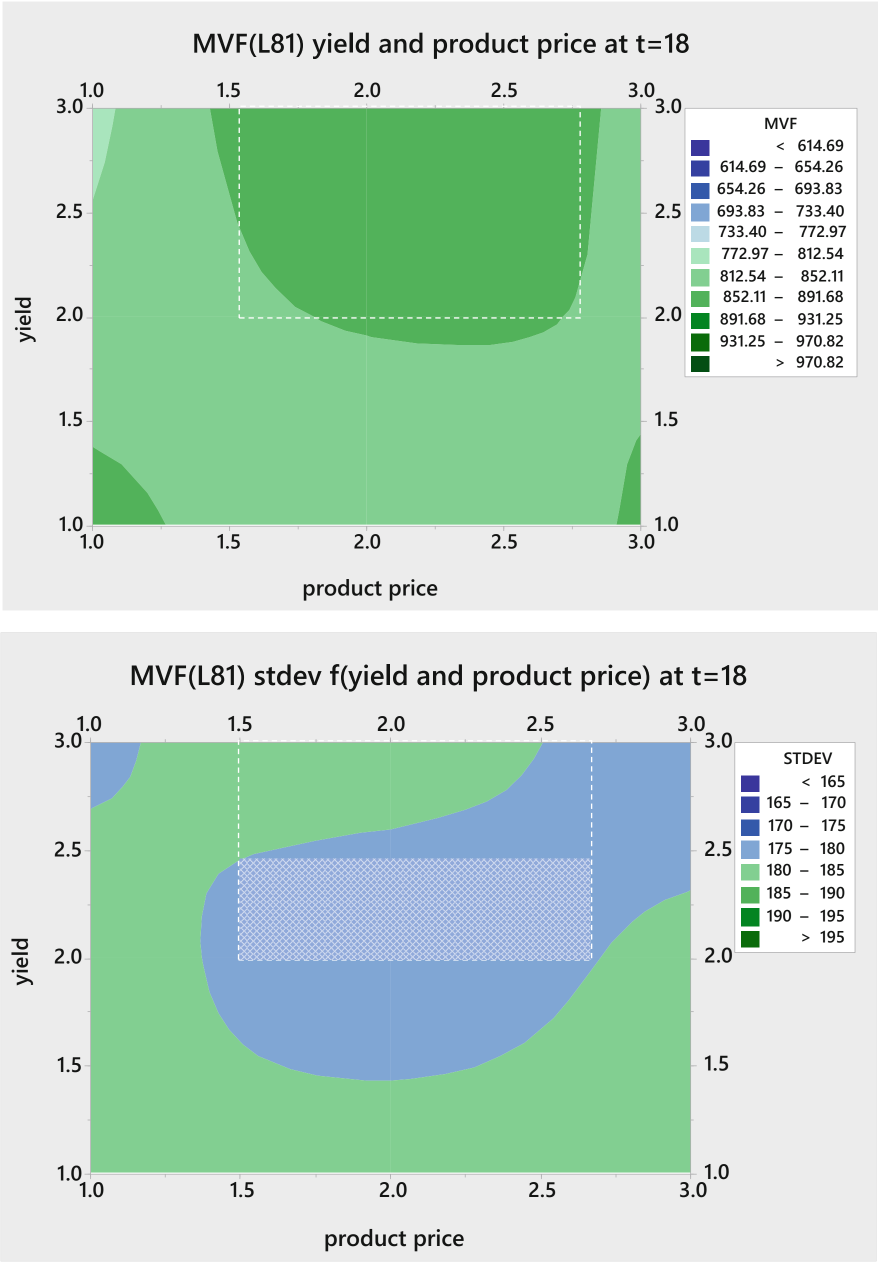

Fig. 1.3 Outcomes in $ and standard deviation. The highest outcome is insufficient if it is more risky. Executive decisions can be designed to perform even when the risk factors that affect performance are not removed. This is the idea of robust decision design

t = 18. The dark green area shows the region where influence of the variables *product-price* and *manufacturing-yield* produce the highest values for standard deviation. The area marked by the dashed rectangle is the region where MVF is lower. The bottom panel of Fig. 1.3 shows the risk associated with that region, where we use standard deviation as a proxy for risk. Designing robust decisions enables us to land in the hatched area. This region is where the output is high and simultaneously risk is lower, and notably where the risk factors have **not** been removed.

How is robustness designed and achieved? It begins by recognizing that two types of variables in the specification determine the behavior of the sociotechnical systems in the Operations space. Managerially controllable variables and managerially uncontrollable (or prohibitively costly to control) variables. Both form the set of variables in the decision specification. The decision design has to determine their right configuration and boundary conditions such that the operations space produces a robust outcome. The uncontrollable variables are an integral part of the design. Of course, the challenges are: how to identify the right set of controllable and uncontrollable variables, how to configure them, and how to specify their boundary conditions. We will show how to design robust decisions.

1.3.2.7 Operational Quality as Repeatability and Reproducibility

Decision is a specification for a sociotechnical system to operationalize in the operations space and produce intended results. Beyond the question of the quality of outcomes, a critical issue is the quality of sociotechnical systems in the operations space. How do we know the data is good enough? How well does the operations space perform?

We adopt the production engineering concept of a *measurement system* to answer these questions. We can think of a measurement system as an ensemble of equipment, procedures, people, and so on, that produces a number, or an index, to a measurement or response. Measurement System Analysis (MSA 2002) is a statistical method to assess the performance of a measurement system (e.g. Montgomery 2001; Creveling et al. 2002). *The operations space is, in effect, measuring outcomes from decision specifications* that are examined in the *outcomes space*. Relative to a reference value, are the outcomes measurements where they are supposed to be? If so, the measurements are *accurate*. Are repeated outcome measurements, under different conditions, produce outcome data that are close to each other? If so, they are *precise*. Does the same social system using the same process and technical system produce the same results? If so, the measurement system is *repeatable*. Does the same technical system using the same process and social system produce the same results? If so, the measurement system is *reproducible*. The key measures *repeatability* and *reproducibility* use statistical variation as indicators. MSA methods enable the analyst to determine the sources of variation in the outcomes and also the quality of the data and processes that generated the outcomes. What are the origins of flaws? Are the measurement tools, the artifact, or the people who are part of the process, or a combination of these factors? Answers to these questions are necessary to help plan improvements to the decision design and the operational sociotechnical systems. In a good quality sociotechnical decision system, one expects to find the large majority of the variation in the design of the alternatives. However, if the bulk of the variation is created by people and processes, then the sociotechnical system may not be suitable.

1.3.2.8 Decision Alternatives as Spanning the Entire Solution Under any Uncertainty Space

This is a surprisingly neglected area (Simon 1997b; Clemen 2008). The executive-management decision process requires the ability to construct alternatives from which a choice can be made. This is very useful, but considerably less so if the alternatives only span a narrow set of alternatives or unrealistic range of uncontrollable conditions. Executives invariably wonder: Are the alternatives sufficiently representative of the possibilities? Have I missed something? And the timeless: "What-if" questions. These questions are impossibly difficult to answer unless the ability to systematically construct alternatives exist.

1.3.2.9 Decisions as Grounded on the Sciences of the Artificial

In spite of the similarities between products and decisions as artifacts, there are also fundamental differences. For the creation of engineering systems, engineers have the singular advantage of physics to inform and guide the design and development of the physical artefact. "Natural science impinges on an artifact through . . . the structure of the artifact itself and the environment in which it performs" (Simon 2001, p. 6). For example, the laws of mechanics and aerodynamics are available to an aircraft designer. Engineers have the physical sciences. Thus armed, engineers can be very rational about decision making.

Executives do not have the advantage of the natural laws of nature to nearly the same extent. Though they have mathematics and the rules of logic, they must also rely on the "soft" sciences; such as, management, psychology and behavioral economics.

Executive management decisions are also based on the Sciences of the Artificial, the science of artefacts (Simon 2001). Sciences of the artificial applies to design. Design of the artificial are concerned with how created functional artifacts achieve satisfactory goals. Sciences of the Artificial is grounded on the doctrine of *bounded rationality*. The doctrine states that decision-makers cannot be perfectly rational, they are limited by the availability of information, time, cognitive capacity and ability. Wehner (2017) writes of the White House: "You're forced to make important decisions in a compressed period of time, without all the information you would like, often causing unintended consequences. There's nothing that prepares you for it, even if you've done it before." Therefore, they cannot optimize or maximize by exploring all possible solutions under all possible conditions with all possible information. Therefore, they **satisfice**. Satisfice means that given the limitations of information, time, and cognitive capability, it suffices to have a satisfactory solution from a set of alternatives. The chosen alternative "is not guaranteed to be either unique or in any sense the best" (Simon 1997a, b, 295), but it satisfices. It is satisfactory and sufficient under the circumstances. But the sciences of the artificial does not exclude optimization or maximization when it is possible.

We address these questions in two ways. One is by providing procedures that permit the exploration of the entire solution space. The executive decision-maker can specify any point or region in the solution space, and have the capability to predict its outcome. Two is the equally useful ability to specify the specific configuration of uncertainties, which cannot be removed but which can negatively impact the outcomes of a decision alternative.

In addition to the ability to explore **any** hypothetical "what-if" question is the ability to predict the standard deviation of any "what-if" decision alternative. This capability gives us the ability to determine the magnitude of the risk. An alternative with a large standard deviation is more risky than one which has a lower standard deviation. Frequently it is useful to be able to make trade-offs between output and risk.

The important question is how to mitigate biases in the management decision process. We present actionable technical and social procedures, grounded on managerial practice and research findings, on ways to mitigate individual and group biases.

1.3.2.10 Paradigm Effectiveness as Readiness for-Work and to-Work

Our paradigm is prescriptive. The goal is an executive decision-management methodology for robust decisions. The question is: Does the methodology work? The answer to this question cannot be approached with a mental model of the light bulb metaphor. Executive decisions are not simple physical artefacts. The organizational units that analyze a decision situation, design the decision as an intellectual artefact, and sociotechnical units that enact and execute the decision specifications are non-trivial complex sociotechnical systems. We approach the question of "does it work using the analogy of a new prescriptive pharmaceutical drug. First, the chemists and developers of the drug must verify the drug is *functional* in their laboratories. This confirms the drug is *ready-**to**-work* out of the laboratory. Second they must verify the drug's *efficacy* with people in the field. This confirms the drug is *ready-**for**-work* with people. A drug works if and only if both of these conditions are satisfied. The US Food & Drug Administration (FDA) has stringent laws to ensure this kind of readiness. To our knowledge there is no such rigorous process to verify readiness for executive decision readiness. To that end we develop a metrology and instruments to meet this need. *To our knowledge this is the first instance of* *such an approach and such a metrology in the field of the field of prescriptive paradigms.*

1.4 What Makes Executive-Management Decisions Challenging?

No executive needs to be convinced that executive management decisions are difficult and risky. But what are the reasons that makes them difficult and risky? Management and organization scholars argue that the structure, form, and conditions of ill-structured, messy, and wicked problems reveal and explain the problematic nature of executive management decisions. These are the subjects of discussion in this section.

1.4.1 Ill-Structured, Messy and Wicked Problems

Ackoff (1974), the seminal systems and management scholar, was the first to observe that the difficulty of corporate problems arise from the fact these decision situations are caused by problems of problems, systems of problems. He called these situations *messy* because addressing only one problem in isolation invariably results in unintended effects. "Time after time. . .you'll find people are reacting to a problem, they think they know what to do, and they don't realize what they're doing is making a problem" (Dizikes 2010, p. 20). Ackoff (1974) also argued that the sum of optimal solutions to elemental problems may, in fact, be suboptimal to the whole. Our example, of IBM's growth strategy, illustrates this phenomenon. One must address a system problem by understanding the behavior of the subsystems, as well as, how they interact to collectively determine the behavior of the whole. Otherwise the problem and the results become messy. The word "mess" has negative connotations. But we should also view it as a colorful descriptive term for difficult and complicated system problems; rather than only as a pejorative adjective.

Rittel and Webber (1973), also ground-breaking system thinkers and management scholars, created the idea and coined the term *wicked* to characterize another challenging and complementary property of systems (Appendix 1.1). Wicked means resistant to formulaic or structured programmed solutions, rather than evil or malicious. Global warming, safety, poverty, competitiveness, and most social problems are wicked. Typically wicked problems have many stakeholders with disparate interests and inconsistent interpretations of the problems. The upshot is ambiguous objectives and confounded evaluations of performance. Such problems are very difficult to satisfy all stakeholders equally well. The effort to solve one aspect of a wicked problem may reveal or create other problems. And what is possibly worse, some stakeholders "fight back when trying to deal with them

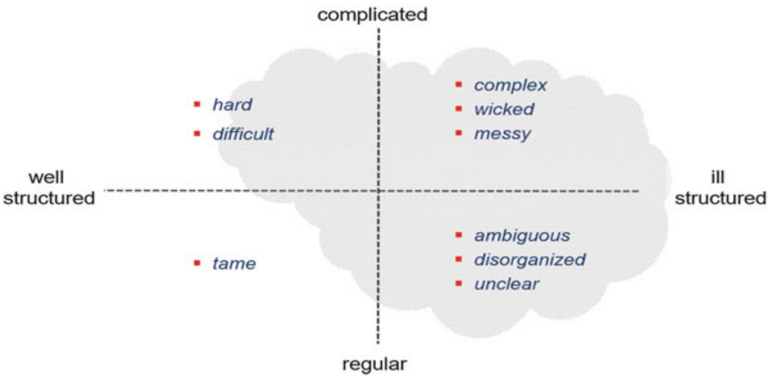

Fig. 1.4 A taxonomy of executive-decisions and their distinguishing attributes

(Ritchey 2005).” Wicked problems are *iatrogenic* (Boal and Meckler 2010). In our earlier IBM China example, IBM made a sizeable contribution of computers and software to a large number of Chinese universities. Unexpectedly, we were subjected to criticisms from some powerful Chinese authorities suggesting that the contributions would have been more appropriate and useful had they been directed at their favorite national research laboratories. The old saw, “no good deed goes unpunished”, seems appropriate to wicked problems. This property causes wicked systems to punish problem solvers, send false and mixed feedback (Hogarth 2001).

There is also the class of *super wicked* problems (Levin et al. 2012). To qualify, four additional criteria to the original ten from Rittel and Webber (1973) must apply (Appendix B). “Time is running out” and the “problem solvers themselves may be part of the problem” are two such criteria. A result of super wicked problems is what Levin et al. (2012) call a *tragedy*.

Tame problems are what Rittel and Webber (1973) describe as well posed and have known solution framework and methods that produce true-or-false answers. Many engineering problems belong to this class, Operations Research problems also belong to this class. *Tame* does not mean easy; it means tractable. Nobel laureate Herb Simon classifies tame problems as *well-structured* (Simon 1977). The complementary set, he calls *ill-structured*. With great insight, he argues cogently that the boundaries between ill- structured and well-structured problems are **not immutable**; new scientific findings and concepts can make investigation and solution of ill-structured problems possible. Although executive management situations and decisions are not tame; and indeed ill-structured, messy and wicked, our new prescriptive paradigm to executive-management decisions is an example of a new and effective approach to a special class of ill-structured, messy, and wicked problems. The shaded region in Fig. 1.4 illustrates the space of executive-decisions.

How and why these problems become wicked? We need to explore the issues and their implications on executive-management decisions, so that then we can formulate principles for the design of effective decisions to ill-structured, messy, and wicked problems.

1.4.2 Determinants of Messes and Wickedness

It is not sufficient to have a taxonomy and classification criteria to know we are facing a messy or wicked problem that is ill-structured. We would like to have a typology of messes and wickedness, as well as, their key determinants so that we can take appropriate countermeasures in the decision space. Revisiting Fig. 1.2, it is natural to turn our attention to the problem, solution, operations, outcomes, and commitment spaces as the loci where specific messes and wickedness are concentrated. A review of the literature, and of Appendices 1.1, 1.2, 1.3, 1.4 are summarized in Table 1.2. The dearth of items in the commitment spaces identifies a neglected research area. The emphasis is biased towards the "front end" of the process—problem formulation, analysis, design, and how to get "good"" outcomes. The life-cycle of the entire process is truncated. This is similar in engineering and product design. The life-cycle process is truncated at release to manufacturing. Work on the front-end, then "toss it over the wall".

What are the drivers of these issues? Close examination of the issues in Table 1.2 reveals that four factors make executive-management decisions' difficult and risky. They are: *complexity, uncertainty, organizational, and disciplinary* factors (e.g. Leleur 2012; Kahlen et al. 2017; Keeney 1992). We will sketch each of these factors, examine how they interact and infer the system effects they create. By understanding the system effects, we hope to isolate impactful executive-management policies on the behavior of sociotechnical systems in the operations-space.

1.4.3 Contributing Factors: Complexity, Uncertainty, Disciplinary, and Organizational Factors

In this section we discuss the complexity, uncertainty, organizational and disciplinary factors. The columns of Table 1.3 summarize the key variables for each factor. For example, the number of subsystems determine the complexity of a system. The combination, of the various disciplines and practice of engineering, design and cognitive psychology, contribute to the messiness and wicked nature of a problem. We first explain each factor in broad strokes, then we examine the interactions between them (Table 1.4); we then discuss the implications to executive-management decisions. We follow with measures that can deal with each of these factors. Consistent with the view that executive management decisions are messy and wicked systems problems, we close this section with a system view of these factors to draw some inferences.

Table 1.2 Loci of concentration of executive management decision issues

Problem space	• *RW1*. No definite formulation of wicked problems. • *RW7*. Wicked problems are essentially unique. • *RW9*. Every wicked problem can be explained in numerous ways. • *Simon*. Cannot have or know all relevant information. • *Kahneman & Tversky*. Cognitive biases.	• *Simon*. Ill-structured problems. • *Weick*. Importance of sense making. • *March*. Proper problem framing is fundamental. • *Vennix*. Group mental model building. • *Grote*. Not knowing for sure. • *Howard*. Right frame as a criterion for a good decision. • *Mohammed et al*. Team mental models. • *Hester et al*. Too many goals.
Solution space	• *RW2*. No stopping rules for wicked problems. See RW4. • *RW6*. Wicked problems. No enumerable set of solutions. • *RW3*. Wicked problems have no true-or-false solutions. • *Ackoff*. Solutions seldom stay solved. • *RW4*. There is no immediate test of a solution to a wicked problem. • *RW8*. A wicked problem is a symptom of another wicked problem. • *RW10*. With wicked problems, the planner has no right to be wrong. • *Erden*. Team tacit knowledge for implementation and execution. • *Brodbeck et al*. Effect of team hidden knowledge and information. • *Mohammed et al*. Team effectiveness in problem solving.	• *Levin et al. #4*. Policies discount future irrationality. • *Vennix*. Group mental model building. • *Simon*. Ill-structured problems have no precedents to follow • *Kahneman and Tversky*. Existence of systematic bias. • *Howard*. Right alternatives as criterion for a good decision. • *Howard*. Right information as criterion for a good decision. • *Edwards*. Bad decisions unlikely to lead to good outcomes. • *Levin et al. #3*. Those seeking to end problems may also be causing them. • *Lu et al*. Hidden information in team decision analysis. • *Kahneman & Klein*. Expertise improves intuition. • *Hester et al*. Data sufficiency. • *Otto and Wood*. *Ex ante* vs *ex post* modeling.
Operations space	• *RW2*. Wicked problems have no stopping rules. • *RW4*. No immediate test of a solution to a wicked problem. • *RW5*. Solution to wicked problem is one shot, no learning by trial-and-error • *RW6*. Wicked problems do not have enumerable potential solutions. • *Levin et al. #1*. Time is running out.	• *Levin et al. #2*. No central authority. • *Levin et al. #4*. Policies discount future irrationality. • *Simon*. Bounded rationality. Constraints of processing time and resources. • *Cherns*. Principles. Sociotechnical systems design. • *Howard*. Clear preferences as a criterion for a good decision. • *Howard*. Right decision procedures a criterion for a good decision

(continued)

Table 1.2 (continued)

	• *Levin et al. #3*. Those seeking to end the problem are also causing it. • *Banks & Milland*. Distributed mental models. • *Hester et al*. Temporal effects.	• *Ropohl*. Hierarchical execution • *Hogarth*. Wcked propoblems have wrong feedbacks.
Performance space	• *RW3*. Solutions to wicked problems are not true-or-false. • *RW4*. There is no immediate test of a solution to a wicked problem. • *RW8*. Every wicked is a symptom of another wicked problem.	• *RW10*. With wicked problems, the planner has no right to be wrong. • *Levin et al. #4*. Policies discount future irrationality. • *Simon*. Bounded rationality. Satisficing. • *Thompson*. Uncertainty. • *Taguchi*. Robustness.
Commitment space	• *Howard*. Quality decisions require decisive executive. • *Potworowski*. Indecisiveness defined and its causes identified. • *Simon*. Ambivalence is a negative executive trait.	• *Bernheim and Bodoh-Creed* People prefer decisive leaders. • *Kelman et al*. Decisiveness differentiates outstanding leaders.

RW#: criterion # of Rittel and Webber (1973)
Levin et al. # (2012): criterion # of Levin et al. (2012), Mohammed and Dumville (2001), Bernheim and Bodoh-Creed (2016)
Weick (1993, 2001), Weick et al. (2005), Grote (2009), Ropohl (1999), Simon (2006), Hogarth (2001), Cherns (1976), Ackoff (1974), Simon (1977), Lu et al. (2012), Otto and Wood (2001), Lipshitz and Strauss (1997), Rotmans and van Asselt (2001), Tang and Salminen (2001), Banks and Millward (2000), Kahneman and Tversky (2000), Dantan et al. (2013), Schulz-Hardt et al. (2006), Kahneman and Klein (2009), Howard (2007), Vennix (1999), Taguchi et al. (2000), Potworowski (2010), Hester and Adams (2017), Erden et al. (2008), Edwards (1992), Thompson (2004), Brodbeck et al. (2007), Kelman et al. (2014)

Table 1.3 Factors contributing to messy and wicked problems

Factors' variables			
Complexity	Uncertainty	Disciplinary	Organizational
# subsystems # variables # disciplines # organizations # interactions	# aleatory factors # epistemic factors knowledge, information # psychological factors doubt, fear…	• complex systems • decision theory • cognitive psychology • engineering design	• decision-maker • sociotechnical systems control • bias • goal congruence • as a production system

is shorthand for "number of …"

Table 1.4 Results of two factor interactions

	Complexity	Uncertainty	Disciplinary	Organizational
Complexity	***Variables*** *# factors, variables* *# disciplines* *# organizations* *# interactions*	↑ uncertainty space ↑ cognitive load ↓ controllability	↑ complexity space ↑ disciplinary factors ↑ cognitive load ↓ controllability	↑ complexity space ↑ managerial factors ↑ bias ↑ cognitive load ↓ controllability
Uncertainty	↑ uncertainty space ↑ uncertain space ↑ cognitive load ↓ controllability	***Variables*** *# aleatory factors* *# epistemic factors* *# psychological factors*	↑ uncertainty space ↑ disciplinary factors ↑ cognitive load ↓ alignment ↓ controllability	↑ uncertainty space ↑ managerial factors ↑ bias ↑ cognitive load ↓ controllability
Disciplinary	↑ complexity space ↑ disciplinary factors ↑ cognitive load ↓ controllability	↑ uncertainty factors ↑ disciplinary factors ↑ cognitive load ↑ bias ↓ alignment ↓ controllability	***Variables*** • *complex systems* • *decision theory* • *cognitive psychology* • *engineering design*	↑ disciplinary factors ↑ solution space ↑ managerial load ↑ bias ↓ alignment ↓ controllability
Organizational	↑ complexity space ↑ disciplinary factors ↑ cognitive load ↓ controllability	↑ uncertainty factors ↑ managerial factors ↑ bias ↑ cognitive load ↓ controllability	↑ disciplinary factors ↑ solution space ↑ cognitive load ↑ bias ↓ alignment ↓ controllability	***Variables*** • *managerial load* • *bias* • *alignment* • *control: stability & flexibility*

The diagonal cells summarize the factor's characteristics. Off-diagonal are interactions

Complexity factors Complexity is an emergent property of systems that makes it difficult to understand the ins and outs of the behavior of a system. Complexity is an emerging property of a system that is comprised of a large number of interacting parts. Interactions among these elemental units creates complexity. The parts can be physical as in products, social units as in organizations, or conceptual units as in a mathematical theorem.

Possibly the most detrimental effect of such diverse complexity is that it imposes a formidable cognitive load on those who must deal with it. Complexity adds to the sense-making efforts necessary to develop an effective mental model of the decision situation and to formulate potential solutions (e.g. Kahlen et al. 2017; Hester and Adams 2017; Weick 1993, 2001). In addition to these impacts in the solution-space, complexity also stresses a system's ability to maintain a stable operating equilibrium, homeostasis, especially under uncertain environmental conditions. Non-trivial social and technical control mechanisms must be designed, developed, and operated to maintain homeostasis and exceptional design for homeorhesis.

Executive management decisions are necessarily complex. Simple problems do not come to the attention of senior management. To attack complexity, we must address the cognitive load imposed by the problem. A decision situation and its potential solutions need not be represented in all its glorious complexity. Making complexity less complicated is a very effective strategy to make complexity more tractable. Complexity is a technical property of systems. Complicatedness, a cognitive property, is the intensity of the mental load imposed on the person or organization that has to deal with the complex artifact (Tang and Salminen 2001). Complicatedness is our incompetence to make complexity cognitively tractable and manageable. Engineers routinely address this problem with great effectiveness.

Consider a car's automatic transmission. As a physical artefact, it is substantially more complex than a manual transmission. Yet no one will claim that the manual transmission is easier to use. It is far less complicated to use—not because the automatic transmission is less complex as an engineering object, but because, to the driver, it is operationally uncomplicated. As this example shows, it is a fortunate paradox that architected complexity, which addresses how a system will be used, can make a complex system less complicated. Complexity is like cholesterol. There is good cholesterol and there is bad cholesterol. There is good complexity and there is bad complexity. Complexity that is complicated is bad complexity. Designed complexity, which presents a simple system image with uncomplicated operational interfaces to those who must made operational decisions, is good complexity. The operational interface that is presented is the **system image** behind which is the sociotechnical system structure of parts. By design, the system image can be made uncomplicated without exposing the technical complexity to the one who must make specific use of the system.

But how to make decisions less complicated? Look past surface details, focus on underlying principles to develop a "big-picture" to form an abstraction that cuts through layers of the problem. The abstraction identifies only the essential variables of the problem (Etmer et al. 2008; Simon 1997a, b). The big-picture problem, of the manual transmission, is its clumsy set of gear-shifting operations that require hand-foot-pedal dexterity and synchronization. The essential variable is the clutch, which is now eliminated in an automatic transmission. The abstraction is the new operational interface, which is no longer complicated for the driver. The face of a watch face is another exemplar of a well-designed system image. No matter what technology is used under the covers, the cognitive and operational system image is consistently the same. A short hand for hours and a long hand for minutes. An uncomplicated **system image** has been designed for those who do not have the need to deal the complexities of the system. Even a toddler can tell time without imposing knowledge of springs, gears and escapements.

Uncertainty factors Frank Knight (1985–1972) renowned professor, at the University of Chicago and teacher to Nobel economists, defined uncertainty as those situations that cannot be represented with probabilities (Knight 1921, 2009). Risk, on the other hand, can be imputed with probabilities. Uncertainty is a more abstract concept than risk (Grote 2009; Dizikes 2010). "Uncertainty appears as the fundamental problem for complex organizations, and coping with uncertainty as the essence of the administrative process" (Thompson 2004, p. 159), particularly to executive-management decisions. Downey and Slocum (1975) write that uncertainty is so frequently used that "it is all too easy to assume that one knows what he or she is talking about." Notwithstanding, this is our definition:

Uncertainty is a condition which makes a decision-maker insecure or unable to commit to specified outcomes due to variables outside management's control.

Uncertainty diminishes management's ability to act deterministically (Thompson 2004; Dizikes 2010) or with confidence (e.g. Dequech 1999). A key inescapable and consistent question to decision-makers is "what-if?" The question is undecidable without knowledge of the uncontrollable variables that interact with governing variables designed to produce intended results. What are the managerially uncontrollable variables? They are the aleatory, epistemic, and psychological variables that are part of the decision situation. Aleatory uncertainty is the inherent, irreducible, randomness in the universe, environment and systems. For example, the frequency of sun spots, a resistor's thermal noise, a person's motives and intentions. Epistemic uncertainty is about not knowing due to "incomplete knowledge about a physical system or environment" (e.g. Dantan et al. 2013) or about insufficient information to act (Lipshitz and Strauss 1997). Uncertainty is also about having too much (correct and incorrect) information, which can lead to the inability to make-sense or infer meaning of a decision situation (Weick 1993, 2001). Finally, uncertainty is psychological. It is "not knowing for sure" (Grote 2009; 11). "In the context of action, uncertainty is a sense of doubt that blocks or delays action" (Lipshitz and Strauss 1997). Individually and collectively, these factors contribute to uncertainty.

However, not all uncertainty is bad. Uncertainty is neutral. There is good uncertainty and there is bad uncertainty. Uncertainty also presents opportunities. For example, consider IBM's Burlington microprocessor plant. At the end of the production line, some chips' exceed performance parameters; others underachieve them. IBM's answer, to this kind of uncertainty, is to use the high performance chips for pricey high-end servers. Low performance chips are used in low-end and lower-price servers. With one design and one manufacturing facility, IBM is able to produce a family of compatible computer-servers across a wide range of price-performance. This was an effective strategy to lower the cost base of all servers. This is good use of uncertainty. But uncertainties can also be catastrophic. For example, the unexpected collapse of highway bridges, leaks in nuclear power plants. When or whether these events will occur are unpredictable.

Thus uncertainty can be understood "in terms of lack of control..." ... and "inability of an individual or system to influence situations for achieving certain goals (Grote 2009, p. 15, 51)".

What can be done about uncertainty? In the solution-space characterize design the decision in an uncomplicated manner, but do not omit uncertainty. Use a frugal number of the set of key managerially controllable variables and characterize uncertainty by identifying the key managerially uncontrollable variables. Using both of sets kind of variables, design the decision systems so that its intended outputs are highly immune to the behavior of uncontrollable variables. Design (verb) decisions that are robust using our engineering approach. This is what this book is about.

Disciplinary factors Executive-management decisions "do not observe disciplinary boundaries" (Rotmans and van Asselt 2001). These decisions are necessarily multidisciplinary. For example, for a high-technology consumer-product business such as Apple, executive decisions necessarily involve technologies, consumers' psychology and tastes, manufacturing, distribution, sales and services, financial considerations such as cost, pricing, and so on. The interactions and the system effects among these disciplines are many and intricate. All these considerations reinforce the messy and wicked nature of the decisions that executive management must address.

The variety, of disciplines, challenges executive managers in four major ways. One is it adds to the cognitive load. Senior executives are unlikely to have expertise in the all areas they are responsible for. Certainly their direct reports will have more experience, expertise, and nuanced appreciation of subtle significances of fine grained details. Two, during the decision development life-cycle, a variety disciplines are required at different phases of the process. Three, the decision engineering process must consider the behavior and performance of the sociotechnical systems and processes that will execute a decision. If such systems are operating in place, the decision must consider their behavior. If creating a "green-field" organization from the ground up, then we must consider how to design such a system. Regardless, the effect of uncertainty on system behavior must be addressed. And four, the field of executive-management decisions is multidisciplinary. For example, Howard (2007) writes that four disciplines are integral to decision analysis—system analysis, decision theory, epistemic probability, and cognitive psychology. (We will discuss in great more detail in the next chapter). To this list we add engineering design.

The target of our system analysis are complex social technical systems that must be put in place for the decision execution. The premise is that organizational objectives and performance are best met by the synergistic interactions between social and technical systems. The idea is not new. Cherns (1976), Clegg (2000), Baxter and Sommerville (2011) present principles to guide the design of the design and management of such systems (Appendix 1.3 and 1.4). Unexpectedly, uncertainty is nearly invisible as a factor.

The corpus of decision theory and practice is segmented into four schools of thought—normative, descriptive, prescriptive, and declarative. Inevitably there is overlap among the four strands. Descriptions and prescriptions need norms from normative theory, but each theory has distinct areas of emphasis. The focus of normative theory is the logical consistency of decision-making. It is grounded on the axioms of utility theory (von Neumann and Morgenstern 1964). Descriptive theory is, as a general rule, concerned with explaining why and how people decide the way they do. Descriptive theory emphasizes empirical and experimental results of behavioral economics and psychology. The priority of prescriptive theory is to help people and organizations make better decisions. The theory emphasizes practice and demonstrable usefulness. Declarative strand are declarations, admonishments, proverbs and narratives from high profile successful executives, consultants, self-proclaimed experts and the like. (We will discuss these four strands in more detail in the next chapter.)

The implementation of a decision must work within the streams of action of multiple disciples, which must interoperate and interact with an uncertain environment in different and difficult ways. "… the nexus is not only moving but sometimes quite difficult to fathom" Thompson 2004, p. 148).

Organizational factors We defined an executive as one who is designated as the person responsible and accountable for an organizational mission, whose span of control is at least three layers deep, and has the power and resources to commit to action. Each level of his organization can be considered as an action system, an operational subsystem (Ropohl 1999). Each level is not a random collection, but an abstract, integrated and functionally-thematic operational collection of subsystems. Organizational depth of at least three levels means that the organization's size is an important factor. Size combined with complexity, uncertainty, and disciplinary factors have significant implications. And unlike Robinson Crusoe, executives responsible for decisions and their outcomes cannot do the whole job alone. They must rely on an organization's for advice and counsel, analysis, and implementation. This is the principle of *excluded reductionism.* Sociotechnical systems are organized as hierarchical action systems (Ropohl 1999) to enable specialized initiatives that require special skills. Simon (1997a, b, 2001) articulates a complementary principle of *near-decomposability* of complex systems. It states that complex systems are decomposable into a collection of nearly-linear interacting subsystems.

These considerations lead to the issue of alignment, i.e. the coherence and consistency of agents' perceptions who must apply their skills to the problem. "[Any] formulation of a problem is a result of what the observer can 'see' and what the intentionality is behind the way the problem is understood (Leleur 2012)." Executives must ensure that the social system and its member 'see' the problem or opportunity, to be addressed, in a compatible way. *Seeing* things in a compatible way does not mean the *same* way, but mutually complementary and as a consistent cohesive whole (e.g. Brodbeck et al. 2002; Schultz-Hardt et al. 2006). Designers of a bicycle do not all think only of wheels. Each member will bring complementary information that can make the organization task of "seeing" richer, more complete and compatible. Systems and procedures must exist that can uncover latent information that remains hidden unless elicited through effort. Discussions, analysis and debiasing are critical processes to achieve cognitive alignment of mental models.

In a nearly-linear decomposable system, subsystems forming the organizational partitioning under the decision-maker are thematically specialized into functionally domain-specific groups. It follows that partitioning means that domain-specific subsystems' managers necessarily are supposed to optimize to their organizational objectives. This can occur at the cost of peer organizations, and at the cost of the whole. ***Where partitioning exists, synthesis is necessarily required of the local units for a macro optimization, potentially at the cost of sub-optimizing some to improve the whole.*** The military addresses this problem by clear chains of command and by simultaneously having a staff that reports directly to the senior officer for independent opinions that can, when necessary, *adjust* the actions and judgements of the elements to achieve the coherence of an overall goal. It is standard practice for IBM senior executives to have staffs who play this role. Typically the composition of this group is a mix of deep expertise, experience, and promising young managers to learn in a "penalty free" environment. Kaplan and Norton (2005) recommend this practice for the office of a CEO, although it is not clear why they limit it to that exalted level.

Arrow's Impossibility Theorem comes to mind as an executive management challenge (Arrow 1950, 1963; Morreau 2014). Arrow won the 1972 Nobel Prize in economics. Arrow poses the question whether there are procedures for deriving an ordering of the alternatives that is consistent with every individual preference in the group. The theorem asserts that it is impossible without a dictator. Does this mean that teams and group effort is about dictatorships? And since we consider decisions as an engineering activity, does engineering design requires a dictator? Not at all, Arrow's theorem assumes that preferences are ordinal and does not consider their weights of multi-criteria. Engineering design considers degrees of preference (Scott and Antonsson 1999), which is not considered in the Arrow Impossibility Theorem. Consequently a group preference is achievable. Thompson (2004, p. 158) summarizes the alignment issue in organization management:

> . . . co-alignment is not a simple combination of static elements, but a coherent behavior that is consistent with the meaning of actions in the achievement of organizational goals and objectives—institutionalized action of—technology and task environment into a viable domain . . . keeps the organization at the nexus of several necessary streams of action.

Management of the static must be addressed, as well as, the nexus of action, *viz.* the dynamics of interactions. The statics and dynamics of the complexity, uncertainty, disciplinary, and organizational factors are the next subject in Sect. 1.5.

1.5 System Effects of Contributing Factors

1.5.1 Statics of Factor Interactions

Complexity, uncertainty, disciplinary, and organizational factors interact as shown in Table 1.4. The four factors form a 4 × 4 matrix. The diagonal cells identify the elemental variables of each factor (Table 1.3). Each off-diagonal cell shows the effects of the row-factor and column-factor interactions. The upward arrow ↑ indicates that the interaction increases the identified effect. The downward arrow ↓ indicates the opposite.

A few examples suffice to illustrate cell entries in Table 1.4. For example, the ↑ *cognitive load* entry in the [*complexity* × *organizational*] cell indicates that the combination, of the complexity variables with the disciplinary variables, imposes a *heavy cognitive load* on all who must work with a problem with this kind of combination. This is typical of messy and wicked problems, which frequently lead executives to tackle these problems piecemeal, e.g. IBM "grow with the industry". Optimizing the parts does not necessarily optimize the whole. Similarly, consider the [*uncertainty* × *disciplinary*] cell entries, ↑ *bias* and ↑ *cognitive load.* Weick (1993) wrote of such a case, in which such a combination led to the collapse of sense-making and the death of 13 firemen during a forest fire. Men leading the fire fighters made a series of assumptions about the fire and employed fire-fighting procedures that did not make sense.

Consider the [*disciplinary* × *organizational*] cell entries of ↑ *disciplinary factors,* ↑ *solution space,* ↑ *controllability.* The IBM chip manufacturing example, in the uncertainty section, illustrates how the issues of manufacturing variability and controllability, as well as, chip design were resolved by the decision of using a single design and let manufacturing variability sort themselves into performance categories destined for price-differentiated models of a product family.

Static representations of the factor interactions (Table 1.4) do not reveal the dynamics of the system effects that need to be considered in the design of decisions. To that end, we first simplify Table 1.4 by eliminating repeated entries to get Table 1.5. Using the entries from Table 1.5, we analyze their dynamic system interactions. Our objective is to distill a parsimonious set of fundamental principles for executive-management decisions.

Table 1.5 Key control points of system effects of messy wicked problems

• size uncertainty space • size complexity space • cognitive load	• size solution space • size decision space • disciplinary factors	• bias • controllability • alignment

1.5.2 System Dynamics of Interactions

Executive management decisions are not static situations. On the contrary, they are structures of systemic interactions, of sociotechnical subsystems. We now turn our attention to the dynamic system behavior of these subsystems using a gestalt model of the dynamic system. By analyzing the system, we hope to identify some fundamental policies and decision design principles. Figure 1.5 shows the dynamic factor-interactions and key effects derived from Table 1.5.

The four factors addressed in Table 1.4 are near the top under the label of **problem**. The dynamics of the causal system effects are shown by the sequence of cause and effects identified by arrows. A loop is a continuous sequence of arrows that begins and ends at the same point. We can think of a loop as a subsystem.

For example **B1**, the *fix-errors* loop (Fig. 1.6). The notation is used to indicate that the extent to which *intended-outcomes* are the results of decisions. Dearth of errors reduces the volume of *fixes* required. This promotes positive *learning* that in turn reinforces the *mental model* of the decision's design. This sequence facilities organizational *alignment*, which buttresses the *decision's effectiveness that* of course help generate the right *intended outcomes*. The notation (*effect*.***x***) **+**→ (*effect*.***y***) means that **more** of (*effect*.***x***) produces **more** of (*effect*.***y***). It also means that **less** of (*effect*.***x***) produces **less** of (*effect*.***y***). In other words (*effect*.***x***) and (*effect*.***y***) move in the ***same direction.*** In mathematical terms,

$$\frac{\partial(effect.y)}{\partial(effect.x)} > 0 \tag{1.1}$$

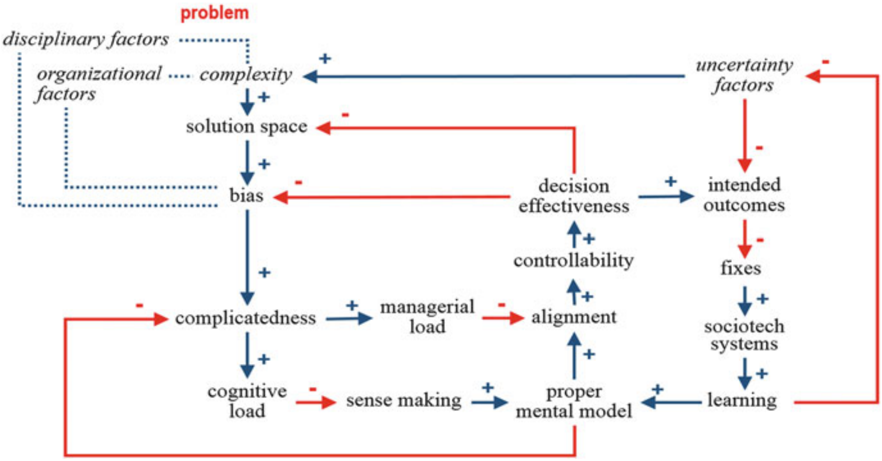

Fig. 1.5 Dynamic system interactions of factors

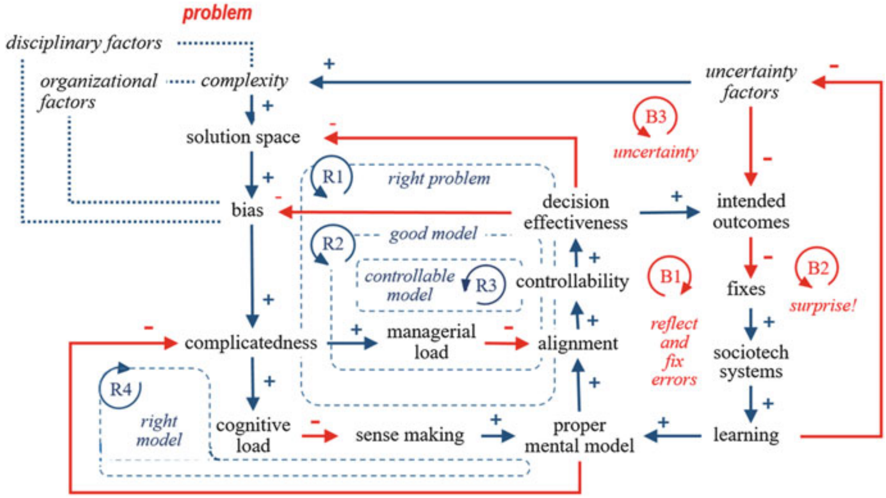

Fig. 1.6 System interactions of reinforcing and balancing loops

The notation (*effect*.***p***) ——→ (*effect*.***q***), means that **more** of (*effect*.***p***) produces **less** of (*effect*.***q***). Also **less** of (*effect*.***p***) produces **more** of (*effect*.***q***); *effect*.***p*** and *effect*.***q*** move in ***opposite directions, i.e.***

$$\frac{\partial(effect.p)}{\partial(effect.q)} < 0 \tag{1.2}$$

Fixes imply that *intended-outcomes* have not been generated. *Fixes* break the positive reinforcing sequence of effects in loop **B1**. Thus, **B1** is a ***negative balancing loop***. A loop of arrows with all the same signs, or with an even number of ——→, produces a ***positive reinforcing loop***. And a loop with arrows that have an odd number of ——→ produces a ***negative balancing loop***. (This follows from the multiplicative nature of the chain-rule for taking partial derivatives)

Now consider the loop **R1**, the *right-problem* loop. This reinforcing loop shows the effects of the ***right problem*** being solved (Weick et al. 2005). This is a subsystem like **B1**. We begin the **R1** loop at the complex *solution space*, in which participants have *biases* that introduce c*omplicatedness to* their cognitive load. *Cognitive load* challenges *sense-making*, which when done properly produces a *proper mental model* for decision making. The ——→ indicates the converse, i.e. an excessive *cognitive load* impedes *sense making*. But proper *sense making,* mediated by proper mental models, promotes *alignment* of the organizational participants (Banks and Millward (2000), management, and processes. Recall we defined alignment as the consistency and coherence of those who have the need and ability to act in order to solve a problem. From a socio-technical system perspective the right interactions must be actionable and executed. It follows that alignment contributes to organizational c*ontrollability,* which improves operations stability, flexibility and therefore advances *decision effectiveness*, which reduces the size and complexity of the *solution space*. **R1** has an even number of $--\rightarrow$ arrows. It is thus a positive reinforcing loop.

R4—the *proper mental model* loop—is a positive reinforcing loop. It shows the reinforcing effect of reducing *complicatedness* on the *cognitive load,* which the senior executive and its staffs have to deal with. Complexity is a technical property of a system. This technical property needs to be transformed into a cognitive representation that is *uncomplicated*, readily understood and useful for the kind of thinking required from the person[s] who have to work with it. An uncomplicated representation of the problem enhances the ability of *sense making* that in turn enhances the prospects of forming a *proper mental-model* (e.g. Erden et al. 2008; Weick 2001; Mohammed and Dumville 2001).

R2—the *good model* loop—is also a positive reinforcing loop. This loop shows the positive reinforcing effect of a *proper mental model* enables *controllability* of operations that demonstrates the mental model works. The **R3**—the *controllable model* loop—is also a positive reinforcing loop. It shows that an *unbiased* and *uncomplicated* operational model makes the process more stable and *controllable* to improve a decision's operational *effectiveness*. The organization must strive for controllability to provide stability and flexibility (e.g. Grote 2009; Banks and Millward 2000).

B1 is the *reflect and fix errors* negative balancing loop. The **B1** loop and the reinforcing loop **R2** are both influenced by *decision design*. The effectiveness of *decision design* determines whether the *controllable model* loop **R2** or the *fix errors* loop **B1** of dominates the interaction. A fundamental property of complex systems is that where there are "positive reinforcing loops" and "negative balancing loops", the behavior of the system is fundamentally determined by the loops that dominate other loops. For example, consider the interactions between **R1** and **B1**. The behavior of the composite **R1** and **B1** is determined by the accuracy of the *mental mode*l that frames the decision, which in turn determines the *decision's effectiveness*. The extent to which the decision is effective determines the nature and number of *fixes*. The volume of *fixes* can be viewed as a proxy for, not only, the accuracy of the *mental model*, the *decision effectiveness,* but also, the organizational ability to reflect and learn from outcomes (e.g. Senge et al. 1994; Greve 2003). We say the reinforcing positive loop **R1** is balanced by the negative reinforcing loop **B1**.

Consider the negative balancing loop **B2**, the *surprise!* loop. As a result of fixes to produce *intended outcomes*, *learning* takes place that reduces *uncertain*ty factors. This process is mediated by the *socio-technical systems* in place. It is here, in conjunction with **B1**, where *reflection* about the outcomes and the effectiveness of the sociotechnical processes take place. *Uncertainty c*ompounds c*omplexity*, by increasing the variety of potentially negative influences on the intended outcomes. This effect expands the *solution space* and sets in motion the **R1**, **R2**, and **R3** loops. The *uncertainty* balancing loop **B3** has the widest coverage—from *uncertainty factors* to *cognitive load*, to *mental model*, to *decision effectiveness*, to *learning* and back to *uncertainty* factors—shows the pervasive influence of uncertainty on the system. And therefore, the importance of addressing uncertain the design of a

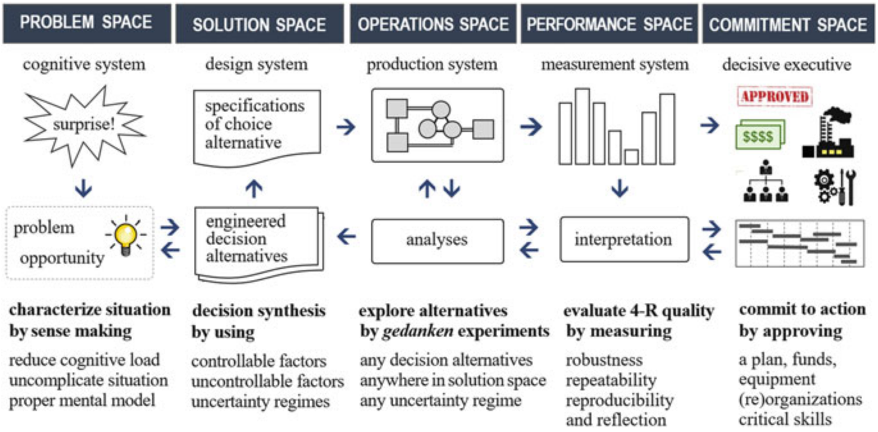

Fig. 1.7 Executive management decision principles

decision. Once again, we see the interactions of the positive reinforcing effects and the negative balancing effects, each seeking to dominate the behavior of the overall system.

These system dynamics clearly demonstrate that executive management decisions are about systems of systems (Ackoff 1974). They also demonstrate how symptoms and solutions of subsystems, of wicked and messy problems, interact to potentially produce symptoms of other problems (Rittel and Webber 1973). The network of problem causes are layered with antecedents and relationships that make exhaustively complete definition of potential solutions large and cognitively challenging for the DMU. This difficulty is compounded by uncertainty of interaction effects (Appendix 1.1, criterion 6).

Examination of the balancing loop's interactions with reinforcing loops reveals the pivotal role of certain effects on the system behavior. From this analysis, we can formulate principles for executive management decisions. The principles are presented in context of the five spaces, Fig. 1.7, from left to right, problem, solution, operations, performance, and commitment spaces.

1.5.3 Executive Decisiveness

Throughout the discussion of the static and dynamic factors of the systems effects, it has been implicitly assumed that the empowered executive will, in fact, elect a course of action and will resolve to commit or **not** commit human, financial and technical resources to its implementation. Decisiveness is both the ability to know when to say *yes* and when to say *no* (Ackoff et al. 2007). However, we know from experience and observation that this is not automatic. The requirement of a decisive executive needs to be made explicit (e.g. Rassin et al. 2007). *Decisiveness* is the "ability to come to a timely, *and stable*, decision despite uncertainty" (Bernheim and Bodoh-Creed 2016). The "and stable" is our addition inspired by Potworowski (2010). *And stable* is important. Vacillating and dithering are sure signs of a wobbly and irresolute person. With great of perspicacity, Potworowski (2010) studies what makes people *indecisive*. And by understanding this weakness, he address the causes that drive indecision. (His catalog of indecision and indecisiveness is impressive. It is summarized in Appendix 1.5). He identifies three behavioral patterns in indecisive executives—"prolonged latency, not deciding, and changing decisions". He discusses procastination, buck-passing, excessive worry, low self-esteem, low confidence, impulsivity, as causes that drive indecision. Kelman et al. (2014) report that "outstanding executives" (their appellation) value decisiveness more than having a diverse and expert group of advisors in the decision process. Anecdotal evidence is plentiful. George McClellan was a brilliant military theorist, but could not muster enough nerve to marshal his troops to engage the Armies of the Confederacy. According to Potworowski (2010) this behavior is indecisiveness. *The tendency to not make a timely and stable commitment to a course of action when the need for such a commitment is acknowledged.* In sharp contrast, Franklin Roosevelt launched the Manhattan project even though there was scant knowledge that the physics or the project would work, but was necessary. Thomas Watson literally bet his company, IBM, to develop the first family of compatible computers, the IBM S/360 series.

The question is then how to address the problem of indecisive executives. First, temperament is the key determinant of decisiveness (e.g. Rassin et al. 2008). Therefore, those who delegate power to command ought to have personal knowledge of the persons they are appointing to decision-making positions. The appointee must have the appropriate temperament for an executive position. This means they are a natural fit for the environment and challenges in which they will find themselves. They must relish the challenge of command and problem-solving that demands their best effort, and reap the satisfaction of a job well done. But also unimpeded by the certainty that they risk visible failure. In IBM, for example, one criterion for executive candidates is that they must have not only a record of successes, but also have demonstrated the ability to operate crisply in environments of high stress and ambiguity. Secondly, Bernheim and Bodoh-Creed (2016) demonstrate that decisiveness is a preferred trait in organizational management. Their mathematical treatment of the subject is a principal agent model between voters and politicians. Their models show that voters prefer leaders who make decisions rapidly, and moreover, those who aspire high office signal decisiveness. Although cast as voter-politician, we think the findings are more general. Ambivalence is not an attractive executive trait (Simon 2006).

1.6 Decision Design Principles

1.6.1 Introduction

Principles are putative normative axioms, which are long enduring and credible. Through the test of time, they have demonstrated to be useful and effective in the development of new knowledge and coherent practice. They are widely accepted as valid and very difficult to refute, if at all. For example, in physics, we have the conservation of energy. In economics, there is the doctrine of supply and demand. In normative decision theory, von Neumann and Morgenstern's axiom of completeness states that given two alternatives, a decision maker can necessarily determine the relative superiority of one over the other (e.g. Loewenstein and Prelec 2000). Although, Nobel laureate Aumann (1962) shows that the completeness axiom is not necessary for rational utility theory, it does not mean that the von Neumann and Morgenstern's axioms are not meaningful. They remain very useful as fundamental rules for rigorous investigation and lucid thinking.

Our intent in articulating principles is not to replace established ones, but to present complementary principles for our paradigm and the practice. Our principles have a unique sociotechnical perspective. The social perspective is presented at the one-person unit of analysis, as well as, the aggregate organization unit of analysis in the engineering practice (e.g. Bucciarelli 1994). The technical perspective reflects the discipline of systematic engineering design of physical and artificial artifacts (e.g. Mathieu et al. 2008; Pahl and Beitz 1999; Otto and Wood 2001; Simon 2001). Figure 1.8 illustrates the attributes of complex, messy and wicked executive decisions, and their contributing factors. The design principles for executive decisions are illustrated in Fig. 1.8.

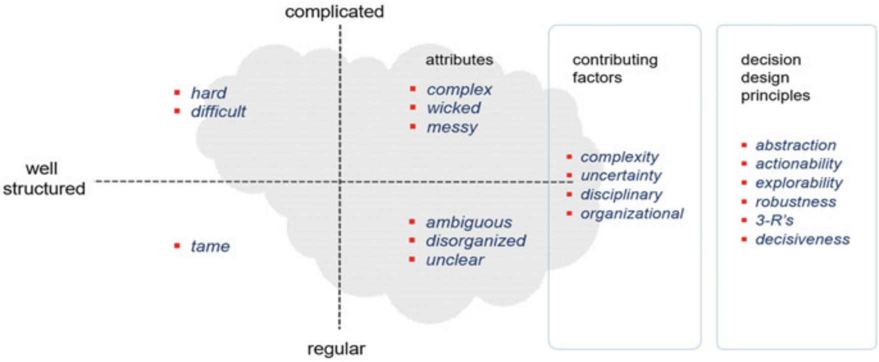

Fig. 1.8 Executive decision design principles

1.6.2 Six Principles

Principle 1. Abstraction *Reduce cognitive load, hide complexity by abstractions.*

The center of gravity of this principle is grounded on the cognitive sciences. Reduce the cognitive load imposed on decision makers and their staffs with representations that do not present unnecessary complexity to the DMU (Jackson and Farzaneh 2012). Complexities need not be exhaustively revealed, in their glorious detail, to those who have to deal with it. Abstraction will facilitate cognition for meaningful sense-making, decision design, and enactment. Thus, the principle of *cognitive load reduction* is the equivalent of the principle of *abstraction*. They are two sides of the same coin. Abstracting is seeing the underlying simplicity of complexity (Wilson 2003; Simon 1997a, b). To abstract, one must suppress a situation's non-essential features and/or attributes of what is observed, so that its essential structure and working principles are revealed, in their most parsimonious and insightful forms. Abstraction reduces cognitive load that facilitates fresh thinking (Spooner 2004; Davidson 2003). Research shows that more creative artifacts are more likely obtained from simpler and abstract characterizations of a problem than otherwise (Condoor et al. 1993). Naturally, abstraction is also necessary for the implementation of a decision by designing sociotechnical systems that attenuate the operational cognitive load required for routine operations. The corollary of the *law of requisite variety* (Ashby 1957) is that the variety of a controller must be larger than the number of **abstracted** states of the system it needs to manage. Our restatement merely adds the adjective "abstracted". Because systems are to be designed and operated by sociotechnical systems, being mindful of Ashby's (1957) law is particularly appropriate for effective operations. Were this not so, the system would present decision situations that DMUs are unable to interpret and control.

Principle 2. Actionability *Ground abstraction on managerially controllable variables that directly influence intended outcomes.*

This defeats the frequent and valid criticism that abstractions are difficult to make actionable. The center of gravity of this principle is grounded on engineering design. All effective engineering design concentrates on essential variables that determine behavior and that can be controlled. Make the abstraction represent an **uncomplicated** mental model of the decision situation and its specification. In Sect. 1.4.3, we discussed the logic and significance of an uncomplicated system image targeted at those who have to design and operationalize a decision specification. Concentrate on decision specifications that will satisfice. Simon (1997a, b, 112) argues the point more precisely by stating that for functional artifacts it is important that "… an understanding of what are the key variables that shape system equilibrium and what policy variable can effect that equilibrium". In engineering this is knowing the working principles that govern the system behavior. And, by the same token, it is necessary to identify the essential variables that contribute to uncertainty and to integrate them into the decision specification in order to diminish their impact.

Principle 3. Robustness *Design decisions so that they are highly immune to uncertainty conditions even when uncontrollable conditions cannot be removed. This is robust design.*

Decisions specifications must be designed for robustness. Robustness will reduce the impact of uncontrollable variables on the intended outputs. Robustness is achieved by identifying the essential uncontrollable variables that directly influence the intended outputs and including them in the design of the decisions. Robust engineering methods for physical products are proven to be highly effective to create artifacts and processes that will produce good results, which are highly insensitive to uncontrollable factors, even though they have not been eliminated.

Principle 4. Unconstrained explorability *Unconstraint actionability by enabling exploration of the entire solution space under the entire space of uncertainty conditions.*

Actionability and Robustness are highly desirable, but not very useful if the decision can operate only in a narrow region of the solution space and only under a very limited set of controlled conditions. It follows that a useful methodology for designing decision specifications must remove these two constraints. Therefore, actionalibility must permit the unconstrained exploration of a decision alternative over the entire solution space and do so under conditions that span the entire space of uncertainty. This capability is required for any design situation. The first idea to solve a problem is unlikely to be the most worthy. A search, for alternative and potentially superior ideas must be permitted without constraints. The DMU must be permitted to pose any hypothetical "what if" question to predict outcome and standard deviation to judge associated risk.

Principle 5. Production Quality is R, R&R *Production quality is robustness, repeatability and reproducibility.*

Principles 1, 2, 3, and 4 deal with definition, design, and exploration of candidate design alternatives. This principle deals with the production of a decision specification. This principle is grounded on performance evaluations and improvements based on measurement data. We want to know the sources of production defects. Are the defects revealed by the measurements, due to the measurement tools, the artefact, the people in the measurement process, or a combination of these factors? If so to what extent is each of these factors contributing to the defects?

Consistently good outcomes must be the result of r*epeatable* and *reproducible processes*. If the same sociotechnical system using the same process produce the same results, the results are *repeatable*. If a different sociotechnical system using the same process produces the same results, results are *reproducible*. These criteria are useful to analyze the quality of results and to identify sources of defects in the processes.

Principle 6. Decisiveness *An executive cannot be irresolute. Executives by definition must decisively formulate a plan, lead organizations to execute and commit irrevocable resources for implementation.*

Teddy Roosevelt famously said, "In any moment of decision, the best thing you can do is the right thing, the next best thing is the wrong thing, and the worst thing you can do is nothing." Doing nothing, at the moment of decision, merely extends the state of uncertainty and prolongs ignorance. Inadvertently doing the wrong thing, in our experience, will produce new information that is confirmatory or troublesome. Regardless, doing something becomes a learning opportunity. When things are at their worse, anything can make it better (Ackoff et al. 2007). It follows that an executive must be decisive, take a decision at the time it is required, not sooner, not later. This means not jumping the gun or procrastinating, but acting with determination and firmness, in the face of uncontrollable uncertainties. Commit irrevocable funds and equipment, lead organizations to enact, and engage existing a new critical skills to implement the plan. Timidity, indecisiveness and reluctance to make a decision is a sure sign of one who should not be in a position of command. Decisiveness is a necessary condition, but insufficient for effective and efficient decisions. Finally it is worth noting that decisiveness means knowing when to say *yes* and when to say *no*.

1.7 What Is a Systematically Designed Decision?

Decision-making is an event. Executive-management decisions are a life-cycle process. The two must not be conflated. A thoughtful decision is one that is the result of a systematic process endowed with the right set of functional properties (Table 1.6).

Characterize the Problem Space
What is the exact problem/opportunity that we are trying to address? How do you describe it? The Goals and Objectives. The governing variables.

- **Sense making. Uncomplicate cognitive load**. Describe a decision situation in its proper context. Interpret the situation as a problem or opportunity. This is sense-making. Sense-making is a cognitive act to attach *meaning* to the situation.
- **Frame problem/opportunity and clarify boundary conditions**. The meaning establishes the boundaries of the decision situation, so that what is included or excluded is understood. This understanding and its assumptions frame the problem/opportunity.
- **Specifying goals and objectives**. Declare intentions in terms of goal and objectives. A goal is superordinate, an aspiration, what is valued. Goals exist in the context of frames. Objectives are derived from goals. They are landmarks to mark progress towards goals. A goal is the "why" of doing the "what", which is evaluated by the attainment of what objectives.
- **Specify essential variables: controllable and uncontrollable**. Goals and objectives are never satisfied without effort. To that end, effort must be exerted on managerially controllable variables. However, managerially uncontrollable variables will impact their performance. Specify the key uncontrollable variables that will directly influence outcomes. They will be needed for the design of decision specifications.
- **Reflect on the results of this phase**.

Table 1.6 Our instantiation of the canonical form: a systematic process

Process phases	Our systematic process	
Characterize **Problem Space**	Sense making—uncomplicate cognitive load	☑
	Frame problem/opportunity and clarify boundary conditions	☑
	Specify goals and objectives	☑
	Specify essential variables Managerially controllable variables Managerially uncontrollable variables	☑
Engineer **Solution Space**	Specify subspaces of solution space Alternatives space and uncertainty space	☑
	Specify entire solution space	☑
	Specify base line and uncertainty regimes Do-nothing case and choice-decision Estimate base line and dispel bias	☑
Explore **Operations Space**	Specify	
	Sample orthogonal array Do-nothing case and choice decision-alternative	☑ ☑
	Predict outcomes	☑
	Design and implement robust alternative Design and implement any what-if alternative	☑ ☑
Evaluate **Performance Space**	Evaluate performance: analyze 4R Robustness, repeatability, reproducibility, reflect	☑ ☑
Enact **Commitment Space**	Decisive executive Approval of plan Commit funds, equipment, organizations	☑ ☑ ☑

☑ indicates required in the process

Engineer the Solution Space

How to construct the set of decision alternatives to investigate? This is the solution space. The key questions are: How to construct the uncertainty space? Define uncertainty regimes. How to avoid bias in data and judgements? Establish and base line and debiasing procedures.

- **Using the controllable variables, construct the solution space**. Discretize the entire solution space into a set of alternatives that span the entire solutions space.
- **Using the uncontrollable variables, specify the uncertainty regimes**. Discretize the entire uncertainty space and specify uncertainty regimes.
- **Using controllable and uncontrollable variables, construct a base line and debias**. Define the base-line by using the current decision specification under a range of uncertainty regimes. Apply the prescribed sociotechnical debiasing procedure.
- **Reflect on the results of this phase**.

Explore the Operations Space

How to systematically collect data? Construct and populate the orthogonal array with data. How to engineer alternatives? Use the statistical response tables to engineer any alternative desired. *Predict outcomes for* ***any*** *alternative under* ***any*** *uncertainty regime by unconstrained exploration.*

- **Construct orthogonal array of experiments under the uncertainty regimes**. Obtain the ANOVA, response, standard deviation tables. Analyze to determine usability.
- **Engineer and predict outcomes for *any* decision alternative under *any* uncertainty regime**. Use statistical response tables to construct any alternative desired in the solution space under any uncertainty regime desired; then predict its output and standard deviation.
- **Predict output and standard deviation for any hypothetical "what-if" decision**. Every executive has hypothetical what-if questions.
- **Reflect on the results of this phase**.

Evaluate Performance Space

How to evaluate the quality of the intended output? Robustness. How to determine the quality of the sociotechnical system? Repeatability and Reproducibility. How to evaluate the quality of the social system?

- **Quality of the intended output is determined by its robustness**. Design decisions that are robust. Robust outcomes that are highly insensitive to uncontrollable conditions, even when they have not been eliminated.
- **Production quality of the sociotechnical system is measured by repeatability and reproducibility**. If a sociotechnical system using the same process must produce the same results, they must be *repeatable*. A different sociotechnical system using the same process and produces the same results, then results are *reproducible*. These criteria are useful to analyze the quality of results and to identify sources of defects in the processes.
- **Reflect on the results of this phase**.

Enact Commitment Space

Action is the operational expression of a decision. Without it a decision is merely an intention. What is necessary and sufficient for action? Decisiveness and committed resources, which are brought to bear on implementation.

- Decisiveness is the sine-qua-non in the commitment space.
- Allocate and commit resources. Consistent with the axiom of "no free lunch" (Sect. 3.3.2.2) resources must be allocated according the specified plan, execute the plan.
- Reflect on the results of this phase.

1.8 Chapter Summary

- Performance is specified as robust outcomes. We define robust performance as outcomes that are highly insensitive to uncontrollable conditions, even when they are not eliminated.
- Decision-making is a *power reserved*. Decision-making is the power to command. It is a power that unless delegated, it remains reserved. With power comes responsibility, obligations, accountability, and resources to produce intended results. Power demands decisiveness; a wobbly irresolute executive is the enemy of effectiveness.
- Executive management decisions are in a class of their own. Their scope and impact are significant. To address this class of decisions, we present a new prescriptive paradigm based on engineering methods for sociotechnical systems.
- We consider a decision as an intellectual artifact, a specification, a blueprint for executive management action to produce intended outcomes. As such, an executive management decision is a life-cycle process. Broader than just decision-making, which is the event that marks the commitment to enact a decision specification with irrevocable resources. “In fact no decision has been made unless carrying out specific steps has become someone’s work assignment and responsibility. Until then it is only a good intention” (Drucker 1967). Decision performance is specified as robust outcomes.
- Executive management decisions are generally messy, wicked, and ill-structured. Messy because they are systems of problems, wicked because they are also social-intensive, and ill-structured because they defy standard operating procedures. But they can be systematically addressed.
- Four factors interact systemically to make executive-management decisions very challenging—complexity factors, uncertainty factors, disciplinary factors, and organizational factors.
- Pivotal factor-interactions among the four factors appear in the five spaces of a decision’s life cycle—the problem space, solution space, operations space, performance, and commitment spaces. They are complex sociotechnical spaces.
- A decisive executive is a necessary condition for efficient and effective decisions. A person who is irresolute, timid, ambivalent—hallmarks of indecisiveness—point to one unfit to command.
- Putting all this together, we infer six decision principles for executive management decisions:

Abstraction Reduce complexity and cognitive load by abstracting,

Actionability Make abstraction actionable by concentrating on essential variables,

Explorability Unconstraint actionability by the ability to design decision alternatives that can cover any region in the solution space under any uncertainty regime.

Robustness Make results insensitive to uncontrollable conditions by robust engineering,

Repeatability, Reproducibility and Reflection Ensure sustainable quality performance by repeatable and reproducible processes, and reflection.

Decisiveness Have resolute executives that know when to act without timidity. Teddy Roosevelt's dictum is particularly relevant: "In any moment of decision, the best thing you can do is the right thing, the next best thing is the wrong thing, and the worst thing you can do is nothing."

Appendix 1.1 Criteria of Wicked and Messy Problems

Rittel and Webber (1973) specify ten criteria that characterize messy and wicked problems. We take the criterion statement verbatim from the referenced paper. Our interpretation is shown in italics.

1. **There is no definite formulation of a wicked problem**. The information needed to understand the problem depends on one's idea for solving it. *We interpret this to mean that how the problem is framed determines how it will be solved and therefore the form of its solution. There are many ways to frame a problem.*
2. **Wicked problems have no stopping rule**. *This is actually a corollary to criteria 3 and 4.*
3. **Solutions to wicked problems are not true-or-false, but good or bad**. *Variety of stakeholders judge the outcomes. They must satisfice, improve, or try something differently. Time, information and processing resources make it a perfect job impossible.*
4. **There is no immediate and no ultimate test of a solution to a wicked problem**. *As a result of trying to solve a problem raises more questions to be answered. Unintended consequences raises additional questions to address.*
5. **Every solution to a wicked problem is a "one-shot operation", because there is no opportunity to learn by trial and error, every attempt counts significantly**. *Most solutions are immutable, costly, if not impossible to reverse.*
6. **Wicked problems do not have and enumerable (or an exhaustively describable) set of potential solutions, nor is there a well-described set of permissible operations that may be interpreted into the plan**. *The network of problem-causes are layered with antecedents and relationships that make exhaustively complete definition of potential solutions prohibitively complex. This difficulty is compounded by uncertainty of interaction effects and uncontrollable variables.*
7. **Every wicked problem is essentially unique**. *This is also follows from criteria 1, 2, 3, 5, and 6.*

8. **Every wicked problem can be considered to be a symptom of another problem**. *This follows from the multidisciplinary and complex system definition of wicked problems.*
9. **The existence of a discrepancy representing a wicked problem can be explained in numerous ways. The choice of explanation determines the nature of the problem's resolution**. *This is a result of criteria 1. How a problem is framed shapes the outcomes obtained. Moreover, complexity can produced confounded outcomes.*
10. **The planner has no right to be right or wrong**. *This is not well stated. What is meant is that since there is no right-or-wrong, true-or-false answers to the wicked/messy problems, making things worse is far more damaging than being wrong. Therefore, goal must always be to make things better.*

Appendix 1.2 Criteria of Super Wicked Problems

Levin et al. (2012) characterize super wicked problems as fulfilling the following four criteria. These criteria are in addition to Rittel and Webber's (1973) ten criteria. Our interpretation is shown in italics.

1. **Time is running out**. *The problem may have a life of its own. The environment is the final arbiter. The problem may be too acute and have had too much impact to stop or reverse. For example, shrinkage of the Amazon forest, melting of the polar icecaps, impoverished people's patience with corrupt officials, controls of cyber-attacks, etc. To this we add: other resources to solve the problem may be running out.*
2. **Central authority is weak or non-existent**. *The conditions can be described as anarchy. Even if solutions are implemented they may operate at different scales, different time constants, under different of control authorities who confused with vague, and ambiguous mandates.*
3. **Those seeking to solve the problem are also causing it**. *Inadvertently or through perverse incentives the problems solvers are part of the problem. To this we add: the beneficiaries of the solved problem may be part of the problem.*
4. **Policies discount the future irrationality**. *For different reasons, short term expedient solutions become the most attractive. When in fact short term solutions that delay or inhibit rational thinking will not necessarily improve solutions in the future.*

Appendix 1.3 Chern's Ten Principles of Sociotechnical Systems Design

A pioneer in formulating principles for sociotechnical systems, Cherns formulated the following ten principles (Cherns 1976). Our interpretation is shown in italics.

1. **Compatibility**. *Design process should be compatible with design objectives.*
2. **Minimal critical specification**. *Do not over specify, it closes options prematurely. For example set-based design is a creative method to keep options open. Specify the "what's", not the "how's".*
3. **Variance control**. *Control (verb) variances at point of origin.*
4. **Boundary control**. *Give autonomy, allow boundary spanning.*
5. **Information flow**. *Provide information at the point of action.*
6. **Power and authority**. *Give power and authority to those who must act.*
7. **The multifunctional principle**. *People should assume boundary spanning roles to increase their ability to respond. Moreover, the sociotechnical systems should have designed processes and incentives to facilitate this.*
8. **Support congruence**. *Systems and social support should be designed to this reinforce behavior.*
9. **Transitional organization**. *Transitions, may require transformations, which require planning and design of the socio-technical kind.*
10. **Incompletion**. *Design never ends. It must continuously improve.*

Appendix 1.4 Clegg's 19 Principles of Sociotechnical System Design

To guide the design of social-technical systems, Clegg framed 19 principles (Clegg 2000). The principles are generic to the design of virtually all systems. We find only principles 9, 10, 11, 14, and 17 specific to sociotechnical systems. They are identified by and *. Our interpretation is shown in italics.

Meta Principles

1. Design is systemic.
2. Values and mindsets are central to design.
3. Design involves making choices.
4. Design should reflect the needs of the business, its users, and their managers.
5. Design is an extended social process. *Introduces stakeholders into the process.*
6. Design is socially shaped.
7. Design is contingent. *Every design is unique to the problem being addressed. There is no such thing as a "best design" prototype. There is a design that can improve a situation, i.e. it is good enough and which can be improved iteratively.*

Content Principles

8. Core processes should be integrated.
9. * Design entails multiple task allocations between and amongst humans and machines. *Introduces the concept of team effectiveness.*
10. * System components should be congruent. *Sub systems and components must all contribute to the goal, i.e. goal congruency outputs are consistently aligned.*
11. * Systems should be simple in design and make problems visible. *This is consistent with our principles of abstraction and uncomplicatedness.*
12. Problems should be controlled at the source.
13. The means of undertaking tasks should be flexibly specified.

Process Principles

14. * Design practice is itself a sociotechnical system.
15. Systems and their design should be owned by their managers and users.
16. Evaluation is an essential aspect of design.
17. * Design involves multidisciplinary education.
18. Resources and support are required for design.
19. System design involves political processes.

Appendix 1.5 Potworowski's (2010) Definitions for Indecision and Indecisiveness

This is a simplified summary of Potworowski's (2010) literature search on definitions for indecision and indecisiveness. Indecision is a state wherein an individual has not made a decision. Indecisiveness is a personal behavioral trait. This work brings clarity on the meaning of these terms and by inference on what decisiveness means. Table below is a direct summary from Potworowski (2010).

• Bacanli (2000, 2005, 2006) – Exploratory indecisiveness—difficulty deciding even when all options have been explored. – Impetuous indecisiveness—quick decision making and giving up easily.
• Callanan and Greenhaus (1990) – Indecision—inability to select a goal, or having done so uncertain about it.
• Chartrand et al. (1990) – Indecisiveness—inability to decide even when the necessary conditions to do so are present. – High indecisiveness means a lack of competence in formulating decisions.
• Cooper et al. (1984), Fuqua and Hartman (1983) – Indecisiveness—difficulty making personal decisions.
• Crites (1969) – Indecisiveness—difficulty in all sorts of life decisions, great or little significance even after all the conditions for doing so, incentives and the freedom to choose are provided.

(continued)

- Danan and Ziegelmeyer (2006)
  - Preference indecisiveness—an individual's inability to determine which of two alternatives would leave her better off.
- Denis et al. (2006)
  - Escalating indecision—continually make, unmake and remake strategic decisions, large expenditure of energy with little concrete strategic action and constant reversal possibilities.
- Elyadi (2006)
  - Indecisiveness—becoming stuck in the decision making process while experiencing negative concurrent emotions.
- Ferrari and Dovidio (2000)
  - Indecisiveness—decisional procrastination is a maladaptive pattern of postponing a decision when faced with conflicts and choices.
- Frost and Shows (1993)
  - Indecisiveness—chronically prolonged decision latency. Procrastination or strategic waiting. Not knowing what one wants. Has decision making and/or planning difficulty. No desire for decision authority. Post-decisional doubt/worry. Decision making worry/anxiety.
- Gati et al. (1996)
  - Indecisiveness—chronic problems individuals may have inmaking decisions.
- Germeijs and De Boeck (2002)
  - Indecisiveness—domain-general difficulty in making decisions, which includes seven categories: (1) latency, (2) delay, (3) avoidance, (4) buck-passing, (5) instability, (6) worry, and (7) decision regret.
- Goodstein (1972)
  - Indecisiveness—inability to make decisions.
- Holland and Holland (1977)
  - Indecisiveness—no explicit definition,. Identify three types of indecisivenesss: (1) doesn't have to decide yet, so stays undecided, (2) mildly anxious, immature, or incompetent, (3) indecisive
- Jones (1989)
  - Indecisiveness—cannot decide without unnecessary delays, difficulty, or reliance on others.
- Mann et al. (1997)
  - Indecision—delay in deciding or acting on a decision.
- Milgram and Tenne (2000)
  - Indecisiveness—inability to make timely decisions in minor matters.
- Rassin and Muris (2005a, b) and Rassin et al. (2007)
  - Indecisiveness—difficulty with decisions.
- Reed (1985)
  - Indecision—failure or hesitation in deciding, an inability to make up one's mind or come to a conclusion. Has *difficulty* in choosing between alternatives.
- Salomone (1982)
  - Indecisiveness: unable to make important decisions not because lack information, but because of personal qualities do not permit to reach a state of mind and take a course of action.
- Van Matre and Cooper (1984)
  - Indecision—*state* of being undecided. On the other hand, indecisiveness is defined as the *trait* of having difficulty making decisions.
  - Indecisiveness—Trait of having difficulty making decisions.
- von Neumann and Morgenstern (1964)
  - Indecisiveness—inability to state which alternative one prefers, while not admitting that the alternatives are equally desirable.
- Wanberg and Muchinsky (1992)
  - Indecisiveness—the inability to make decisions readily.

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Chapter 2
Decision Theories and Methodologies

Abstract This chapter introduces the extant decision theories. Whereas the literature segments the field into the Normative, Descriptive, and Prescriptive theories, we identify a fourth. That is the Declarative strand of decision-making. We discuss all four strands of research and praxis. We locate our prescriptive paradigm in the Prescriptive segment. We discuss the question of what is a good decision and a good process. We will close this question in Chap. 10 after we have had the opportunity to illustrate the use of the machinery of our prescriptive paradigm in the main body of the book.

2.1 Introduction

Scientific knowledge, engineering science, and their best practices are cumulative. Every new idea and improvement is necessarily the result of standing on the shoulders of others. New knowledge, novel and useful practice are all part of evolving and connected strands of understanding, expertise and proficiency. The progression is cumulative and advancing to more insightful understanding and more effective practice. The trajectory is not necessarily a smooth one. There are many false starts and punctuated by what Kuhn (2012) calls paradigm shifts. We think of our approach as opening a new window in a magnificent structure and as a modest punctuation. A new way to think about executive-management decisions. In this chapter, we show its multidisciplinary heritage rooted in mathematics, cognitive psychology, social science, and the practice. We want to show its punctuated continuity with, and its debt to, the achievements of the past. Our debt, notwithstanding, we also draw contrasts between our engineering decision-design methods and other traditional methods.

We sketch a survey of decision theory. The adumbration is necessarily highly selective; the body of work is so vast[1]. Scholars distinguish the domain with three schools of decision theory—the normative, descriptive, and prescriptive schools (e.g. Goldstein and Hogarth 1997). To this, we add what we name as the *declarative*

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[1] Edwards and von Winterfeldt (1986) write that "articles related to judgment and decision-making appeared in more than 500 different journals." Under "decision theory," Google scholar shows 1,870,000 citations, and Amazon.Books show 1744 titles. Downloaded January 15, 2017.

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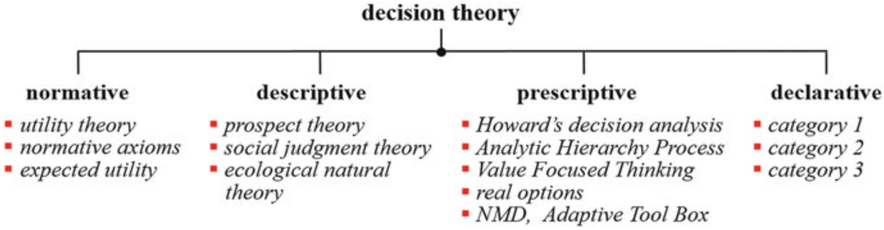


Fig. 2.1 Four strands of decision theory and practice

school, hybrid of the three schools. In what follows, we select representative work from each school (Fig. 2.1). We begin with the normative school, follow with the descriptive and prescriptive schools, and finally with the declarative school. We locate our work, in this book, in the prescriptive branch of the tree in Fig. 2.1.

In the prescriptive stream, we select four strands of research exemplars. These are shown under the prescriptive branch of our tree in Fig. 2.1. Following a survey of the normative, descriptive, and prescriptive schools, we sketch areas of tension among scholars in these schools. We will discuss what we call the *declarative* school, for it appears to be important to executives and consultants. We will also show that although each prescriptive method is unique, there is a *meta-process* that, in the abstract, reveals the essential structure of each method. This meta-process is known in the literature as the "canonical model of decision-making" (Bazerman 2002; Tversky and Kahenman 1974). Central to the canonical model is the analyses of decision alternatives. Unexpectedly, design, the subject of constructing alternatives fails to appear prominently represented in the decision literature. It is generally assumed that alternatives exist, are easily found, or readily constructed. Simon (1997; 126) writes that: "The classical view of rationality provides no explanation where alternate courses of action originate; it simply presents them as a free gift to the decision markers." This void is surprising because design of alternatives must necessarily precede analysis. But analysis is apparently a preferred area of research. Synthesis which deals with the design and construction of decision alternatives is presumed to be readily doable and, as a result, it is barely visible in the literature. Analysis has crowded out synthesis. We will address this gap. And consistent with our engineering approach, we will use engineering design processes and procedures to systematically specify, design, and analyze alternatives to satisfy the requirements of executive management. But we will not neglect the social and organizational management dimensions of executive decisions.

2.2 Origins

Counting methods to impute the odds in gambles is not a recent or modern practice. There is a long tradition that goes back many centuries (e.g. Crepel et al. 2013). Probability calculations appear early in the Roman poems of Ovid (43 BC–17 AD). Cardano (1501–1576), a physician, mathematician, and avid gambler, authored

Liber de Ludo Aleae, a gambling guidebook with statistical calculations (Crepel et al. 2013). The genesis of modern decision theory is found in Bernoulli's (1738) observation that the s*ubjective value*, i.e. utility, of money diminishes as the total amount of money increases. He argued that a poor person perceives value of a thousand ducats very differently relative to a rich one, though the quantity of money are identical. For this phenomenon of diminishing utility, he proposed a logarithmic function to represent value (e.g. Fishburn 1968; Kahneman and Tversky 2000).

However, utility remained largely a descriptive concept until the seminal axioms of Morgenstern and Neumann (1944) and Savage's (1954) seminal contributions on subjective statistical thinking. They generalized Bernoulli's qualitative concept of utility (which was limited to measures of wealth), developed the concept of lotteries to impute it, formulated normative axioms, and formalized the combination into a mathematical system—*utility theory* (Appendix 2.1). Since then, research in decision theory has exploded. Bell et al. (1988) have segmented the contributions in this field into three schools of thought "that identify different issues … and deem different methods as appropriate (Goldstein and Hogarth 1997, 3)." They are the normative, descriptive, and prescriptive schools of decision making. To which we add the *declarative* strand, a hybrid formed from elements of the other schools. We follow Keeney (1992a) and summarize their salient features in Table 2.1. The boundaries between the schools are blurry. For example, one needs normative principles to judge whether a prescription is meaningful or not.

2.3 Four Schools of Decision Theory

2.3.1 Normative Decision Theory

Unlike planetary motion, or charged particles attracting each other, decisions do not occur naturally; they are acts of human will. Therefore, we need norms, rules, and standards. This is the role of normative theory and its axioms that enforce rigor and consistency. Normative theory is concerned with the nature of rationality, the logic of decision making, and the optimality of outcomes determined by their utility. Utility is a cardinal, ordinal, interval, or ratio scale measure of the desirability or degree of satisfaction of the consequences from courses of action selected by the decision maker (e.g. Baron 2000). Utility assumes the gambling metaphor where only two variables are relevant: the strength on one's belief's (probabilities), and the desirability of the outcomes (e.g. Eisenführ et al. 2010). The expected utility function for a series of outcomes, with assigned probabilities, takes on the form of a polynomial of the product of the probabilities and outcome utilities (e.g. Kahneman et al. 1993). For the outcome set $X = \{x_1, x_2, \ldots, x_n\}$, their associated utilities $u(x_i)$ and probabilities p_i for the index set $i = 1,2, \ldots, n$, the expected utility for this risky situation is:

Table 2.1 Summary of normative, descriptive, prescriptive, and declarative schools

	Normative	Descriptive	Prescriptive	Declarative
Focus	How people should decide with logical consistency	How and why people decide the way they do	Help people prepare decisions	Help people make decisions
Criterion	Theoretical consistency	Empirical validity	Efficacy and usefulness grounded on research findings	Famous cases Famous person Prestige institution
Scope	All decisions	Classes of decisions tested and reported	Classes of decisions tested and reported	Executive decision situations
Theoretical foundations	Utility theory axioms Subjective probability	Cognitive sciences Psychology of beliefs and preferences	Normative and descriptive theories Decision analysis axioms	Repackage research Personal organization case studies
Operational Focus	Analysis of alternatives Order rank and preferences	Prevent systematic errors in inference and decision-making	Decision lifecycle Processes and procedures	Simplify and clarify complicated decision situations
Judges	Theoretical sages	Experimental researchers	Applied analysts	Celebrity execs, scholars, consultants Executive journals, magazines Self-proclaimed experts
Also called	Rational decision theory	Behavioral decision theory	Decision making and analysis	Expert help

$$u(X) = \Sigma p_i u(x_i) \text{ where } \Sigma p_i = 1. \tag{2.1}$$

In order to construct a utility function over lotteries, there are assumptions that need to be made about preferences. A *preference order* must exist over the outcome set $\{x_i\}$. And the axioms of: *completeness, transitivity, continuity, monotinicity*, and *independence* must apply (Appendix 2.1). The outcomes and their utilities can be single attribute or multiattribute. For a multiattribute objective $\mathbf{X} = \{X_1, X_2, \ldots X_N\}$ and $N \geq 3$, under the assumptions of utility independence, the utility function takes the form:

$$KU(\boldsymbol{X}) + 1 = \Pi(Kk_iU(X_i) + 1) \text{ for some constant } K \text{ and scaling constants } k_i. \tag{2.2}$$

Where the attributes are independent, the utility function takes the form of a polynomial. A person's choices are *rational,* when the von Neumann and Morgenstern axioms are satisfied by their choice behavior (Appendix 2.1). Subsequently, new principles have been judged to be required as normative principles. For example, the sure-thing principle (e.g. Pearl 2016), which states that any choice should not be altered by independent events. And its close cousin the independence axiom (e.g. Samuelson 1952). And the "no money-pump principle" (Howard, Appendix 2.2), which says that a preference ranking system cannot be circular. The axioms, principles, and desiderata collectively establish ideal standards for rational thinking and decision making. Savage (1954) asserted a principle of rationality, which is now widely accepted. The principle declares that the utility of a decision alternative is calculated by the product of two psychological scales—a subjective probability of the event and a numerical measure of the utilities of the outcomes. The principle also implies how rational choice is be modified with new information. Bayes' rule of conditional probability is an example.

The completeness axiom asserts that given any two lotteries, one is always preferred to the other, or they are equally good. No exceptions. But, Auman the 2005 Nobel economics laureate proved that relative to the von Neumann-Morgenstern utility, a parallel utility theory does not need the completeness axiom (Aumann 1962). Bewley (2002) formulates an alternative theory of choice that does not need the completeness axiom. He introduces an *inertia assumption*, which says that a person never accepts s lottery unless acceptance is preferred to rejection, i.e. one stays with the *status quo* unless an alternative is preferred. These are new, novel and fundamental contributions to normative theory. But these results do not obviate the usefulness of the von Neumann and Morgenstern axioms, which are widely used with proven efficacy.

In spite of its mathematical elegance, utility theory is not without crises or critics. Among the early crises were the famous paradoxes of Allais and Ellsberg (Allais 1953; Ellsberg 1961, e.g. Resnick 1987). People prefer certainty to a risky gamble with higher utility. People also have a preference for certainty to an ambiguous gamble with higher utility. Worse yet, preferences can be reversed when choices are presented differently (Baron 2000). Howard (1992) retorts that the issue is one of education. Enlighten those that make these "errors" and they too will become utility maximizers. Others claim that incentives will lower the cost of analysis and improve rationality, but violations of stochastic dominance are not influenced by incentives (Slovic and Lichenstein 1983). These paradoxes were the beginning of an accumulation of empirical evidence that people are not consistent utility maximizers or rational in the von Neumann and Morgenstern axiomatic sense. People are frequently *arational* (Ariely 2008; Kahneman 2011). The so-called paradoxes are just normal human behavior.

A significant critique of normative theory is put forward with Simon's thesis of bounded rationality (Simon 1997). Simon's critique strikes normative decision theory at its most fundamental level. Perfect rationality far exceeds people's cognitive capabilities to calculate, have knowledge about consequences of choice, or to adjudicate among competing alternatives. Therefore, people *satisfice;* they will be *satisfied* with a *sufficiently* good outcome. They do not maximize. Bounded rationality is rational choice that takes into consideration people's cognitive limitations. Similarly, March (1997), a bounded rationalist, observes that all decisions are really about making two guesses—a guess about the future consequences of current action and a guess about future attitudes with respect to those consequences (March 1997). These guesses assume stable and consistent preferences, which may not always be true, e.g. regret is possible (e.g. Connolly and Zeelenberg 2002).

Kahneman's seminal experiments cast doubt on the assumptions of perfect rationality; for example, they show that decision utility and predicted utility are not the same (Kahneman et al. 1993). Keeney (1992b) a strong defender of classical normative theory, identifies *fairness* as an important missing factor in classical utility theory. In general, people are not egotistically single-minded about maximizing utility. For example, many employers do not cut wages during periods of unemployment when it is in their interest to do so (Solow 1980). The absence of fairness also poses the question about the "impossibility of interpersonal utility comparisons (Hausman 1995)." Sense of fairness is not uniform. Nor does utility theory address the issues of regret (e.g. Connolly and Zeelenberg 2002), something that has become an important research agenda for legal scholars (Parisi and Smith 2005).

New experimental evidence is another major contributing factor to the paradigmatic crises of normative theory. Psychologists have shown that people consistently depart from the rational normative model of decision making, and not just in experimental situations using colored balls in urns. The research avalanche in this direction can be traced to Tversky and Kahneman's (1974) article in *Science* and their subsequent book (Kahneman et al. 1982) where they report that people have systematic biases. For example, Baron (2000) reports 53 distinct biases. In light of these research results, Fischoff (1999), Edwards and von Winterfeldt (1986) report on ways to debias judgments. Moreover, Redelmeier and Kahneman (1996), Kahneman et al. (1993) report cases in which people preferred pain to a less painful alternative, which does not appear rational. The purely rational choice model is not completely supported, by experiments or human behavior, because it does not address many human cognitive "inconsistencies" or "paradoxes" reported by descriptive scholars. As a result, the contributions from psychologists to economic theory and decision-making have acquired a high level of legitimacy and acceptance. Simon and Kahneman have both become Nobel laureates. And research in behavioral economics is thriving (e.g. Camerer 2004).

The arguments and experiments that critique the normative theory are fundamentally grounded on empirical observations and descriptions of how decision making actually takes place, which are not necessarily consistent with how they "should", according to normative axioms. Therefore, we now turn our attention to descriptive theory and then consider prescriptive theory.

2.3.2 Descriptive Theories

2.3.2.1 Introduction

Whereas normative theory concentrates on how people should make decisions, descriptive theory concentrates on the question of how and why people make the decisions they actually make. Fjellman (1976, 77) argued that "decision makers found in decision theory [normative] should not be confused with real people." He points out that people are not nearly as well informed, discriminating, or rational as generally presumed. Nobel laureate Simon (e.g. 1997) cogently argues that rational choice imposes impossible standards on people. He argues for *satisficing* in lieu of maximizing. The Allais and Ellsberg paradoxes illustrate how people violate the norm of expected utility theory (e.g. Allais 1953; Ellsberg 1961; Baron 2000; Resnick 1987).

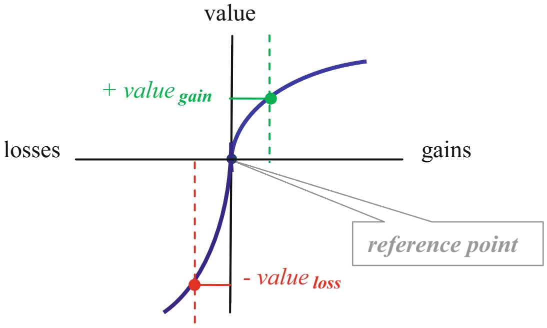
Kahneman's et al. (1982) publication, of "judgments under uncertainty: heuristics and biases", report three biased heuristics: representativeness, availability, and anchoring. These heuristics lead to systematic biases, e.g. insensitivity to prior outcomes, sample size, regression to the mean; evaluation of conjunctive and disjunctive events; anchoring; and others. Their paper launched an explosive program of research concentrating on violations of the normative theory of decision making. Edwards and von Winterfeldt (1986) write that the subject of errors in inference and decision making is "large and complex, and the literature is unmanageable." Scholars in this area are known as the "pessimists" (Jungermann 1986; Doherty 2003)." For our work, the bias of overconfidence is very important (Lichtenstein et al. 1999). They found that people who were 65–70% confident were correct only 50% of the time. Nevertheless, there are methods that can reduce overconfidence (e.g. Koriat et al. 1980; Griffin et al. 1990). In spite of, or possibly because of, the "pessimistic" critiques of the normative school and descriptive efforts have produced many models of psychological representations of decision making. Three prominent theories are: Prospect Theory (Kahneman and Tversky 2000), Social Judgment Theory (e.g. Hammond et al. 1986), and ecological rational theory (e.g. Gigerenzer and Selten 2001; Klein 1999, 2001).

2.3.2.2 Prospect Theory

Prospect theory is similar to expected-utility theory in that it retains the basic construct that decisions are made as a result of the arithmetic product of "something like utility" and "something like subject probability" (Baron 2000). The something like utility is a value function of gains and losses. The central idea of Prospect Theory (Kahneman and Tversky 2000) is that we think of *value* as *changes* in gains or losses relative to a reference point (Fig. 2.2).

The carriers of value are *changes* in wealth or welfare, rather than their magnitude from which the cardinal utility is established. In prospect theory, the issue is

Fig. 2.2 Hypothetical value function using prospect theoretic representation



not utility, but changes in *value*. The value function treats losses as more serious than equivalent gains. It is convex for losses and concave for gains. This is intuitively appealing, we all prefer gains to losses. But if we consider the invariance principle of normative decision theory, this principle is easily violated. Invariance requires that preferences remain unchanged on the manner in which they are described. In prospect theory the gains and losses are relative to a *reference point*. A change in the reference point can change the magnitude of the change in gains or losses, which in turn result in different changes in the value function that induces different judgements. Invariance, absolutely necessary in normative theory and intuitively appealing, is not always psychologically feasible. In business, the current asset base of the firm (the status quo) is usually taken as the reference point for strategic corporate investments. But the status quo can be posed as a loss if one considers opportunity costs and therefore a decision maker may be led to consider favorably a modest investment for a modest result as a gain. Framing matters.

The second key idea of prospect theory is that we distort probabilities. Instead of multiplying value by its subjective probability, a decision weight (which is a function of that probability) is used. This is the so-called **π function** (Fig. 2.3). The values of the subjective probability *p* are underweighed relative to $p = 1.0$ by the π function. And the values of p are overweighed relative to $p = 0.0$. In other words, people are most sensitive to changes in probability near the boundaries of impossibility ($p = 0$) and certainty ($p = 1$). This helps explain why people buy insurance—the decision is weighed near the origin. And why people prefer a certainty of a lower utility than a gamble of higher expected utility. This decision is weighed near the upper right-hand corner. The latter is called the "certainty effect" e.g. Baron (2000). This effect produces *arational* decisions (e.g. Baron 2000; de Neufville and Delquié 1998).

In summary, prospect theory is descriptive. It identifies discrepancies in the expected utility approach and proposes an approach to better predict actual behavior. Prospect theory is a significant contribution from psychology to the classical domain of economics.

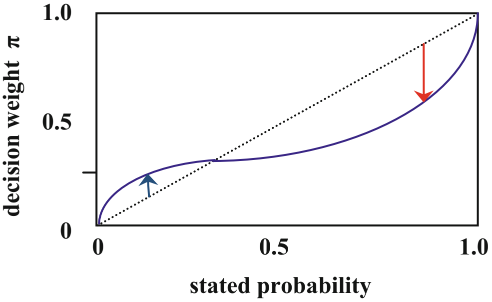


Fig. 2.3 A hypothetical weighing function under prospect theory

2.3.2.3 Social Judgment Theory

Another contribution from psychology to decision theory is Social Judgment Theory (SJT) (e.g. Hammond et al. 1986). SJT derives from Brunswick's observation that the decision maker decodes the environment via the mediation of cues. It assumes that a person, aware of the presence of cues, aggregates them with processes that can be represented in the "same" way as the environmental side. Unlike utility theory or prospect theory, the future context does not play a central role in SJT. Why is this social theory? Because different individuals, for example experts, faced with the same situation will pick different cues or integrate them differently (Yates et al. 2003). The SJT descriptive model (lens model) is shown in Fig. 2.4[2]. The left-hand side (LHS) shows the environment; the right-hand side (RHS) shows the judgment side where the decision maker is interpreting the cues, $\{X_i\}$, from the environment. The ability of the decision maker to predict the world is completely determined by how well the world can be predicted from the cues Y_e, how consistently the person uses the available data Y_s, and how well the person understands the world G, C. These ideas can be modeled analytically.

The system used to capture the aggregation process is typically multiple regression. We have a set of observations, Y_s. We also have *ex post* information on the true state Y_e. The statistic r_a, the correlation between the person's responses and the ecological criterion values, reflects correspondence with the environment. $R_s \leq 1.0$ is the degree to which the person's judgment is predictable using a linear additive model. The cue utilization coefficients r_{is} ought to match the ecological validities r_{ie} through correlations. G is the correlation between the predicted values of the two linear models. G represents the validity of the person's knowledge of the environment. C is the same between the residuals of both models, and reflects the extent to which the unmodeled aspects of the person's knowledge match the unmodeled aspects of the environmental side. Achievement is represented by

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[2] This description is adopted from Doherty (2003).

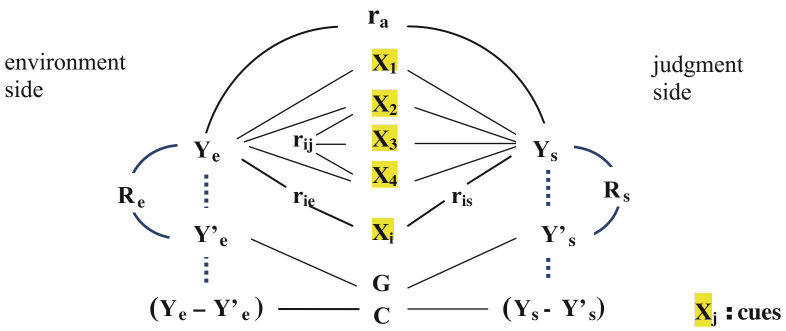

Fig. 2.4 The len's model of social judgment theory

$$r_a = R_e{}^*R_s{}^*G + C\left[\left(1 - R_e^2\right)^*\left(1 - R_s^2\right)\right]^{½} \tag{2.3}$$

The model is somewhat controversial (e.g. Hogarth 2001) on the process of cues, but it is an approach to operationalize and measure judgments. At the cybernetic and systems level, there is similarity of this model with Ashby's (1957) Law of Requisite Variety from complex systems theory. It states that the complexity of environmental outcomes must be matched by the complexity of the system so that it can respond effectively. In order for the system to be effective in its environment, it must be of greater and consistent complexity relative to the environment that is producing the outcomes. Were this not so, the responding system will be consistently overwhelmed by its environment sending signals the system cannot understand.

2.3.2.4 Ecological Rational Theory

We must bring up another strand in the descriptive school, the nascent Ecological Rational Theory. Scholars and practitioners of this strand do not accept the classical notions of utility maximizing and economic rationality; they opt for **descriptive realism** (e.g. Gigerenzer 2008; Gigerenzer and Selten[3] 2001; Klein 2001; Pliske and Klein 2003). Ecological Rational Theory asserts that people act quickly, without necessarily logical or analytic models using probabilities. Whimsically, Gigerenzer (2014; 68) book shows a cartoon of a caveman being attacked by a ferocious lion. The bubble, on top of the caveman defending himself, shows a complicated mathematical equation with many trigonometric and nonlinear functions. The message is that there are many situations in which people must take action without delay or consideration for decision models. Deciding is not necessarily dominated by axiomatic logic alone, but also efficiency. Decision making is "not just logical, but ecological; it is defined by correspondence [with the

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[3] Selten won the 1994 Nobel prize in economics with Harsanyi and Nash.

environment] rather than [analytic or model] coherence (Gigerenzer 2008).” Ecological rationality is an evolutionary perspective, the goal is the pursuit of objectives in the context of its environment. Gigerenzer conceives the mind as a modular system composed of heuristic tools and capabilities. He offers an “adaptive toolbox,” a set of “fast and frugal” heuristics comprised of search rules, stopping rules, and decision rules.

We note that the theory is both descriptive and prescriptive. In contrast to normative methods, Klein’s (1999, 2008, 2011) Naturalistic Decision Making (NDM) can be said to be an exemplar of Ecological Rational Theory. He describes decision making in exceptional situations which are characterized by high time pressure, context rich settings, and volatile conditions. Klein has extensively studied experienced professionals with domain expertise and strong cognitive skills, such as, firefighters, front-line combat-officers, economics professors, and the like. He finds that they are capable of “mental simulations,” that is “building a sequence of snapshots to play out and to [mentally] observe what occurs (Klein 1999).” They rely on just a few factors—“rarely more than three . . . a mental simulation [that] can be completed in approximately six steps (Klein 1999).” This is an important result; we will combine this finding with other similar research findings for our work.

2.3.3 Prescriptive Decision Theories

2.3.3.1 Introduction

Prescriptive decision theory is concerned with the practical application of normative and descriptive decision theory in real world settings. The practice is called *decision analysis*—the body of knowledge, methods, and practices, based on axioms, inferred principles, and effective practices of decision-making. The ethos is social: to help people and organizations make better decisions (Howard 2007) and to make them act more wisely in the presence of uncertainties (Edwards and von Winterfeldt 1986). Decision analysis is a science for the “formalization of common sense for decision problems, which are far too complex for informal use of common sense (Keeney 1982).” Decision analysis includes the design of alternative choices—the task of “. . . logical balancing of the factors that influence a decision . . . these factors might be technical, economic, environmental, or competitive; but they could be also legal or medical or any other kind of factor that affects whether the decision is a good one (Howard and Matheson 2004; 63). . . There is no such thing as a final or complete analysis; there is only an economic [sic] analysis given the resources available (Howard and Matheson 2004; 10).” Decision analysis is, therefore, boundedly rational. “The overall aim of decision analysis is insight, not numbers (Howard and Matheson 2004; 184).”

A comprehensive survey of decision analysis and their applications can be found in Keefer et al. (2004) and Edwards et al. (2007). We will limit our coverage to four

Table 2.2 Summary of four descriptive methods

	AHP	Howard's decision analysis	Value focused thinking (VFT)	Real options	Ecological rationality
Preference basis	Importance	Utility	Utility	Monetary value	Effectiveness and efficiency
Units	Cardinal, ordinal	Problem units	Problem units	Monetary units	Efficiency
Foundations	Ratio scale of pairwise comparisons	Expected utility theory	Expected utility and multiattribute utility theory	Temporal resolution of uncertainty	Mind as a modular system of heuristic
Principles	Linear ordering by importance	Rigorous use of normative axioms of utility theory	Pragmatic use of normative axioms of utility theory	Sequential temporal flexibility	Descriptive realism Efficiency Frugal and lean
Distinctive processes/ analyses	Factors hierarchy Matrix pairwise comparisons Matrix algebra	Deterministic system representation Utility function construction	Specification of values and objectives Guidelines for specifying alternatives	Set of options: abandon, stage, defer, grow, scale, switch	"Toolbox" of frugal heuristics

prescriptive methods, each representing a distinctive way to think about decisions (Table 2.2).

They are: AHP (Saaty 2009); Ron Howard's method, published by Strategic Decisions Group (SDG) representing the Stanford's school of decision analysis (Howard 2007); Keeney's Value Focused Thinking (Keeney 1992b), real options (e.g. Adner and Levinthal 2004) and ecological rationality (e.g. Gigerenzer 2008; Klein 1999).

We begin with AHP. It is original and distinctive. It does not use utility theory. Instead, it uses "importance" as the criterion for decisions. It is an exemplar of a prescriptive approach that departs from the conventional approaches of utility theory. In contrast, Howard's method adheres rigorously to the normative rules of normative expected utility theory. As such, it is an example of a normative prescriptive approach. Keeney's Value Focused Thinking (VFT) is also utility theory based. Keeney has defined and specified comprehensive and pragmatic processes that strengthen what are usually considered as the "soft" managerial approaches to the specification of objectives and to the creation of alternatives. It is an archetype of an analytically rigorous and simultaneously managerially pragmatic prescriptive method. Real options are discussed because it a relatively more recent trend in decision analysis. Table 2.2 presents a summary of the four descriptive methods. More detail is presented in the paragraphs that follow.

2.3.3.2 Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is a distinctive prescriptive method that does not rely on classical utility theory (Saaty 2009). AHP is predicated on four principles for decision problem solving: decomposition, comparative judgments, synthesis of priorities, and a social consensual process. The decomposition principle calls for a hierarchical structure to specify all the elemental pieces of the problem. The comparative judgment principle uses pairwise comparisons using a ratio scale to determine the relative priorities within each level of the hierarchy. The principle of synthesis of priorities is applied as follows (Forman and Gass 2001):

(1) given $i = 1,2,\ldots,m$ objectives, determine their respective weights w_i,
(2) for each objective i , compare the $j = 1,2,\ldots,n$ alternatives and determine their weights w_{ij} with respect to objective i , and
(3) determine the final alternative weights (priorities) $\boldsymbol{W}_j$ with respect to all the objective by

$$\boldsymbol{W_j} = w_{1j}w_1 + w_{2j}w_2 + \ldots + w_{mj}w_m.$$

(4) the alternatives are then ordered by the $\boldsymbol{W_j}$.

The social principles are met by the enactment of a multidisciplinary open interactive and voting process that is based on open discussions to arrive at relative priorities of importance (Saaty 2009).

AHP is now widely used as an alternative to expected utility theory for decision making (Forman and Gass 2001). Forman and Gass (2001) report that over 1000 articles and about 100 doctoral dissertations have been published on AHP. AHP has been extended using fuzzy set theory (Deng 1999) and is used in a wide variety of applications (Saaty and Peniwati 2013), such as national defense, mega projects, and the like.

2.3.3.3 Howard's Decision Analysis

Howard is a renown professor at Stanford University. We will use his approach to decisions as an exemplar for normative prescriptive decision-making. We will also call it the Howard's Decision Analysis and, at times, the Stanford model. "Decision analysis" was coined by Howard (2007). His approach to decision analysis is predicated on two premises. One is the inviolate set of normative axioms (Appendix 2.1) and the other is his prescriptive method to decision analysis. Collectively these form Howard's canons of the "old time religion" (Appendix 2.2). Non-adherents to the normative axioms and sloppy practitioners are positioned as "heathens, heretics, or cults" (Howard 1992). For example, AHP is explicitly dismissed as an invalid decision prescriptive process (Howard 2007), which we will discuss in another section of this chapter. Howard's methodology takes the form of an iterative procedure he calls the Decision Analysis Cycle

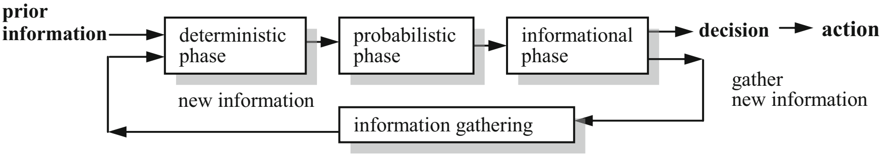

Fig. 2.5 Howard's decision analysis cycle

(Fig. 2.5) comprised of three phases, which either terminates the process or drives an iteration (Howard and Matheson 2004; 9). Numerous applications from various industries are reported Howard and Matheson (2004).

The first phase (deterministic) is concerned with the structure of the problem. The decision variables are defined and their relationships characterized in formal models. Then values are assigned to possible outcomes, which Howard calls "prospects". The importance of each decision variable is measured using sensitivity analysis, and at this stage without any consideration of uncertainty. Experience with the method suggests that "**only a few of the many variables under initial consideration are crucial** . . . (von Holstein 2004; 137)".

Uncertainty is explicitly incorporated in the second phase (probabilistic) by assigning probabilities to the important variables, which are represented in a decision tree. Since the tree is likely to be very bushy, "back of the envelope calculations" (von Holstein 2004; 139) are used to simplify it. The probabilities are elicited from the decision makers directly or from trusted associates to whom this judgment is delegated. Outcomes at each end of the tree are determined directly or through simulation. The cumulative probability distribution for the outcome is then obtained. The decision maker's attitude toward risk is taken into account. This can be determined through a lottery process. A utility function is then encoded. The best alternative solution in the face of uncertainty is called the *certainty equivalent*. Sensitivity to different variables' probabilities are performed.

The third (informational) phase follows review of the first two phases to determine whether more information is required. If so, the process is repeated. The cost of obtaining additional information is traded-off against the potential gain in performance of the decision. Numerous application examples are presented in Edwards et al. (2007).

2.3.3.4 Value Focused Thinking

The prescriptive approach of Keeney's (1992b) Value Focused Thinking (VFT) shifts the emphasis of decision making from the analysis of alternatives to *values*. In VFT, values are defined as what decision makers "really care about" (Keeney 1994). The emphasis on values is motivated to avoid anchoring and framing errors (Kahneman and Tversky 2000), i.e. positioning a problem or opportunity so narrowly that it will preclude creative thinking. Instead, anchor on values and frame the decision situation as an opportunity. The assumption is that value based

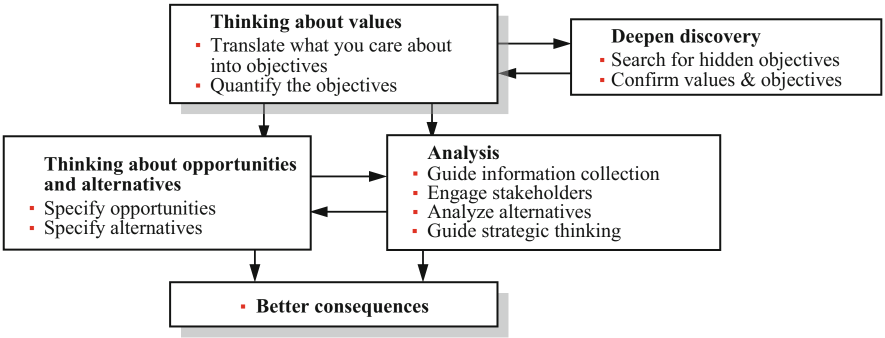

Fig. 2.6 Operational architecture of the value focused thinking process

thinking leads to more meaningful alternatives to attain what decision makers really care about. The theoretical assumptions of VFT are found in expected utility theory, multi-attribute utility theory (Keeney and Raiffa 1999) and axioms of normative decision theory (Keeney 1982, 1992b). Keeney is more liberal than Howard, Keeney is prepared to consider a suboptimal decision if it is more fair (equitable) (Kenney 1992a). He writes that “the evaluation process and the selection of an alternative can then be explicitly based on an analysis relying on *any e*stablished evaluation methodology (Keeney 1992b).” Adapting from Keeney (1992b), the operational highlights of the VFT method are illustrated below (Fig. 2.6), where the arrows mean “lead to.”

What is distinctive is that this method has specified an iterative phase at the front-end where the values of the decision-maker are thoroughly specified prior to the analysis of alternatives. The goals of this phase are to avoid solving the wrong problem and to identify a creative set of alternatives. These steps tend avoid many of the biases identified in descriptive decision theory, such as, framing, availability, saliency and the like. Keeney (1994) observes that the most effective way to define objectives and values is to work with the stakeholders. He offers ten techniques for identifying objectives and nine desirable properties for fundamental objectives. Having an initial set of objectives is a prerequisite to creating alternatives. Creativity is the most desirable characteristic for alternatives and VFT presents 17 ways to generate alternatives (Keeney 1996). Keeney’s book VFT (1992b) discusses 113 applications.

2.3.3.5 Real Options

Myers (1977) is credited with coining the term *real options*. An *option* is a right, but not an obligation, to take action, such as buying (call option) or selling (put option) of a specified asset in the future at a designated price (e.g. Amram and Kulatilaka 1999). Options have value because the holder of the option has the opportunity to profit from price volatility while simultaneously limiting downside risk. Options give its holder an asymmetric advantage. Real options deal with illiquid real assets, unlike financial instruments traded in exchanges (e.g. Barnett 2005) in very efficient markets.

Holders of an option have at their command a repertoire of six types of actions: to defer, abandon, switch, expand/contract, grow, or stage (Trigeorgis 1997). Unlike traditional techniques like discounted cash flow (DCF), real options are a flexible method for making investments. Unlike DCF, A real option is not subject to a one-time evaluation, but a sequence of evaluations over the course of the life-cycle of a project. This flexibility to postpone decisions, until some of the exogenous uncertainties are resolved, reduces risk. The Black-Scholes equation is a financial tour-de-force (e.g. Brealey and Myers 2002) and it is inextricably linked with options. But its use in real options has limitations. Returns in the Black-Scholes equation must be log normal; and it is assumed that there is an efficient market for unlimited trading. For securities, the value of the asset is observable through pricing in an efficient market. For real options the value of the asset is still evolving (Brach 2003); such as, an airport. Fortunately, there are many techniques for valuation (e.g. Neely and de Neufville 2001; Luehrman 1998a, b; Copeland and Tufano 2004). However, the managerial implications for real options remain non trivial. It requires substantially more management attention and domain skill to monitor and act on the flexibility of the method (Adner and Levinthal 2004). The value of the real option lies in exploiting favorable opportunities when the right conditions present themselves. "This perspective contrasts with the traditional view of a project as set of decisions made once at the beginning and unchanged during the life of the project" (Neely and de Neufville 2001). Barnett (2005) finds that discipline and decisiveness required to abandon a project are rare and demanding traits in executive management. Many applications using real options are reported in the literature (e.g. Luehrman 1998a; Fichman et al. 2005).

Real options scholars present a three phase process for real options analysis in systems planning and design (e.g. Neely and de Neufville 2001; de Neufville 2002). It is comprised of the discovery, selection, and monitoring phases (Fig. 2.7). Discovery is a multidisciplinary activity. It entails objectives setting and identifying opportunities. The selection phase is analytic intensive to calculate the value of the options in order to select the best one. Monitoring is the process to determine when the conditions are right to take action. Copeland and Tufano (2004) concentrate on the selection phase and present a procedure using binomial trees. Luehrman (1998a, b) present an elegant and more sophisticated analytic procedure to create a partitioned options-landscape. The landscape identifies six courses of action: invest now, maybe

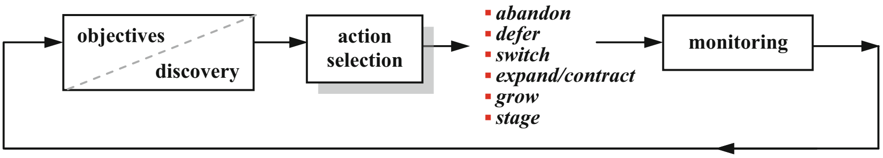

Fig. 2.7 Active management of real options

now, probably later, maybe later, probably never, and never. These choices are based on financial metrics. Barnett (2005) describes a framework for managing real options. It is somewhat generic and not directly actionable. We adapt de Neufville's three phase approach and combine it with Trigeorgis (1997) repertoire of six actions to illustrate a prescriptive decision process for real options (Fig. 2.7).

In summary, real options represent a newer direction in decision analysis. It is distinctive; it avoids the limitations of the discounted cash flow (DCF) investment approach. The method is more dynamic and based on sequential incremental decision making to make temporal resolution of uncertainty workable. This makes decision-making process more flexible (e.g. de Neufville 2008).

2.3.3.6 Ecological Rational Theory: Adaptive Tool Box

Recall that according in Ecological Rational Theory the enactment mechanism is the mind, as a modular system, that triggers without conscious effort "fast and frugal heuristics" (Gigerenzer 2008; Gigerenzer and Selten 2001; Klein 2015). This mechanism, however, does not preclude mental deliberation. Darwinian evolution has made the mind capable of selecting a working heuristic given the decision situation. Evolution has also made the mind capable of learning through reinforcement and repeated usage (Rieskamp and Otto 2006). Thus heuristics are *satisficing* heuristics. We present two examples to illustrate the point.

The tit-for-tat heuristic (Axelrod 1997) is used in a game theoretic situations in which two parties have to cooperate, but one party cheats. The decision the aggrieved party has to make is to forgive and continue cooperating or to retaliate? If forgive, how many times? Modeling this game is not simple. For there are many contingencies. The heuristic suggests that imitating the other party's behavior is effective. In other words. Immediately stop cooperating. Research from Axelrod (1997) shows the effectiveness of this simple approach over many substantially more complex statistical strategies.

I had the opportunity to host Boston Chicken's CEO, who was then affiliated with the IBM Board of Directors. He had come to Beijing for a meeting I was leading for the IBM CEO Lou Gerstner with cabinet-level Chinese government officials. During a relaxed moment, I commented on Boston Chicken's remarkably successful market expansion and diversification initiatives in China and the US. He said his company's strategy was simple. Find where MacDonald is building, follow suit and also build there. This is the "imitate the successful" heuristic (Boyd and Richerson 2009). It is a widely used heuristic; it is effective and lowers the cost of learning. Overall, the case for "fast and frugal heuristics" (Gigerenzer 2008; Gigerenzer and Selten 2001) is persuasive by their research based in the Max Plank Institute, and evolutionary arguments that support the heuristic's effectiveness. Also consistent with bounded rationality, this approach is parsimonious. And it is lean in terms of information gathering and analysis.

2.3.4 Declarative School

In the previous sections we have concentrated on what scholars identify as the three main schools of decision theory. This fourth school—the **declarative**—is our recognition of the existence of a fourth. The other three schools—normative, descriptive, and prescriptive—are all research intensive, each directly grounded on science and theory that locates the work. Many of their seminal thinkers are Nobel laureates, giants and prominent scholars in their chosen field of research, e.g. von Neumann, Savage, Simon, Selten, Kahneman, Aumann, Samuelson, Raiffa, Saaty, Nash, and so on. They shaped the foundations and influenced the directions of the research and the practice. Scholars follow and diligently discuss their work.

Our concentration is on executive decisions. We feel obligated to call attention to some of the ways executives learn how to improve their own skills and quality of decisions for which they are responsible and accountable. Many enterprises and large companies have management training programs to bring important and useful research findings and best practices to executives as they rise through the ranks. However this kind of learning opportunity does not exist for many. Without meaning any disrespect, it is unlikely that a large majority of executives, or that their direct reports or staffs, regularly read the research literature or ruminate about theory. Knowledge of sound theory, effective methods and practices are propagated, not as much by academic journals or scholars, but more by trade-press books, executive magazines, articles in prestigious newspapers, consultants, celebrity executives, self-proclaimed experts, and word of mouth. The mechanisms are by exposition and **declaration** of summaries, repackaging, personal and second hand experiences. These are packaged so the material is more easily understood and delivered in dosages that do not stress readers' attention span. After all not everyone is a research scholar who is inclined to read journal papers. By definition, the corpus of work and products of this school of hybrid decision theories, is wide ranging and very diverse. We organize the declarative hybrid school into three categories.

Category 1. Much of this work is useful and solid. It does not sacrifice rigor. Academic concepts and research findings are explained in everyday language. The hurdle of academic and expert knowledge are lowered and therefore understandable to those who desire to learn from their writings. For example, *The psychology of Judgment and Decision Making* (Plous 1993)*, Administrative Behavior: A Study of Decision-Making Processes in Administrative Organizations.* (Simon 1997), *A Primer on Decision Making* (March 1994), *Smart Choices* (Hammond et al. 1999), *Decision Traps* (Russo et al. 1989), *Risk Savvy* (Gigerenzer 2014), *Predictably Irrational* (Ariely 2008), *Thinking Fast and Slow* (Kahneman 2011), and so on. These are admirable exemplars of the declarative genre. Their attention to clarity, in non-technical terms, make these works conspicuous.

Category 2. This is another body of work that is informative and educational directed at more specialized practitioners. The scope is generally broader and more diverse than Category 1. The presentation style is less arcane, less intimidating, more general, very practical and notably more declarative. The prolific contributions of Peter Drucker mark his work as a distinguished exemplar (e.g. Drucker 1995, 1993, 2016). His writings are smart, erudite and bring unusual clarity and insight to the practice of executive management and decisions. They inform and provoke thinking. Other examples are Courtney et al. (2013) on how to decide and limiting bias (Soll et al. 2015), avoiding cowardice (Charan and Melino 2013), and so on. They play an important role in propagating practical knowledge that goes beyond interesting and colorful narratives.

Category 3 has the admirable goal of popularizing the field. Contributors necessarily simplify and generalize, to a high degree the technical rigor, and the specialized domain knowledge. Frequently, subtle nuances and fine texture of important ideas and theoretical concepts are omitted or lightly covered. This category is useful to popularize decision theory and practice. For example titles such as, "... the 15 min ...", "... dozen most ....", "... seven of ...", "... art of ...", " ... every time ...", and so on, belong to this genre. We are more cautious about this body of declarative work. We call this genre—the ***putative*** strand of the declarative school.

The declarative school, a hybrid strand, is an under—investigated domain. It is a new potentially fruitful area of study to investigate—to what extent, what content, how communicated and how they impact the practice and scholarship.

2.4 Tensions Between the Three Schools

> Rationality is only one of several factors affecting human behavior; no theory based on this one factor can be expected to yield reliable predictions. (Robert Aumann[4])

We have seen how paradoxes (Allais 1953; Ellsberg 1961) and the landmark experiments of Tversky and Kahneman (1974) present evidence that people arrive at decisions in ways that are not consistent with normative theory. These paradoxes and experiments are descriptive. The Naturalistic strand of research describes how professionals under situations of extreme pressure and volatile conditions make decisions, it presents a picture that is different from normative theory. These inconsistencies with the axioms of utility theory and the requirements for "perfect" rationality are a source of tension between normative and descriptive scholars.

Zeckhauser (1986) articulates the debate with three insightful axioms and three practical corollaries. They are paraphrased below, they capture the spirit of the research directions in decision theory and opposing views.

Axiom 1 For any tenet of rational choice, the behavioralists can produce a counterexample in the laboratory.

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[4] Aumann won the 2005 Nobel in Economics for work on the axioms of normative decision theory. The quote appears in Wolpin's book (2013) "the Limits of Inference without Theory".

Axiom 2 For any “violation” of rational behavior, the rationalists will reconstruct a rational explanation.

Axiom 3 Elegant formulations will be developed by both sides, frequently addressing the same points, but freedom in model building will result in different conclusions.

and . . .

Corollary 1 The behaviorists should focus their laboratory experiments on important real world problems.

Corollary 2 The rationalists should define the domains of economics where they can demonstrate evidence that supports their view.

Corollary 3 Choice of competing and/or conflicting formulations should be decided on predictive consistency with real world observations.

The Nobel Prizes in the behavioral sciences; such as Simon, Kahneman, Selten, Ostrom (Prizes in Economic Sciences 2015) are evidence of the importance of behavioral and social factors in decision making as an adjunct to normative theories. Frisch and Clemen (1994) assert that utility theory as normative does not justify its use by psychologists as a standard by which to evaluate decision quality.

Researchers are looking deeply at the fundamental ideas, e.g. what is utility? Is it in our interest to maximize utility? What are the deep mental and psychological processes for decision making and how do they work?

For example, utility is not a monolithic invariant. Kahneman and Thaler (2006), Kahneman and Tversky (2000) distinguish between *experience utility* and *decision utility*. They show that utility preferences will differ on how and when it is measured, as experienced or recalled. Experiments reveal that recall is imperfect and easily manipulated. This is another kind of bias. These findings go to the heart of the assumptions of normative theory: that individuals have accurate knowledge of their own preferences and that their utility is not affected by the anticipation of future events. Schooler et al. (2003) argue that people suffer from inherent inabilities to optimize their own level of utility. The deliberate efforts to maximize utility may lead individuals to engage in non-utility maximizing behaviors. They suggest that “utility maximization is an imperfect representation of human behavior, regardless of one’s definition of utility (Schooler et al. 2003).” Klein (2001) argues that “optimization is a fiction”. The cognitive processes for decision making appear to be more sophisticated than merely optimizing utility. Bracha and Brown (2012) suggest a novel framework, individuals have two internal accounting processes, a rational account and a mental account. A choice is the result of intrapersonal moves that results in a Nash equilibrium. This game theoretic approach is also adopted by Bodner and Prelec (2003) where they model utility maximization as a self-signaling game involving two kinds of utility: outcome utility and diagnostic utility.

Neuroeconomics is a new research strand. It seeks to understand decision processes at a physiological level (e.g. Camerer et al. 2005). It uses technology like *f* MRI to understand which areas of the brain are used during decision making.

McCabe et al. (2005) found that people that cooperate and those that do not cooperate have different patterns of brain activity. The evidence suggests that different mechanisms are at work for the same problem. Legal scholars are very active in the study of irrational behavior to understand the issues of reciprocity, retaliation and their implications on judicial punishment (Parisi and Smith 2005).

The tension between the normative school and prescriptive is also visible. For example, normative scholars raise concerns about AHP (e.g. Belton and Gear 1982). Under certain conditions, intransitivity and rank reversal are two deviations from normative axioms that can occur in AHP (e.g. Dyer 1990; Triantaphyllou 2001). Saaty (1990) and Forman and Gass (2001) retort that rank reversal in systems can be expected and can be even desirable when new information is introduced; learning effects can take place. The rank reversal problem is discussed and ways to address can be found in Saaty (2009), Saaty and Peniwati (2013) and Millet and Saaty (2000). Consistent with the pragmatics of a prescriptive approach to decision-making, they write "There is no one basic rational decision model. The decision framework hinges on the rules and axioms the DM [decision maker] thinks are appropriate (Forman and Gass 2001)." Saaty (1990) quotes McCord and de Neufville (1983): "Many practicing decision analysts remember only dimly its axiomatic foundation . . . the axioms, though superficially attractive, are, in some way, insufficient . . . the conclusion is that the justification of the practical use of expected utility decision analysis as it is known today is weak."

2.5 The Canonical Normal Form

> We assume that the decision maker's problem has been identified and viable action alternatives are prespecified. . . . with all due apologies, we assume that the pre analysis stage has been completed. (Keeney and Raiffa[5])

Although each prescriptive method is unique, we argue that they are all instantiations of the meta "canonical paradigm" of decision making (Bell et al. 1988, 18). This meta model is widely adopted in the literature in various forms (e.g. Bazerman 2002; March 1997; Simon 1997; Keeney 1992b; Hammond et al. 1986). The canonical paradigm is a meta-process—a process for defining a specific processes and procedures for the practice. For example, the Scientific Method is a meta-process. Biologists, chemists, and physicists routinely perform experiments that bear little resemblance to each other, but their methods align consistently with the Scientific Method. Even within a single domain there are many instantiations of the Method. A cosmologist and an elementary particle physicist are both doing physics according to the Scientific Method. Though the specific procedures and instruments of their practice vary widely in detail, they are completely consistent with the scientific method. One uses radio telescopes and another uses accelerators. The

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[5] Keeney and Raiffa (1999, pp 10–11).

Engineering Method (Seering 2003) is another meta-process. Electrical, mechanical, and aeronautical engineers build artifacts that are quite distinct from each other, but their methods are isomorphic to the engineering method. In this same way, each of the prescriptive methods we have described on decision theories, although uniquely distinctive, align consistently with the canonical model for decisions. The canonical model is a meta-process for decision analysis (Table 2.3).

There are many ways to instantiate the meta-model with a specific model comprised of concrete and actionable procedures. Our decision complex of five spaces is such an instantiation. Our systematic approach to executive-management decisions maps coherently onto the canonical form (Table 2.3).

Our systematic process is very explicit in the solution space and operations space. Specifically, they are: (i) debiasing procedures are called for, (ii) focus on distinct sets of decision variables, managerially controllable and managerially uncontrollable, (iii) ability to systematically construct alternatives, (iv) ability to systematically explore entire solution space under the entire space of uncertainty, (v) pose and analyze any "what if" hypothetical question, (vi) systematically predict their outputs and standard deviations, (vi) construct robust alternatives of choice and also systematically predict their outputs and standard deviations. The ability to systematically construct alternatives cannot be overemphasized. Simon (1997, 126) writes:

> The classical view of rationality provides no explanation where alternate courses of action originate; it simply presents them as a free gift to the decision markers.

> the lengthy and crucial processes of generating alternatives, which include all the processes that we ordinarily designate by the word 'design,' are left out of the SEU account of economic choice.

The research on this crucial design phase of decision making (step 4 of the canonical paradigm) does not appear to be emphasized in the decision-making literature. Its importance is recognized, e.g. "the identification of new options is even more important and necessary than anchoring firmly on analysis and evaluation as goals of the analysis (Thomas and Samson 1986)." Alexander (1979) presents case studies of design of alternatives and unfortunately finds a tendency to prematurely truncate the building of the repertoire of alternatives in the overall process. He concludes that "alternatives design is a stage in the decision process whose neglect is unjustified … (Alexander 1979)." Arbel and Tong (1982) prescribe the use of AHP as a means to identify the most important variables that affect the objectives of a decision for creating alternatives. But they fall short of providing a actionable construction processes for alternatives. Yilmaz (1997) argues for a constructive approach to create alternatives and presents a way to do so using explicitly identified decision factors and their range of responses. His construction requires full-factorial information, which makes the construction process very complicated.

This thin presence in design of alternatives is discernable with the exception for our prescriptive methodology (Tables 2.3 and 2.4).

Table 2.3 Our instantiation of the canonical form: A systematic process

Process phases	Our systematic process	
Characterize **Problem Space**	Sense making—uncomplicate cognitive load	☑
	Frame problem/opportunity and clarify boundary conditions	☑
	Specify goals and objectives	☑
	Specify essential variables Managerially controllable variables Managerially uncontrollable variables	☑
Engineer **Solution Space**	Specify subspaces of solution space Alternatives space and uncertainty space	☑
	Specify entire solution space	☑
	Specify base line and uncertainty regimes Do-nothing case and choice-decision Estimate base line and dispel bias	☑
Explore **Operations Space**	Specify	
	Sample orthogonal array Do-nothing case and choice decision-alternative	☑ ☑
	Predict outcomes	☑
	Design and implement robust alternative Design and implement any what-if alternative	☑ ☑
Evaluate **Performance Space**	Evaluate performance: analyze 3R Robustness, repeatability, reproducibility	☑ ☑
Enact **Commitment Space**	Decisive executive Approval of plan Commit funds, equipment, organizations	☑ ☑ ☑

☑ indicates required in the process

Given a set of alternatives, AHP offers guidelines for creating a hierarchy of decision factors. AHP assumes that the alternatives are known, the weights of the factors that will enter into the selection of an alternative are also unknown. By building a hierarchy of the decision factors, the objective, factors, followed by group discussions, the relative importance of the variables are revealed. Then using the relative importance of the factors, the AHP calculations rank the alternatives. In Stanford's method, through sensitivity analysis one finds the variables that have the highest impact on the output. Using those variables, we are directed to specify creative alternatives, but we are not presented with explicit means to construct those creative alternatives. With the alternatives at hand, utility theory is used to identify the best one.

Value Focused Thinking makes creating alternatives the centerpiece of the method and it presents a comprehensive approach to objectives specification. Objectives are used to guide the creation of alternatives. To create alternatives, 17 useful guidelines are presented. We are reminded that "the mind is the sole source of alternatives" and therefore creativity is important. Although we are given a comprehensive set of guidelines and many examples of alternatives from a wide

Table 2.4 Summary comparison

	AHP	Decision analysis	VFT	Real options	Ecological rational	Our paradigm
Detect problem/ opportunity	○	○	○	○	○	⊙
Define problem/ opportunity	○	○	⊙	○	○	⊙
Specify objectives	⊙	○	●	⊙	⊙	●
Specify alternatives	⊙	◉	⊙	◉	⊙	●
Analyze of alternatives	●	◉	◉	●	⊙	●
Select alternatives	●	●	●	●	●	●
Learn, communicate	○	○	○	⊙	○	⊙

○ assumed doable, ⊙ guidelines provided, ◉ generic alternatives defined, ● explicit prescriptions

range of applications, Value Focused Thinking does not seem to offer a construction mechanism for the creation of alternatives.

At the core, real-options is about two things: sequential incremental decisions, and temporal resolution of uncertainties as time progresses so that the valuation and selection of alternatives are more certain. Like other prescriptive methods it assumes that alternatives can be analyzed rigorously following the procedures of their method. What is distinctive about the real options method is that has a predefined set of generic alternatives (e.g. Trigeorgis 1997). For example, see Fig. 2.7.

This void in step 4 of the canonical model—the construction of alternatives, is unexpected. It would be like having Thanksgiving dinner and assuming the turkey is there for everyone. It is generally assumed that alternatives exist, are easily found, or readily constructed. These assumptions are surprising because synthesis must necessarily precede analysis; analysis that determines the decision maker's preferences among the alternatives and which culminates in the selection of the one choice to act upon. This is like the apocryphal basketball team that only shoots free throws at every practice. The assumption being that "the rest of the game is a straight forward extension of making free throws and can best be learned by experience in a game situation (Seering 2003)."

Our work does not assume that alternatives are present and ready for analysis. They must be constructed. We will specify prescriptive methods for the engineering of decision alternatives. We will use the engineering methods of Design of Experiments (DOE) (e.g. Montgomery 2008; Otto and Wood 2001). These are the subjects of this book and we will show that our work is distinctive because:

- We provide an explicit construction mechanism for designing decision alternatives.
- Alternatives are constructed using variables that are under managerial control.

- Variables that are not managerially controllable are used to specify a set of uncertainty regimes that span the uncertainty space.
- Alternatives span the entire solution space and uncertainty space. The outcome and standard deviation of every decision alternative can be predicted.
- The analysis of alternatives does not require exhaustive analysis of every possible alternative. Using our methodology, any decision alternative can be designed for the type of outcome desired; for example, for the maximum outcome regardless of standard deviation, robust outcome that has satisficing outcome and is insensitive to uncontrollable conditions.
- The analysis does not require the subjective translation from natural units (e.g. profit, safety, …) into subjective utility or ordinal judgments. All the analyses are performed in their natural units. A mix of variables of categorical, ordinal, interval, ratio scales are allowed.
- We can predict the outcome and standard deviation of any hypothetical what-if question to operate under any of the specified uncertainty regimes. This permits unconstrained exploration of the solution space under any uncertainty regime.

The ultimate goal of any decision methodology is helping people make better decisions. The question we must ask is: What is a good decision? This is the subject of the next section. The more comprehensive questions of the pragmatics and rigor of our paradigm are deferred to Chaps. 4 and 10, respectively. Then we will have more data and conceptual machinery to address these two questions.

2.6 What Is a Good Decision?

> We can never prove that someone who appeals to astrology is acting in any way inferior to what we are proposing. It is up to you to decide whose advice you would seek. (Howard)

2.6.1 Introduction

There is no general consensus among scholars on what is a good decision. It is an area that has drawn much scholarly research and attention (Keren and de Bruin 2003), which is not to say what makes a bad decision is a topic that has been avoided. Scholars' differences, by and large, align along the schools of decision theory. For example, the debate centers on what Keren and de Bruin (2003) call "outcome versus process". Good processes do not guarantee good outcomes, and bad processes can, at times, produce good outcomes (Hazelrigg 1996, Appendix 2.5). The normative school prefers good process over good outcomes. A strong argument is that the good results from a bad process are unlikely to be repeatable or reproducible. This also what Yates and Tschirhart (2006) call the "satisfying results" versus "coherence" perspective. Yates et al. (2003, 52) present data and argue that "a good decision process is one that tends to yield good decisions [outcomes]". They note that "a striking feature of the results is that subjective notions of decision quality are overwhelmingly dominated by outcomes" (op. cit. 28). Each of the three schools has a distinct position on what is a good decision. And each school of decision theory has different criteria to evaluate decisions. For a detailed discussion, we defer to Keren and de Bruin (2003) who present a thorough review and comprehensive analyses of the process versus outcome debate and other findings about what scholars consider to be good decisions (Chaps. 4 and 10).

In this section, we adumbrate the representative positions from the main schools of decision theory. We close with a discussion with our position on the subject of "a good decision".

2.6.2 Three Dogmas: Normative, Descriptive, and Prescriptive

Those that favor the normative school of decision-making draw a sharp distinction between a good decision and a good outcome (e.g. Howard 1992, 2004, 2007). A good decision is a rational decision, in which every procedure adheres to the axioms of normative theory and principles. Examples of these principles include the principles of the sure-thing, independence, non-materiality of sunk costs, and so on (Appendix 2.1). To these scholars, outcome is not a sufficiently valid determining factor because any decision can produce bad results given the stochastic nature of events (e.g. Hazelrigg 1996, Appendix 2.5). Aleatory factors exert their influence in unpredictable ways.

Stated in layman's language, the normative axioms are:

- *Completeness***.** Given any two alternatives, *a* and *b*. Then *a* is preferred to *b,* or *b* is preferred to *a*, or *a* and *b* are equally attractive. (See Appendix 2.1 for a brief note on this axiom, Aumann (1962) shows that a utility theory can be built without this axiom.).
- *Transitivity*. If *a* is preferred to *b*, and *b* is preferred to *c*; then *a* is preferred to *c*, i.e. preferences are transitive.
- *Continuity*. If *a* is preferred to *b*, and *b* is preferred to *c*; then *b* can be represented as a weighted average of *a* and *c*.
- *Monotinicity***.** Given two alternatives with the same outcome, the choice which is more likely is the preferred one.
- *Substitution*. If two alternatives are identical, i.e. indifferent to the decision-maker, then either one can be substituted for the other.

The unconditional mathematical adherence to these axioms characterize the practitioners of the "old time religion" of decision analysis (Howard 1992). Appendix 2.2 shows the additional canons of the old time religion. These four axioms assume the decision alternatives can be represented by probabilities and potential outcomes. These assumptions have proved to be extremely useful and productive in research and the practice.

In contrast, scholars from the descriptive school report on experiments where people, in fact, do consider good results, missed opportunities, difficulty, and other factors as important factors of decision quality (e.g. Yates et al. 2003). Research in behavioral decision making shows a more complicated picture about the mental processes of decision making than single minded "utility" maximization (e.g. Kahneman et al. 1993; Kahneman and Thaler 2006; Schooler et al. 2003). Yates et al. (2003) surveyed people think about their serious decisions and whether they were "good" or "bad" and why. Overwhelmingly, 95.4% of the "good" decisions, and 89.0% of the "bad" decisions were attributed to experienced outcomes. And only 6.4% attributed process to "good" decisions; while 20.2% attributed process to "bad" decisions. Many in the descriptive school argue that outcomes are a factor by which people judge decisions. These scholars would be reluctant to declare a surgical operation as successful should the patient die during the procedure. "… there is no unequivocal answer to the question of how to judge decision goodness; in particular whether it should be based on process or outcome" (Keren & de Bruin 2003).

We adopt the view that the axioms of rationality cannot be ignored, but practical criteria are appropriate, for example, "practical analysis", "maximize professional interest" (Appendix 2.4, Keeney 1992b). Those of the prescriptive school are more pragmatic and embrace bounded rationality. Edwards (1992) presents guidelines for descriptive theory that he calls "assumptions and principles" (Appendix 2.4). Keeney (1992b) writes that the problem should guide the analysis and the choice of axioms and he offers the guidelines in Table 2.5.

To maximize the quality of an analysis, he specifies objectives for the practice (Table 2.6).

To those from the normative school, a good decision is coherence and invariance with the axioms of utility theory. Given the unpredictability of future events, the

Table 2.5 Objectives of axiom selection for decision analysis

Objectives of axioms for decision analysis	
Provide the foundation for a quality analysis	Address the problem's complexities explicitly provide a logically sound foundation for analysis provide for a practical analysis be open for evaluation and appraisal

Table 2.6 Objectives of decision analysis quality

Objectives of decision analysis	
Provide insight for the decision	create excellent alternatives understand what and why some alternatives are best communicate insights
Minimize effort necessary	time utilized cost incurred
Contribute to the field of decision analysis	
Maximize professional interest	enjoy the analysis learn from the analysis

quality of a decision is uncoupled from outcomes. To those who favor descriptive theories, outcomes **and** other behavioral variables are important factors for decision quality. Their argument is buttressed by empirical evidence. Those in the prescriptive camp are more boundedly rational, the specific problem guides the selection of axioms, and insights that are useful to the client are determinants of decision quality.

Edwards (1992) reports on an informal survey he took at a prestigious conference. His survey showed an overwhelming agreement that expected utility theory is the appropriate normative standard for decision making under uncertainty. The same group also showed an overwhelming agreement that experimental evidence shows that expected utility theory does not fully describe the behavior of decision makers. Kahneman and Tversky (2000) summarize work from scholars that show that dominance and invariance axioms are essential and that selective relaxation of other axioms is possible. This lends force to Keeney's (1992b) pragmatic objectives for prescriptive decision analysis and axioms selection.

2.6.3 Howard's Good Decision

Howard (2007) identifies six criteria to evaluate decision quality. They have a strong influence and broad adoption by normative scholars (e.g. Edwards et al. 2007). Howard's six criteria to evaluate decisions are as follows:

- **A committed decision-maker**. By definition a decision is making a choice of what to do and what not to do with a resolute commitment to action. A decision does not exist without an executive who is ready to take action and reallocate resources for more attractive outcomes.
- **A right frame**. Framing is the process of specifying the boundaries of a decision situation. It shapes a decision maker's conception of the acts, outcomes, and contingencies associated with a particular choice to be made (Kahneman and Tversky 2000). A meaningful decision is not possible without a clear view of what is considered relevant and what is irrelevant. Framing helps do this (Weick 2001).
- **Right alternatives**. This is the most "creative part of the decision analysis procedure" (Howard and Matheson 2004; Simon 1997). A creative alternative is one that might resolve a decision situation, remedy defects of the present situation and improve future prospects.
- **Right information**. Information is a body of facts and/or knowledge that will avoid a chosen alternative being inferior had more accurate, complete and timely information being available.
- **Clear Preferences**. Every alternative has a measurable value, that permits an ordering of "goodness". For example, given two different alternatives x and y, a decision-maker can say x is better than y. In other words, x is preferred to y. The rules that determine preference must be defined. According to Howard the four

axioms of Morgenstern and Neumann (1944) must apply, as well as his set of "decision desiderata" (Appendix 2.2).

- **Right decision procedures**. Having the right decision procedure means having a process like the canonical paradigm, a process like Howard's Decision Analysis process (Howard 2007), a set of reciprocating processes between the DMU and implementing groups throughout the decision life cycle (Spetzler 2007). Our systematic paradigm is our approach for a "right decision procedure".

Howard's criteria concentrate on the tasks leading to the event of decision-making. It also requires the necessary condition of a committed decision-maker who will move forward and enact the decision specification. **Decisiveness** is implied by his requirement of "ready to take action." The nexus of Howard's criteria are in the Problem Space, Solution Space, and Commitment Space (Fig. 1.2, Sect. 1.3.2.1) of the Decision life-cycle.

2.6.4 Carroll and Johnson's Good Process

In contrast to Howard's ***ex ante*** evaluation (op cit 2001), Carroll and Johnson's (1990) six criteria for evaluating methods' processes is an ***ex post*** evaluation process. Its locus of evaluation is the Performance Space. Carroll and Johnson's (1990) specify six criteria.

- **Discovery**. "Having the power to uncover new phenomena, surprise the researcher, and lead to new creative insights."
- **Understanding**. "Providing a cause-and-effect analysis that uncovers the mechanisms or processes by which decisions are made."
- **Prediction**. "Having logical or mathematical rules that predict the judgement and decisions that will be made. The rules need not represent the actual decision processes."
- **Prescriptive control**. "Providing opportunities and techniques for changing the decision process, as in prescribing better decision rules or testing potential manipulations."
- **Confound control**. "Creating controlled situations so as to rule out other explanations of the results (Known as confounds)."
- **Ease of use**. "Taking less time and resources for the same progress to the other goals."

2.6.5 Our Four R's: Robustness, Repeatability, Reproducibility, and Reflection

The first of our three R's—robustness—is located in the Solution Space and concentrated in Performance Space.

- **Robustness** is the property of a decision, such that its outcomes are highly insensitive to uncontrollable conditions, even when the uncontrollable factors have not been eliminated.
- Design of robust decisions uses managerially controllable and uncontrollable variables. This is an *ex ante* activity for *ex post* desirable outcomes. In the next chapter we will show exactly how this is done.

The next two R's—Repeatability and Reproducibility—are located in the Performance Space. These measurements determine the variations that result during production of an artifact, the measuring instrument or the person who is making the measurements. The ability to isolate the causes and magnitudes of these measurements provide actionable insight into quality improvements that can be made in the sociotechnical system.

- **Repeatability** is the variation in measurements taken by a person or instrument on the same artefact, under the same conditions. The objective is for measurement results that differ by only a small amount. This is indicative of good repeatability. A distinctive feature of our methodology is that we consider decisions as intellectual artefacts and use engineering and social methods for their design and implementation. The same social system using the same process and technical system produce decision outcomes that differ by only small variations. Such a sociotechnical system is said to be *repeatable*.
- **Reproducibility** is the property of a process, or an entire experiment, to be duplicated—either by someone else working independently or the same person—and produce results that differ by only a small amount. Can the same sociotechnical system using the same processes and social system produce the same results? If so, the measurement system is *reproducible*.

The next R is Reflection, which is required to be practiced in all five spaces, but most intensely in the Performance Space.

- **Reflection** is thinking about experiences either *ex post* or *ex inter,* both directed at learning for better *ex ante* decisions for the next experience (e.g. Mesirow 1990). To us "experiences" are the DMU's work leading to the outputs and *ex post* reviews, as well as, discussions of the in-process outputs and end-process outputs. Rodgers (2002, 855) writes with great pith that "reflection is not a casual affair". It is, by no means, wooly or undisciplined thinking. Quite the contrary, "Reflection is a systematic, rigorous, way of thinking, with its roots in scientific inquiry" (Rodgers 2002, 845). The subject has its origins in Deweys' (1933) work on thinking, learning and reflecting.

Why reflect at all? Dewey argues that reflecting is an inherent human quality—to learn from experiences, to be able to improve subsequent experiences. Knowledge must be experienced. Survival drives this instinct. The possibilities of improved effectiveness are strong and natural drivers that motivate reflection and learning. Through reflection and thinking, we can "understand at a grander scale" (Dewey 1933). Dewey anticipated Arrow (1962, 155) who wrote that "learning is the product of experience". Work on learning-by-doing from von Hippel and Tyre (1996). Schön's (1983) segments reflection into reflection-**in**-action and reflection-**on**-action. Reflection-in-action is learning by doing, *ex inter* learning. Reflection-on-action is *ex post*. Reflection is not navel-gazing, it requires systematic disciplined processes, close cousins of the scientific method. Dewey (1933), Rodgers (2002) and Moon (2004) discuss various strategies for systematic reflection. Reflection can be taught. While solitary reflection is useful, carried out in a sociotechnical community environment is far more effective. It stimulates personal and organizational learning.

Napoleon Bonaparte, one of history's most decisive leader, famously said:

> If I seem always equal to the occasion, ready to face what comes, it is because I have thought the matter over a long time before undertaking it. I have anticipated whatever might happen. It is no genius which suddenly reveals to what I ought to do or say in any unlooked-for circumstances, but my own reflection, my own meditation. (Morgenthau 1970, 180).

2.6.6 Discussion

Translating the work of scholars into a single set of measures for a "good decision" will certainly be challenged from many quarters, each armed with unique, rigorous and defendable mental models. The scope, details, problem/opportunity, domain-disciplines, organizational structure and culture, and situational environment of decisions with vary greatly for every decision situation. This is particularly true of messy and wicked executive decisions.

Therefore, we must defer the judgement of *goodness* to the executives who are responsible and accountable for the decisions and their outcomes. This is realistic. In the final analysis, they are the ones who must defend their judgments and actions, and they are the ones who have their careers, bonuses, and promotions at risk. ***They, who have been given the power to command, must be able to explain their decisions to whom they must answer***. Between them and collectively, their judgement of a "good decision" must have a high degree of compatibility. This is a necessary part of the sociotechnical component of reflection (Sect. 2.6.5). The judgement is unlikely to be based entirely on outcomes or exclusively on process. Personal experience and scholars' research persuade us that having strong arguments, to justify a decision and an outcome, is an effective management practice (Keren and de Bruin's 2003). Consequently, we find ourselves concurring with

Keren and de Bruin's (2003) assertion "there is no an unequivocal answer to the question how to judge decision goodness". We are, by no means, suggesting a "do nothing" approach to the question of a good decision. Research must continue, and the flow of meaningful descriptions and effective prescriptions must also continue. All this will add to the cumulative knowledge about good decisions.

We are convinced that measurements and systematic reflections are necessary procedures to have in place. We are not suggesting a monolithic process, but a set of meso-processes for use at different stages of the decision life-cycle.

Considering the time dimension of the life-cycle, we mark the time at which the decision is taken, when the executive commits to a decision specification and assigns scare resources to its implementation. Using the term from the military, we call this the *zero-hour*. Informed by the work of scholars, for the following time periods—*ex ante* (before zero-hour), *ex inter* (during zero-hour), and *ex post* (after zero-hour)—the following requirements must be satisfied:

- ***ex ante***. The judgments must consider the actions before zero-hour. For example, Howard's criteria for a decisive executive (Sect. 2.6.3) and design for Robustness (Sects. 2.6.5 and 1.6.2) are examples of actions taken *ex ante*.
- ***ex inter***. The sociotechnical system must have a decisive executive who can commit at zero-hour, the moment of decision (Sect. 2.6.3). At the moment of decision, the executive must decide. Executives must be resolute
- ***ex post***. Every decision involves an outcome, it follows that it is necessary to evaluate the quality of the sociotechnical system that produced this outcome. Recall we stated that the sociotechnical system is the production of the decision as intellectual artefacts. For example, Repeatability and Reproducibility (Sects. 2.6.5 and 1.6.2) are quality measures of such a production system. Measurements are meaningless without learning from them; learning is a key requirement of a high performance organization. It follows that reflection is a must (Sect. 2.6.5).

2.7 Chapter Summary

- There are four strands in the field of decision theory—normative, descriptive, prescriptive, and our discovery of the declarative school. Their goals are to understand: how people should decide with logical consistency, how and why people decide the way they do, how to help executives and managers prepare people to design good decisions and how to evaluate decisions in a life-cycle framework.
- We are the first to identify the existence and influence of the declarative strand. We are also the first to segment it into three categories of progressive rigor.

- Our methodology to executive-management decisions is located in the prescriptive school of decision theory. It presents a new paradigm to help executives prepare and make robust decisions
- The traditional *canonical* paradigm of decision making is meta- process. It is a structural model of specific meta-process for instantiation with actionable processes. The meta model, implicitly and explicitly, is widely accepted and used in many forms of instantiations by researchers, practitioners, writers and journalists.
- Each school of decision theory stipulates different criteria for evaluating decisions.

The normative school insists on adherence to normative axioms and normative principles to evaluate logical consistency.

The descriptive theories concentrate of how people actually make decisions, with many imperfections and behavior that sometimes violates normative principles. Psychology is a key disciplinary domain that explain many of these phenomena. Which is why this school is also frequently referred to as the behavioral school. The numerous Nobel awards have positioned this school as a *bona fide* main stream research discipline. Their evaluation criteria are more pragmatic and relaxed relative to the normative scholars.

The prescriptive school draws from the normative and behavioral school to provide prescriptions to help people make decisions. It is practical and its evaluations place a stronger emphasis, than the other schools, on empirical results from the practice. Prescriptions that cannot be buttressed with theory are suspect.

The declarative school is a hybrid of the previously identified schools. It is very diverse and varied. We identify three categories of work in this hybrid school. Category 1—Concepts and research findings are explained in everyday language (without sacrificing rigor and accuracy) and therefore understandable to those who desire to learn from their writings. Category 2 material is less arcane, less intimidating, more general, and notably more declarative. The work is practical. Category 3 has the admirable goal of popularizing the field. It must be said also that many simplify and generalize, to a high degree, the technical rigor, specialized domain knowledge that is communicated. We call Category 3—the *putative* strand.

- On the question of what is a good decision. We are in Keren and de Bruin's (2003) camp which says that "there is no unequivocal answer to the question how to judge decision goodness". To which we add the qualifier "at this time". But we insist that consistent measures of decision quality be put in place at the key spaces of our decision life-cycle. We address this topic more fully in Chapter 10.

- Consistent with our thesis that a decision sociotechnical system is also a **production system**, a factory, that manufactures designed decisions, we propose, with conviction and confidence, our four R's—Robustness, Repeatability, Reproducibility, and Reflection as required measures of decision quality.

Appendix 2.1 Axioms of Normative Decision Theory

A *lottery, or gamble,* is central to utility theory. It specifies an alternative for decision making.

Mathematically, a lottery is a list of ordered pairs $\{(x_1,p_1), (x_2,p_2), \ldots, (x_n,p_n)\}$ where x_i is an outcome, and p_i is the probability of occurrence for that event.

- **Completeness**. For any two lotteries g and g′, either $g \geqslant g'$ or $g' \geqslant g$. *i.e. given any two gambles, one is always preferred over the other, or they are indifferent.*
- **Transitivity**. For any 3 lotteries, g, g′, and g″, then if $g \geqslant g'$ and $g' \geqslant g''$, then $g \geqslant g''$. *i.e. preferences are transitive.*
- **Continuity**. If $g \geqslant g' \geqslant g''$, then there exists α, β in (0,1) $\ni$: $\alpha g+(1-\alpha)g'' \geqslant g' \geqslant \beta g+(1-\beta)g''$. *i.e. the Archimedean property holds, a gamble can be represented as a weighted average of the extremes.*
- **Monotinicity**. Given (x_1,p_1) and (x_1,p_2) with $p_1>p_2$, then (x_1,p_1) is preferred over (x_1,p_2). *i.e. for a given outcome, the lottery that assigns higher probability will be preferred.*
- **Independence (substitution)**. If x and y are two indifferent outcomes, $x \sim y$, then $x\text{p}+z(1\text{-p}) \sim y\text{p}+(1\text{-p})z$. *i.e. indifference between two outcomes* also *means indifference between two lotteries with equal probabilities, if the lotteries are identical. i.e. two identical lotteries can be substituted for each other* (Morgenstern and Neumann 1944).

Appendix 2.2 Desiderata of Normative Decision Theory

One of normative decision theory's strongest evangelist is Howard from Stanford. He puts forward the canons of "old time religion" as principles for the practice of normative decision analysis. These are summarized by Wu and Eriksen (2013) as shown in Table 2.7 as direct quotes.

Table 2.7 Desiderata of Normative Decisions

‘Essential properties
applicable to any decision
must prefer deal with higher probability of better prospect
(prospects=outcomes in Howard's vocabulary)
indifferent between deals with same probabilities of same prospects
invariance principles
reversing order of uncertain distinctions should not change any decision
order of receiving any information should not change any decision
"sure thing" principle is satisfied (Pearl 2016)
independence of immaterial alternatives
new alternatives cannot make an existing alternative less attractive
clairvoyance cannot make decision situation less attractive
sequential consistency, i.e. at this time, choices are consistent
equivalence of normal and extensive forms
Essential properties about prospects
no money pump possibilities
certain equivalence of deals exist
value of new alternative must be non-negative
value of clairvoyance exists and is zero or positive
no materiality of sunk costs
no willingness to pay to avoid regret
stochastic dominance is satisfied
Practical considerations
individual evaluation of prospect is possible
tree rollback is possible’

Appendix 2.3 Keeney's Axiomatic Foundations of Decision Analysis

Keeney articulates 4 sets of axioms of decision analysis. The following are direct quotes from (Keeney 1992a, b) except for our comments in italics.

> **Axiom 1**
> **Generation of Alternatives**. At least two alternatives can be specified.
>
> **Identification of Consequences**. Possible consequences of each alternative can be identified.
>
> **Axiom 2**
> **Quantification of Judgment**. The relative likelihoods (i.e. probabilities) of each possible consequence that could result from each alternative can be specified.

Axiom 3
Quantification of Preferences. The relative desirability (i.e. utility) for all possible consequences of any alternative can be specified.

Axiom 4
Comparison of alternatives. If two alternatives would each result in the same two possible consequences, the alternative yielding the higher chance of the preferred consequence is preferred.

Transitivity of Preferences. If one alternative is preferred to a second alternative and if the second alternative is preferred to a third alternative, then the first alternative is preferred to the third alternative.

Substitution of consequences. If an alternative is modified by replacing one of its consequences with a set of consequences and associated probabilities (i.e. lottery) that is indifferent to the consequence being replaced, then the original and the modified alternatives should be indifferent.

Note: *"People are sensitive to the manner in which an outcome has been obtained … decisions with identical outcomes are judged as worse when they result from acts of commission than acts of omission". (Keren and de Bruin 2003).*

Appendix 2.4 Foundations of Descriptive Theory

The following are direct quotes from Edwards (1992) except for our comments in parentheses and italics.

Assumptions

1. People do not maximize expected utility, but come close.
2. There is only one innate behavioral pattern: they prefer more of desirable outcomes and less of undesirable outcomes. These judgments are made as a result of present analysis and past learning.
3. It is better to make good decisions than bad ones. Not everyone makes good decisions.
4. In decision making, people will summon from memory principles distilled from precept, experience, and analysis.

Principles

Guidance from analysis

1. more of a good outcome is better than less
2. less of a bad outcome is better than more

3. anything that can happen will happen *(we interpret this to mean that outcomes are uncertain.)*

Guidance from Learning

4. good decisions require variation of behavior (e.g. be creative)
5. good decisions require stereotypical behavior (e.g. be thorough, don't play around)
6. all values are fungible
7. good decisions are made by good decision makers based on good intuitions
8. risk aversion is wise. "look before your leap."

Guidance from experience

9. good decisions frequently, but not always, lead to good outcomes
10. bad decisions never lead to good outcomes *(we interpret this to mean that poorly formulated problem statements, ad-hoc decision analyses, poor data are unlikely to produce relatively good outcomes even in favorable conditions.)*
11. the merit of a good decision is continuous in its inputs
12. it is far better to be lucky than wise" *(we interpret this to mean that the stochastic nature of future events may surprise the decision maker with a favorable outcome. We are certain Edwards is not suggesting that we depend on luck as the basis for decision making.)*

Appendix 2.5 Results, Outcomes and Decision Quality

A decision implies a commitment to a specification with allocated resources. Outcomes are the results of the execution of such action. They are separated by time. A good decision is a good choice given the alternatives at the time when a commitment and resources are pledged. A good outcome is one which was intended. The chronological separation, between commitment and outcomes, permits uncertainty to intervene, aleatory unpredictable conditions that can generate an unintended outcome.

This example is due to Hazelrigg (1996). Consider a two round bet on a fair coin toss (Fig. 2.8). Bet \$2.00. Get \$5.00 if bet heads and get heads. Get \$3.00 if call tails and get tails. After betting either heads or tails, the outcome is either head or tails. If betting heads, at the outset, and get heads, the best payoff is a net of \$3.00. But if betting tails, the best case, is only a payoff of \$1.00. As a bet, betting heads is better since it has a better payoff even though there is possibility of a loss of \$2.00. A good decision can lead to a bad outcome. Similarly a bad decision, betting tails, can lead to the possibility of a \$1.00 gain.

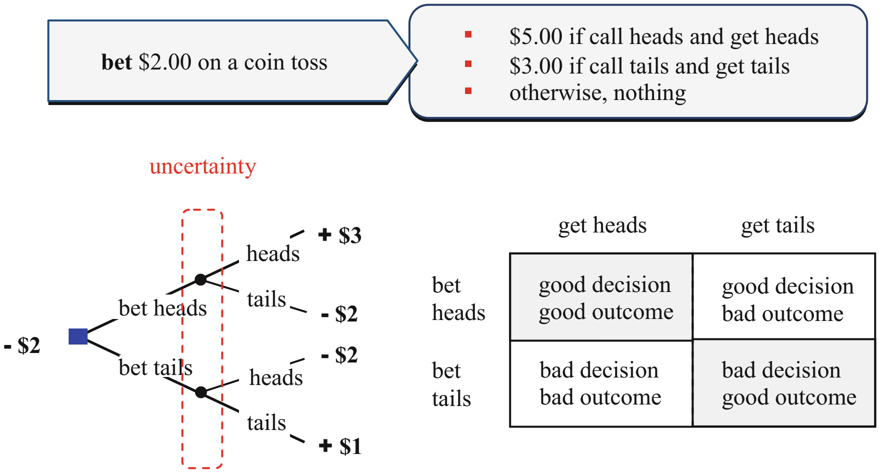

Fig. 2.8 A good decision and good outcomes are independent

Note: *In retrospect, what could have been anticipated (in foresight) is consistently overestimated (Fischhoff* 1975*). This is a form of hindsight bias and overconfidence. Moreover, people justify how the decision process and the outcome could have been better using hypothetical "only if", "could have", and counterfactuals (Roese and Olson* 1995*). Especially in situations that "almost" happened (Kahneman and Varey* 1990*).*

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Chapter 3
Operations: Foundations and Processes

Abstract We introduce the conceptual and theoretical foundations of our prescriptive paradigm for robust decisions. Whereas decision-making is an event, executive decision management is a life-cycle of a complex of five spaces. The five spaces are: The Problem Space, Solution Space, Operations Space, Performance Space and the Commitment Space. Consistent with the prescriptive nature of our paradigm, we concentrate on actionable processes and procedures within each of those five spaces. The goal of our prescriptive paradigm is to enable systematic design of robust decisions. The key sociotechnical processes are robust design synthesis, Design of Experiments (DOE) using *gedanken* experiments, Gage R&R, making uncertainty tractable with spanning set of uncertainty regimes, and the process to represent system behavior phenomenologically.

3.1 Introduction

This chapter completes the conceptual progression begun in Chaps. 1 and 2. With this chapter, we will have covered the ground of the conceptual foundations, key processes, and the unique operating conditions of executive-management decisions. In this chapter, we show how to **operationalize** executive-management decisions while adhering to the principles stipulated in Chap. 1 and also relative to other methods described in Chap. 2. We show why our methodology is distinctive. We pay particular attention to the neglected area of designing diverse decision alternatives. Namely, we answer the questions of: what other choices do I have? And unconstrained "what-if?" hypothetical alternatives. We show how to design decisions that are robust under uncertainty conditions, even when uncertainty variables are not removed. We also prescribe how to specify uncertainty regimes that can span the entire uncertainty space. We demonstrate how to predict decisions' outcomes and their standard deviations under any uncertainty regime. And finally, we show how to analyze the quality of the data that is used and how to analytically evaluate the quality of the sociotechnical system that implements a decision.

Using illustrative examples, we describe the key processes, of each of the life-cycle's spaces. In Chaps. 1 and 2, we introduced the theoretical foundations for executive-management decisions. We surveyed the decision literature and introduced the subject and the practice of executive-management decisions. We argued

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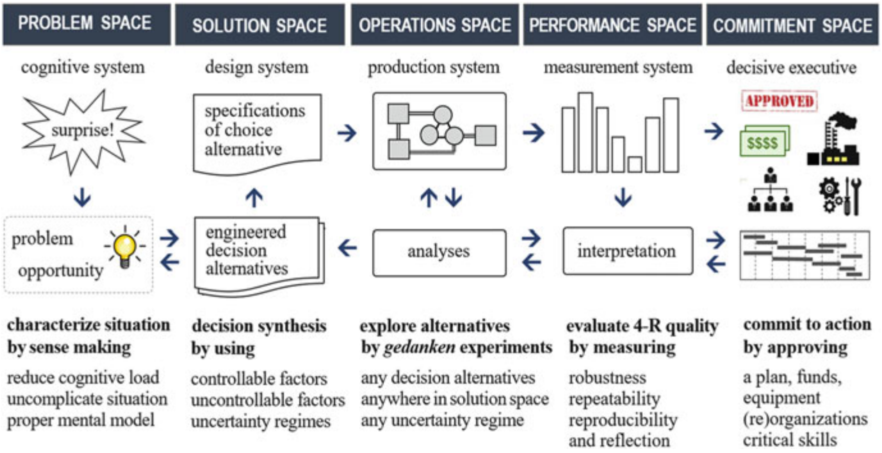

Fig. 3.1 Five spaces of the executive decision life-cycle

why our paradigm is distinct from other methods. We stated that our focus is on executive decisions—a distinctive class of generally ill-structured sociotechnical and managerial problems and opportunities that arise from messy and wicked situations. After considering these problems in a life-cycle context, we partitioned executive-management decisions into an end-end process of five spaces—the p*roblem, solution, operations*, *performance* and *commitment* spaces (Fig. 3.1).

In this chapter, we concentrate on **how to operationalize** our approach to executive-management decisions in each of these five spaces. The object is to operationalize problems' resolutions in ways that will meet a DMU's intentions and *ex post* inform the DMU and decision-maker of the quality of execution. Quality evaluation is an analytic process not the usual qualitative evaluation using ordinal measures. We propose to approach the operational tasks very deliberately and systematically, steps by step.

First to refresh our memory, we restate our first-principles we derived in Chap. 1. Second, we identify the operational center of gravity for each of the spaces in the decision life-cycle. The operational centers of gravity highlight the central governing concepts for the working processes in each space. Third, we will show that the working processes fulfill the requirements for rigor and systematicity of our executive decision methodology (Table 3.1).

Our detailed analyses in Chap. 1 on the dynamics of ill-structured, messy, and wicked executive- management decision-situations enabled us to distill the fundamental factors and key principles required by our methodology throughout the decision's life-cycle. They are:

- **Abstraction.** Reduce complexity to reduce needless imposed cognitive load by abstracting,
- **Actionability.** Make abstraction actionable by concentrating on essential variables,

Table 3.1 Our instantiation of the canonical form: a systematic process

Process phases	Our systematic process	
Characterize **Problem Space**	Sense making—uncomplicate cognitive load	☑
	Frame problem/opportunity and clarify boundary conditions	☑
	Specify goals and objectives	☑
	Specify essential variables Managerially controllable variables Managerially uncontrollable variables	☑
Engineer **Solution Space**	Specify subspaces of solution space Alternatives space and uncertainty space	☑
	Specify entire solution space	☑
	Specify base line and uncertainty regimes Do-nothing case and choice-decision Estimate base line and dispel bias	☑
Explore **Operations Space**	Specify Sample orthogonal array Do-nothing case and choice decision-alternative	 ☑ ☑
	Predict outcomes	☑
	Design and implement robust alternative Design and implement any what-if alternative	☑ ☑
Evaluate **Performance Space**	Evaluate performance: analyze 4R Robustness, repeatability, reproducibility, reflect	☑ ☑
Enact **Commitment Space**	Decisive executive Approval of plan Commit funds, equipment, organizations	☑ ☑ ☑

☑ indicates required in the process

- **Explorability**. Enable unconstrained exploration of the Solution Space by providing the capability to design decision alternatives that can cover any region in the solution space under any uncertainty regime.
- **Robustness**. Make results highly insensitive to uncontrollable conditions by robust engineering, Robustness is the property of a decision that will perform well even when the uncertainty conditions are not removed. The decision is highly immune to uncertainty (Klein 2001).
- **Repeatability, Reproducibility and Reflection.** Ensure and sustain quality performance by repeatable and reproducible processes, and drive improvements through disciplined reflection.

The center of gravity of each space is identified in Fig. 3.1. In the Problem Space, it is sense making. That is develop a meaningful interpretation, of the decision-situation, in order to appropriately frame the problem/opportunity. The key disciplinary science in this space is cognitive psychology applied to the problem at hand. In the Solution Space, the center of gravity is design, *viz*. engineering design of decision alternatives from which a preferred one can be chosen or additional better ones constructed. The key discipline in this space is robust engineering design. In the Operations Space, the center of gravity is production, *viz*. developing

Fig. 3.2 Schematic of the problem space

phenomenological models of the sociotechnical system that enacts decisions. The strategy is to use of *gedanken* experiments, thought experiments (e.g. Brown and Yiftach 2014, Sorensen 1992). The key discipline in this space is the Design of Experiments (DOE) engineering method to discover the phenomenological behavior of socio-technical systems (e.g. Otto and Wood 2001; Montgomery 2001). Finally, the Outcomes Space's center of gravity is measurements, *viz.* measuring and evaluating inputs and outcomes, analyzing operational quality, and improving performance of the sociotechnical systems that enact decisions. The strategy is to concentrate on robustness of outcomes, gage reproducibility and repeatability (Gage RR) of the operational sociotechnical systems, and making improvements and learning by reflecting on what has been measured.

The remainder of this chapter is devoted to the operationalization of each space of the executive-management decision life-cycle (Fig. 3.2). We concentrate on the *know-why* and the *know-how* of our systematic process (Table 3.1). We will narrate processes descriptively and prescriptively, and illustrate them with examples. We are motivated that our processes rise to solid standards of rigor. Inevitably some statistics creeps into the narratives. But, we will use prose to explain the math and its meaning in the context of executive-management decisions.

3.2 Problem Space

A surprise has come to the attention of executive-management DMU. In this section we discuss how to decode a surprise as a trigger that initiates an executive decision-situation life-cycle. A surprise signals the presence of an event that cannot be ignored. It is a call to action. A meaningful explanation of the decision situation and its causes are needed by the DMU to succinctly articulate the problem, to specify goals and objectives that will drive the design of decision alternatives (Fig. 3.2).

The key questions the DMU must address in the problem-space are: First, what is going on? The answer to this question is provided by *sense-making* of the decision situation. Second, what is the problem? The answer to this question frames the situation as a problem or an opportunity. And the third question: What do we want? Clear goals and concrete objectives answer this question.

A DMU can be easily overwhelmed by the complexity and uncertainty of the decision situation. The operating principle, in this space, is ***abstraction*** to reduce the apparent complexity and the cognitive load on the DMU. The principle obliges the DMU to represent the situation in an uncomplicated way in order to facilitate the formulation of a response. We will show how to do this.

3.2.1 The Decision Making Unit (DMU)

> . . . most decisions derive from thought and conversation rather than computation. (Ron Howard)[1]

Executives very rarely work alone to single handedly perform every analysis, task or enact every process during the decision life-cycle. There is too much to do, not enough time, too much data to process, too many people to direct and too much uncertainty. This is a typical and realistic description of the conditions that define bounded rationality. As a result, in practice, executives assign much of the analyses and key deliberations to staffs, direct reports, and experts. With the executive, this working group forms a team to make better decisions. We call this organizational ensemble, a *decision-making unit,* a DMU. Executive level decision situations frequently requires special expertise. In those cases, experts are invited to participate as temporary adjunct members. DMU members, because they are also executives or senior managers, also have staffs, organizations, and experts they can assign for special work. This extended network effectively expands an executive's and organizational cognitive aperture, implementation, and execution resources. The DMU and its adjuncts serve as sociotechnical mechanisms during the executive-management decision life-cycle. DMU's exist for "participants [to] develop a shared understanding of the issues, generate a sense of common purpose, and gain commitment to move forward (Phillips 2007, 375)".

In the problem space, the DMU's key responsibilities are *sense-making* and specifying the goals and objectives of the decision situation. This process is mediated by DMU members' *mental models,* which must to be *harmonized.* Harmonized does not mean made identical. Traditional thinking emphasizes "the creation of appropriately shared mental models of the system" (Fischhoff and Johnson 1997, 223) for a group to do its work efficiently and effectively (e.g. Jones and Hunter 1995). However, our experience and current research reveal a more comprehensive and complete view of the meaning of *shared mental models* (e.g. Banks and Millward 2000; Mohammed et al. 2010). Shared does not necessarily mean identical or same; but consistent, aligned, and complementary. Each DMU member must understand the game plan. No one wants a basketball team of players who see the game as consisting entirely of free throws.

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[1] E.A. Howard (2007), 7.

In Chap. 1, we discussed complexity, uncertainty, disciplinary, organizational factors, and their interactions as contributing to the difficulty of executive-management decision situations. Given the diversity of the disciplinary domains, required expertise, and the varied organizations that DMU members are responsible; the mental models must be consistent, complementary, compatible, and aligned. An executive from the manufacturing function, is unlikely to have the same mental model of executives from the technology, r&d, or sales functions. Given clearly articulated goals and an understanding of their meaning, they must frame differentiated but complementary models that enable commitment to move forward while simultaneously preserving individual pathways to action and the attainment of organizational goals and objectives (Castro 2007). Yaniv (2011) reports that group heterogeneity attenuates bias and has positive framing effects. Banks and Millward (2000) cogently argue the case of aligned complementary mental models by describing the task of navigating a US warship as a distributed task. Notably, no single person completes this task single handedly, the location of the boat is not bound by a single individual. The ship's navigation must "move through the system of individuals and artefacts." Consistent, complementary, compatible, and aligned mental models are required for distributed processing systems like a DMU. Scholars call this concept Team Mental Models or TMMs (Mohammed et al. 2010).

Phillips (2007) calls these DMU-like meetings "decision conferencing". The membership, scripts, principles, mechanics for facilitating these meetings, even physical space and sitting arrangements are variously described by scholars (e.g. Rouwette et al. 2002; Andersen et al. 1997; Phillips 2007). We defer those topics to these scholars' publications. In the discussions that follow, we concentrate on content intensive operations that are specific to our paradigm.

3.2.2 Sense Making and Framing

A problem is an obstacle, impediment, difficulty, challenge, or any situation that insists on a resolution. Problems are stubborn things. They cannot be left unattended. They do not go away, they must be resolved. They need a solution, which dissolves the difficulty and makes a meaningful contribution towards a known purpose or goal. A problem implies an undesirable situation, which is coupled with uncertainty, conjoined with deficiency, doubt or inconsistency that can prevent an intended outcome from taking place satisfactorily (Ackoff 1974). The first part views a problem as difficulties to overcome. The second part considers a problem as an opportunity to exploit, a prospect to contribute to the achievement of a goal. Opportunities and problems are merely *decision situations* that demand executive attention. We do *not* distinguish between a problem and an opportunity. They are two sides of the same coin, a situation. If interpreted and addressed as an opportunity, it can have an upside; or if otherwise, it is a difficulty to be resolved, dissolved, or ameliorated. In either case, we want to be better off than before. Whether a decision situation is a problem or an opportunity depends how it is posed and described to a concerned observer. Keeney (1994) argues for framing the opportunity side by concentrating on providing *value*. He defines value as what decision makers care about. He writes that the "idea is to create an alternative that gets you what you want and at the same time makes others better off". Henceforth, we will use the term *problem* with the understanding that we mean a problem or opportunity.

The ***need*** for executive attention is triggered by a surprise, which signals the need to uncover and decode the conditions that caused it (Fig. 3.2). The imperative is to answer: "what is going on?" and "what do I have to do? (Weick et al. 2005; 412)." Frequently, triggers are the result of an executive initiated study for staff work, which results in counter intuitive information. Other triggers are: stochastic surprises, reviews of new data that challenge the validity of mental or operational models (Bredehoeft 2005), or unanticipated outcomes of known initiatives by nature of their effects, and inconsistent content or timing (Allen et al. 2010). Or even simply not knowing how to respond (Horwitz 2003). In other words, they are situations of cognitive dissonance, in which the "... world is perceived to be different from the expected state of the world, or when there is no obvious way to engage the world" (Weick et al. 2005, 409). People and organizations prefer an orderly and readily explainable world so they know what to do, explain action and reestablish predictability, stability and system homeostaticity. These imperatives drive the need for sense making.

To these ends "top managers need to provide cognitive leadership—i.e. create a common frame of reference for key employees—to assure the growth of the organization can be interpreted through this selection process (Murmann 2003, 229)." These are prerequisites for the organization to move forward with confidence (Phillips 2007). Regan-Cirincione (1994) shows that an able group facilitator and leader can make a group outperform its most skilled member of the group and improve the accuracy of the group's judgement. Moreover, scholars have shown that there is a causal linkage between success and failure in business problem-solving and the frequency of diagnosis and the extent to which they precede action (e.g. Schulz-Hardt et al. 2006; Brodbeck et al. 2007; Lipshitz and Bar-Ilan 1996).

The case for appropriate situational analyses and sense making is very compelling. A ***major pitfall is to interpret a significant event too narrowly.*** This can cause half measures or unsustainable ameliorations to important problems. This is particularly urgent for unexpected signals from pressing, messy and wicked situations. The executive and the decision-making unit must "look past the surface details in a problem to focus on the underlying principles or big ideas embedded in the situation" (Etmer et al. 2008; 31). ***However, it is also dangerous to interpret the situation too broadly.*** This can result in vague, ambiguous, or conflated views of the situation. This can drive unimportant, irrelevant information, and noise to be included in framing the problem. This has the pernicious effect of adding complexity and complicating the cognitive load for all concerned. Executives and the DMU need to focus on the essential causes of the event, their context, cause-and-effect relationships; ignoring gratuitous details, in order to develop a meaningful interpretation that makes sense without injecting noisy information. Interpretation requires a *synthesis process* that puts key relevant causes together into a meaningful whole. This synthesis is a creative act that considers what is needed to satisfy the goals of the organization and how to put together what is observed and analyzed

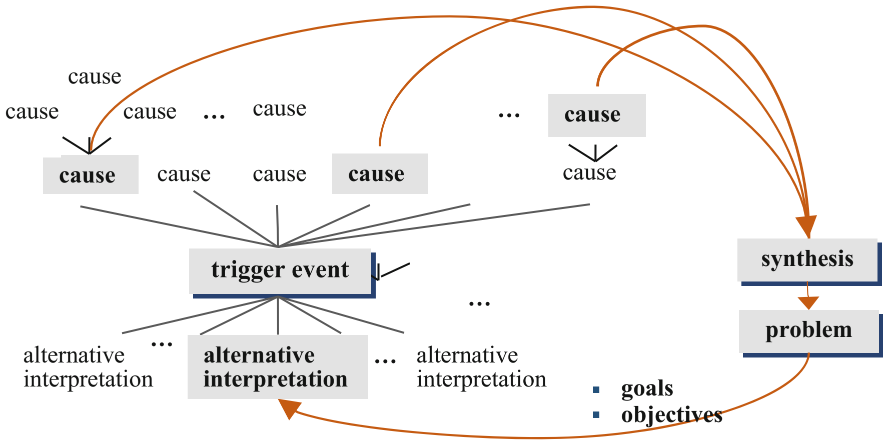

Fig. 3.3 Partition and synthesis of a trigger event

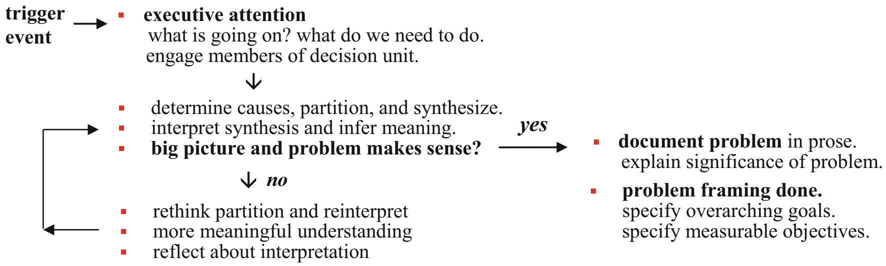

Fig. 3.4 Procedure for problem space

into a coherent concept that is actionable. The ethos is identical to the engineering design process. This kind of design thinking is critical to sense making.

We propose a procedure shown schematically in Fig. 3.3 and specified algorithmically in Fig. 3.4. This process generally takes more than one iteration. At each iteration, it is useful to group the most important and significant causes into thematic groups. The design of a decision should not just address the trigger situations but its thematic causes. In medicine, a thematic cause is recognized as a pathology. Like physicians, executives must not just address symptoms at the exclusion of root causes. Two aspirins will not remedy a pathology. Our process concentrates on critical decision variables, the ***essential*** variables. Unnecessarily broadening exploration, with excessive iterations, is not useful either. But what is a practical stopping rule? A useful heuristic is to constrain the scope of the explanation at the jurisdictional boundaries of the executive's superior or nearest peers. Why? This allows the decision makers to broaden their field of vision and enable fact-finding and negotiations with their peers. ***This process brackets the problem and specifies its boundaries.***

This heuristic provides guidelines for deciding what is integral to the problem and what can be excluded from consideration. The stopping rule prevents "boil the ocean" of unsolvable problems; such as "save the Amazon forest", though noble, their scope and scale make them intractable and not actionable. Another pitfall is to be overwhelmed by the causes and associated information after some iterations. As we discussed, the analysis gets more complex at each iteration. Facts and information become more abundant and therefore more difficult to digest and put into a coherent picture. Recall our principles—synthesis follows partitions, and the principle of ***uncomplicating complexity***. Synthesis and abstraction are ways to synthesize partitions and reduce complexity such that the result is cognitively uncomplicated. The synthesis must be *thematically driven* so that the new whole makes sense and is meaningful. The culmination of these efforts result in the *aufgehoben* moment in the *process*. This is the "ah-ha" moment when there is a crystallization that reveals new clarity of a coherent and meaningful story. This is the insight that can explain and interpret "what is going on" by pulling the right pieces into a coherent whole (Fig. 3.3). The iteration-exit condition (Fig. 3.4), delimits the scope and tightens the meaning of the problem.

Executive-management decisions have the complex systems property that there is more than a single satisfactory resolution to a complex, difficult, and risky problem. Solutions are not necessarily unique. Unlike the roots of a quadratic equation, for which solutions are unique. A developed synthesis, from multiple causes, is not the only one possible. There are other coherent, and legitimate interpretations that can differ due to organizational and stakeholders' differences. There is substantial plasticity in the synthesis, which are socially constructed, embedded in specific organizational situations and particular mix of disciplinary domains.

As a last step, document the problem in prose. In our teaching and management experience, we find that prose documentation is one of the most effective ways to enforce clarity. These documents are also carriers of knowledge for those who have a need to know. Carlile (2002, 2004) calls these documents "boundary objects". They travel across human and organizational boundaries to transmit information and knowledge. Gerstner, IBM CEO, insisted on prose documentation as a prerequisite to all management meetings with him. His guidelines were simple and effective: maximum of ten pages written in narrative prose; without complicated graphs, tables, numbers, or equations. These and long difficult explanations were to be attached as appendices, for which there were no page limitations. Any interpretation and conclusions inferred from graphs and complicated information required terse and clear summaries within the ten pages of prose. FOS was a format many executives found useful. FOS stood for *facts, opinions,* and *so-what's*. Present the facts, offer your opinion, and finally explain what all this means to the deciding executive by presenting an action plan. The FO part, of FOS, addresses the question of "what is going on". FOS is, in effect, a dialed-down version of the scientific method**.**

3.2.3 Specifying Goals and Objectives

The next step is to address the goals and objectives, i.e. "what is it we want?" What we want must be driven by goals and objectives. A goal is a ***what***. An objective is a ***how.*** The difference is between *means* and *ends*. A goal is thus superordinate. An objective is subordinate and should be measurable. "Top managers cannot possess all the knowledge that the various individuals in and organization have about their task environment. It is more effective to specify goals and selection criteria and allow lower-level employees to find the best solution to their particular task (Murmann 2003; 290)." A goal is ***what*** you want to achieve, in qualitative terms. Consider for example, the personal goal: "to become an educated person". The goal expresses a need, a want. Implied is a commitment of time, money, and other costs to achieve the intended goals. Objectives could be, "earn a college degree, learn two foreign languages, and play a musical instrument by age 25". The objectives should be measurable and used as indicators of progress or failure towards a goal.

In subsequent chapters, we will discuss many business examples of goals and objectives. In the ADI case study, the surprise was the plunge in stock price from $24 to $6 (Chap. 5 and 6). This was serious, but the more ominous threat was the possibility that the company could be acquired on the cheap. It became a goal of the ADI company to avoid a hostile takeover. A key objective was to increase the market value of the firm so that it would not be affordable to potential buyers. Thus enabling the achievement of the specified goal of maintaining ownership of the firm.

Goals and objectives are necessarily contextually positioned in an organizational structure. They are recursive. *An objective at one level of the organization becomes the goal at the next level of the organization* (Fig. 3.5). At the executive management level, the goals are prescribed by the set ***{g1, g2}***. The objectives to attain these goals have been specified as ***{o1, o2, o3, o4}.*** Applying the management principle of *excluded reductionism* (Ropohl 1999) of complex organizational structures, the objectives are partitioned to managers **x, y**, and **z** as objectives. The objectives ***{o1, o2}*** are delegated as goals to *manager **x**,* who then specifies objectives ***{o11, o22, o21, o22}*** to meet its goals. *Manager **y***'s goal and objectives

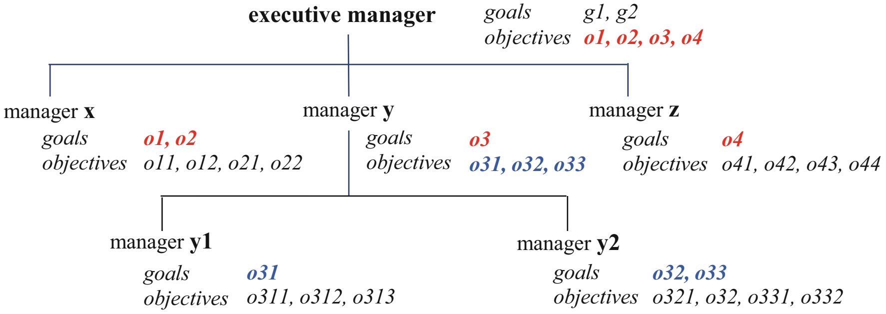

Fig. 3.5 Relationship of goals and objectives—hierarchy and inheritance

are {***o3***} and {***o31, o32, o33***}**,** respectively. Similar explanations apply for manager **z**. Manager **y** partitions and delegates its objectives as goals to *manager* ***y1*** and *manager* ***y2***. For example, manager ***y1***'s goal and objectives are {***o31***} and {***o311, o312, o313***}. In turn, manager ***y2****'s* goal and objectives are {***o32, o33***} and {***o321, o322, o32, o332***}.

To guide setting goals and specifying objectives, we find it useful to apply Keeney (1992, 1994) and Smith's (1989) guidelines for conceptualizing business problems and specifying solution objectives (Appendix 3.1 and 3.2). Focus on values, opportunity, and closing aspirational gaps. In Fig. 3.5, the distribution of goals and objectives illustrate the properties of *recursive hierarchy and heredity*. We can express the goal and objectives setting process by the recursive expressions (3.1) and (3.2) that reflect the hierarchical and the hereditary property, respectively.

$$\text{goals}\big|_{(\text{level i+1})} \Rightarrow \cup_n \text{objectives}\big|_{(\text{level i+1})} \Rightarrow \text{indicates``derive''} \tag{3.1}$$

$$\cup_i \text{objectives}\big|_{(\text{level i})} \geqq \cup_m \text{goals}\big|_{(\text{level i+1})} \geqq \text{indicates``span''} \tag{3.2}$$

3.3 Solution Space

In the solution space, the problem has been clearly defined, Goals and objectives have been specified. The next step is to develop a series of decision alternatives from which a choice alternative, which *satisfices* intended goals and objectives, can be designed. This process is schematically shown in Fig. 3.6 (Table 3.1).

Specifying alternatives is the "most creative part" of the executive-management decision life cycle (Howard and Matheson 2004, 27). The goal of developing alternatives is to determine whether different executive-management decisions and sociotechnical systems can outperform current outcomes. This necessarily requires the ability to predict outcomes of decision alternatives. Predictions must depend on rational methods and repeatable practices. Otherwise, predictions become guesses. Guesses are not very persuasive or convincing. Rational methods result in representations of problems and potential solutions, which can be more

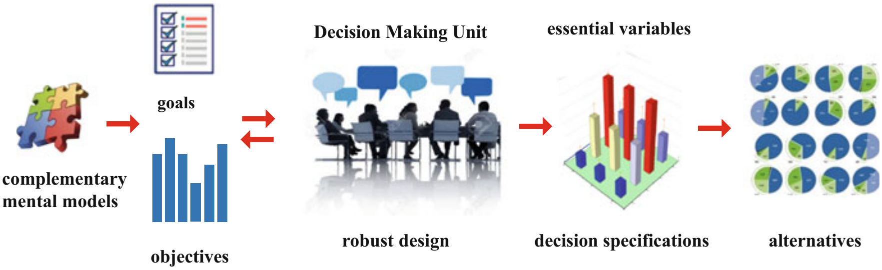

Fig. 3.6 Schematic of the solution space

readily accepted as meaningful. Alternatives do not appear out of thin air, they must be defined and then constructed. This construction process is one of synthesis; alternatives must be designed.

The operating principle for this phase is to design of decision alternatives that can span the entire solution space anywhere in the uncertainty space. This imposes four design requirements. The DMU must design decision alternatives that:

- can explore anywhere in the Solution Space within the *entire* space of uncontrollable conditions,
- are robust under uncontrollable conditions even when these conditions are not removed,
- are systematically designed artefacts of technical and social processes, and have been subjected to debiasing procedures.

Decision alternatives that can meet these requirements requires knowledge of the problem domain and the behavior of sociotechnical systems that generate the intended outputs. Given the complexity of messy and wicked executive-management decisions, how do you represent the operational structure and behavior of these sociotechnical systems? Scholars and practitioners consider this as one of the most challenging problems in management decision (von Winterfeldt and Edwards 2007). These are the topics we will address next.

3.3.1 A New Strategy: Induction, Phenomenology

> Inductive inference is the only process known to us by which essentially new knowledge comes into the world . . . Experimental observations are only experience carefully planned in advance, and designed to form a secure basis of new knowledge; that is they are systematically related to the body of knowledge already acquired. (R.A. Fisher)[2]

> . . . inductive reasoning is more strict that deductive reasoning since in the latter any item of data may be ignored, and valid inferences may be drown from the rest;; . . . where as in inductive inference the whole of data must be taken into account. (R.A. Fisher)[3]

Scholars suggest ***two*** distinct strategies to develop engineering design alternatives (Otto and Wood 2001, 894). One is the analytical model development based on *ex ante* analytical frameworks and models. The other is the empirical development based on experiments that reveals an *ex post* model. This experimental method is how Watson and Crick determined the structure of the DNA and won them the Nobel Prize. The structure of the DNA *revealed itself*. This is the conceptual basis of our paradigm, the structure of the socio-technical system, we are dealing with, will reveal itself by means of experiments. This strategy is an exemplar of our principle of uncomplicating complexity.

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[2] R.A. Fisher (1971), 7–8.

[3] R.A. Fisher (1955a, b), 7–8.

The most widely used conventional strategy is to model decisions using *ex ante* postulated analytical representations. Then use these representations to make *predictions* and analyze how well they can generate the intended outputs. The challenge, for this kind of modeling, is for experts "to specify the [mathematical] relationship of the system variables (Howard and Matheson 2004, 28)". Because they have domain knowledge to identify the variables, executive and practitioners can develop models that have satisfactory fidelity of the problem and of the sociotechnical systems. *These models represent an explicit representation of the behavior of the sociotechnical machinery that will enact a decision specifications.* von Winterfeldt and Edwards (2007) specify eight mathematical structures to model the system behavior to predict and analyze variables that have an influence the outputs (Appendix 3.3). This repertoire of structures exhibit mathematical rigor and precision, but the authors are largely silent about verisimilitude, i.e. the question of model fidelity. We overcome this conceptual lacuna with our executive-management decision paradigm.

We elect to use and entirely different strategy from that of an *ex ante* and *a priori* formulation of closed-form analytic representations. We exercise a strategy that does **not** presume to know *a priori* the explicit analytic representation of the sociotechnical system. Our strategy is an experimental one. The idea is to estimate predictions by *gedanken* experiments (e.g. Hopp 2014) rather than mathematical equations and estimates of probabilities. Unlike the analytical approach which presumes mathematical expressions of variables to make predictions, we *determine ex post* the sociotechnical system behavior from experimental outputs. *We do not need to know the analytical representation of the machinery of the sociotechnical systems.* Clearly, we still need to know the causal variables that influence the outputs, but we do not need "to specify the relationship of the system variables (Howard and Matheson 2004, 28)" using equations. We can estimate the performance of alternatives by *gedanken* experiments to determine a **phenomenological model**. Phenomenology is the scientific methodology which describes and helps explain observed experiences. Appearance reveals and explains reality (Smith 2013). This is the conceptual basis of our executive-management decision paradigm.

3.3.2 Essential Variables

We now turn our attention on the variables that influence the intended outcomes of executive- management decisions.

From an executive-management perspective, it is natural that the variables be partitioned into two classes—managerially *controllable* variables and managerially *uncontrollable* variables. (The literature also calls the variables—inputs, factors, or parameters. We will use these terms interchangeably.) There are many possible variables that management can control, so a critical question is: how are these variables identified? Heinz von Foerster (1981) and von Foerster and Poerksen (2002) argue forcefully and convincingly that for complex sociotechnical systems, this task is *impossible* without observers' prior knowledge and experience. To manage and operate complex sociotechnical systems the role of the observer is essential to identify the most sensitive variables that influence the behavior of such a system. Achterbergh and Vriens (2009) call these variables **essential variables.** They coined the term *essential variables* in the context of controllable variables. Variables that directly influence the intended outputs, which by definition, determine the ***variety*** of the operational sociotechnical system that will implement the decision specification. Variety is defined as the number of states a system can take (Ashby 1957). Clearly the variety of a socio-technical system must exceed that of the external environmental conditions to enable the system to cope with it (Ashby 1957). It follows that the uncontrollable variables that are relevant to the decision situation must be also addressed. For, they too influence the behavior of the sociotechnical system and the quality of outputs. For this reason, we include uncontrollable variables as essential variables. Naturally, prior knowledge from the observers is also mandatory to be able to identify them.

3.3.2.1 Controllable Variables

Controllable variables are the variables that management can directly control and have a direct impact on the outputs. Executives have the power and the resources to use these controllable factors to meet goals and objectives. Controllable variables can be continuous or categorical. For example, closing or not closing a manufacturing plant is a categorical variable. On the other hand, the number of new employees to be hired is generally a continuous variable. Discrete settings, of a variable's value, are called *levels*. For example, the hiring level can be specified as 10% higher than the current employee population, 5% lower, or it can remain exactly at the same level. The desirability of higher or lower levels is very much dependent on context. If the firm is on a growth spurt and under favorable market conditions of booming demand, then 10% higher is better, and 5% lower is worse. But if the firm is in an unprofitable down market with uncompetitive products, then 10% higher unprofitability is worse, but 5% lower unprofitability is better.

This points out a defining property, of decision variables, known as their ***characteristic***. Variables can be *characterized* into one of three types. Those for which *more of their output is better, less of their output is better, or exact value of an output is better*. As illustrated in the previous examples, the desirability of "more" or "less" is determined in the solution context.

From a managerial perspective, the DMU needs to address these key questions:

- What is the characteristic of the variable and its output?
- How many levels for each variable? How to specify the levels?
- How many controllable variables do we need?
- How do I identify a meaningful set of the uncontrollable variables?

Identifying the controllable variables. Corporate problems, proposed solutions, and their consequences depend on the behavior of corporate business systems and processes. To find the requisite controllable variables, we must focus on the essential variables they can directly control to affect the system behavior and the outputs that are important to the executives. Therefore, goals and objectives must be considered to determine the controllable variables that are to be chosen. Once goals and objectives are specified, executives and the DMU's must filter through layers of a problem situation in order to determine the key essential controllable variables. And as a first step to conceptualize the ill-defined issues of a problem, they must draw on their previous knowledge and personal experiences (e.g. von Foerster 1981; von Foerster and Poerksen 2002; Etmer et al. 2008). Clearly one ignorant of domain knowledge will not be able to specify the control variables.

Prior knowledge on the part of the executive and DMU members, means that for a given decision situation, the controllable factors must be specified at a consistent level of abstraction and scale of their mental capacities to meet the objectives that have been specified. Scale is a system descriptor that determines the level of abstraction and detail that are visible and consistent to the DMU. At a higher scale, less detail is visible and fewer descriptions of the systems processes are necessary for the observer. At a lower scale, more detailed and textured descriptions of the system behavior are visible and required (Bar-Yam 2003). Paraphrasing Simon (2000, 9), looking from the top downwards, at a large scale, we can say that the behavior of the units at any given scale does not depend on the details of the structures of the lower scale below, but only upon the steady state behavior, where the detail can be replaced by a few aggregated variables. The decision situation, the goals and objectives, and prior knowledge enable the appropriate scale for the definition of decision alternatives (von Foerster 1981; von Foerster and Poerksen 2002).

Given a consistent level of abstraction for the decision maker and the decision-making unit, the variables must be specified to meet the objectives that are being studied. The variables must be actionable and consistent with the principle of excluded reductionism, (Ropohl 1999) and Ashby's (1957) principle of requisite variety, we discussed previously. DMU members are experts. As experts, the expertise they bring to the discussion is invaluable. Experts are able to perceive the "deep structure" of a problem or situation (Chi 2006, 23) and "scan the problem features for regularities, incorporate abstraction, integrate multiple cues, and accept natural variation in patterns to *invoke* aspects of the relevant concept" (Feltovich et al. 2006, 55). "Experts are good at picking out the right predictor variables and at coding them in a way that they exhibit a conditionally monotonic relationship with the criterion" (Dawes 1979, 574). It is entirely appropriate and necessary to have the DMU membership identify the essential controllable variables and specify their levels.

Setting the levels of the variables. In general, we recommend a three-point specification for the controllable variables. More than three levels may be necessary for complex and complicated problems. Two levels would work almost as well, at a cost of detail of the outputs, e.g. determining whether there is a curvature. Of the three kevels, we require that one level be the point that marks the current operational condition, assuming no change. This the "business-as-usual" (BAU) condition. This establishes a base line. The "maximum effort" level is that at which management is still in control, but at the edge of impossibility. Operating at the highest level should be a "stretch", i.e. doable with a maximum strong effort, but not impossible. This could be the current operating BAU-level, if currently operating under those conditions. To determine the maximum requires domain expertise and deep operational knowledge of the firm's business processes. The "minimum effort" level should be at a level of performance, which is adjacent to not-acceptable. It could be the BAU level of performance or less. Note that the "maximum effort" may, in fact, be a small number. For example, consider the controllable variable "scrap and rework" in manufacturing. Ideally that level should be zero, which requires a maximum and heroic effort. Why three points? This is a compromise between just two points and four or five or more points. With two points we cannot get a picture of any potential curvatures in the response. But there are many cases where two levels are appropriate. With more than three points, we risk making the cognitive load intractable.

As we shall see, *r&d budget* is a controllable variable in one of our case studies. Top management of the ADI company can choose to invest in r&d at three levels. Level 1 is lowest acceptable level of $747.8 M, at the current level (BAU, level 2) of $753.3 M, and at a more intense level 3 of $760.4 M. These r&d levels are at the discretion of the senior management of the firm; therefore, *r&d budget* is a controllable variable.

But how many variables are needed? For complex systems and complicated decision situations, decision makers should consider only as many variables as they can cognitively address (Bar-Yam 2003). This is what is meant by requisite variety. The chosen variables must be appropriate to the cognitive level of abstraction that the decision maker can handle. And it must also be consistent with the decision objectives, and the maximum variety of the decision situation the sociotechnical system is able to handle (Ashby 1957). The requisite variety of the controller must be larger than that of the controlled system. Research shows that, in general, the number of variables is not large. Klein (1999) reports that in high stress environments, like in fire-fighting or combat, line officers "rely on just a few factors—rarely more than three." Isenberg (1988) writes that "… senior managers I studied were preoccupied with a very *limited number* [4] of quite general issues, each of which subsumed a large number of specific issues." A study on the number of factors to predict heart failure identified five factors (Skånér et al. 1988; Hoffman et al. 1986). Another study of a $150 M investment of a pesticide product-development and manufacturing decision shows that seven variables were used for the decision (Carl-Axel and von Holstein 2004). Corner and Corner (1995) in a large survey of strategy decisions report that, in 73% of the cases they studied, use less than nine attributes (decision variables), and that only six alternatives are considered. These studies support Miller's (1956) "magical" 7 ± 2. In summary, we propose the following rules for identifying controllable variables:

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[4] Italics are ours.

- domain knowledge and expertise is mandatory,
- specify only as many controllable variables as the decision-maker needs and can address, a useful rule-of-thumb is Miller's 7 ± 2,
- ensure the variables are at a consistent scale and level of abstraction,
- specify three levels for each of the variables,

  the highest level as one that requires maximum effort, but at the edge of impossibility,

  the lowest level that is the minimum level of acceptable performance, but at the edge of doability.

3.3.2.2 No Free Lunch

As in nature, in business and organizational management, it is not possible to get something for nothing. This is colloquially articulated as the axiom of "There is no free lunch." It follows that the set of controllable and uncontrollable factors of a decision specification must reflect the spirit of this reality. Otherwise, the ensemble of variables are meaningless. The DMU can simply specify that all controllable variables be exercised at the levels that achieve all the objectives without regard to cost or effort. It would be like trying to design a frictionless machine, a money pump, or a perpetual motion machine. In one of our case studies, we discuss *r&d budget* as a controllable variable. This variable reflects the need to commit of resources to meet an objective. At the same time, the customer's *budget flexibility* to pay for project overruns was specified as an uncontrollable variable. This case reflects the need to identify resources as an important factor that influences intended outcomes. In every decision, the no-free-lunch rule must be reflected.

3.3.2.3 Uncontrollable Variables

Uncontrollable variables are secular variables that management cannot control, or are so costly to control that they are, in effect, uncontrollable. But nevertheless uncontrollable variables can have a direct and strong influence on the outcome objectives of the decision. Uncontrollable variables are the key sources of uncertainty and risk. As in controllable variables, the questions on the number of variables and their levels apply here as well. Domain experience and expertise are required to identify and use them. Their number must be cognitively manageable. Lempert (2002) reports that in a policy study for climate-abatement strategies that from a set of 60 possible uncontrollable variables, only 6 were found to produce meaningful scenario differences. The levels for the uncontrollable variables represet the *extreme* ***but*** *realistic* conditions of the secular variables that can influence the outcomes (e.g. Otto and Wood 2001).

Consider for example, a case which we will discuss in later chapters. A consulting firm is performing a special risky project, which very likely require the client to make potentially costly repairs to the sociotechnical system in question. Whether the client has budget flexibility, and, how much, to handle potential cost overruns is an unknown to the consulting manager. Budget flexibility is thus an uncontrollable variable. The lowest cost level for the client, is the condition that the client will accept no overruns, causing the consulting firm to bear all costs. The highest cost level for the client is the condition that the client will pay for all overruns to keep the project from failing. These unknowns represent uncertainties to the consulting firm, and two levels is acceptable.

3.3.2.4 Social Process for Identifying Essential Variables

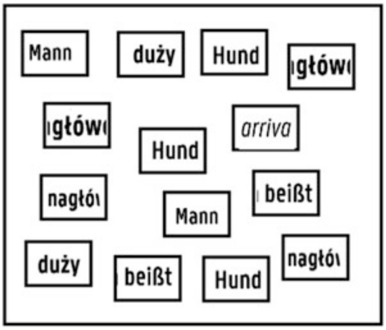
The solution space is also a social space. The DMU is a social organization tasked with the responsibility of identifying the essential variables for decision situations in its jurisdiction. We will now sketch a process to obtain an integrated and harmonious perspective from the participants (Rentsch et al. 2008). It is a procedure that improves individual judgements by providing complementary knowledge and information from each member in the DMU. Harmony here is used to mean the absence of mental dissonance or cognitive conflict. It is not meant to mean that the DMU holds hands as a group and sing Kumbaya. Harmony is desirable because it promotes a complementary mental model that enriches the ones carried individually but which collectively forms an integrated whole. Complementary does not mean identical mental models, but it does mean consistent. The social goal is consensus so that the diverse actions from executives with diverse responsibilities will deal with their distinct domain so that the whole will make sense. For example, the executive from finance is unlikely to have a mental model that identical to that of a technology executive. But their mental models must cohere as a whole. The goal is to cultivate a consensual sense-making to improve alignment of goals and objectives, and coherent action. Complementary mental models cannot be imposed, they are cultivated.

With a small group of 10–20 people, the social process is straightforward. Without great difficulty, an experienced group facilitator can readily obtain a set of 7 ± 2 controllable variables. In this case, the process we will sketch may not be necessary. However, if the group is large, the procedures to be described next, we have found to be effective.

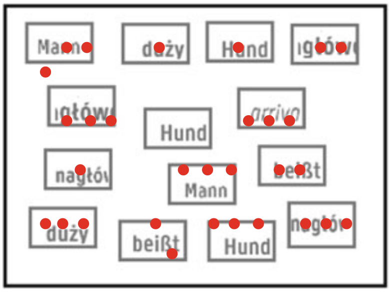
In the prescription that follows, we concentrate on controllable variables. It works equally well for uncontrollable variables. The process is an adaptation of the Language Processing (LP) Method of Shiba and Walden (2001). LP is a refinement of the well-known JK method to gather and organize ideas from a group of experts (Kawakita 1991; Ulrich 2003). We have used this process in many different decision situations; for engineering design problems, strategy formulation, financial investment strategy, public sector social creativity and innovation workshops, issue definition, and so on.

The social process has seven steps. All steps must be performed in silence. No talking is permitted to avoid discussions that inject bias and disrupt individual reflective thinking.

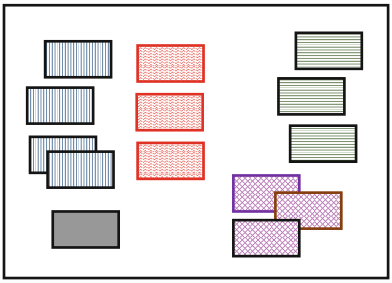
Step 1 *Specify the goals and objectives.* A goal is superordinate, it is thematic (Sect. 3.2). They are the "what". Objectives are the "how and by how much". Goals and objectives must make sense to all participants.



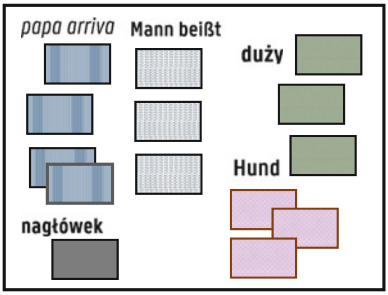
Step 2 *Write the controllable variables.* Each group person writes a controllable variable on a 3 × 5 post-it® card. Each person can write as many as desired. Paste all cards on the conference table or a wall so that they can be easily read by all. The wall is now dense with cards. The variables, on the cards, will not be of equal importance, nor be at same level of abstraction. Some will be trivial, others inappropriate, and many will be subordinate elements of other variables. Down selection will be necessary to organize and cull the proposed set of variables.



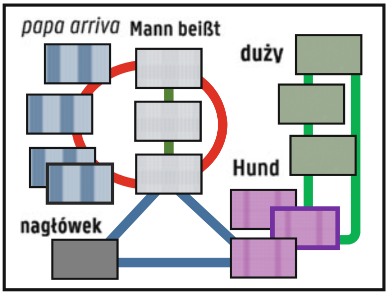
Step 3 *Down-select variables.* Begin by giving each person α number of dots to paste on cards, where $1 \leq \alpha \leq k$ and $k \approx 15$–25% of the group size. Each person is permitted to paste one or more dots on a card, as they wish, until their dots are exhausted. This forces making choices and judging the importance each person attaches to a variable. Cards that have no dots or have the least number of dots can be discarded. Continue until there are approximately 40–60 cards left.



Step 4 *Group variables.* All cards will be at random locations. Instruct the group that each person must move cards close to other cards they judge to have some kind of affinity. The affinity criteria are personal and forbidden to be communicated. The silence rule applies. Any card can be moved an unlimited number of times. Proceed until all card movement stops and sets of grouped cards appear. There will be a few singletons that have no affinity to any group. That is permitted. The final grouping represents the closest group's mental model that is closely aligned with individual mental model.



Step 5 *Name each group*. Each group is given a thematic name that characterizes and reflects the collective character of the cards in the group. As a result of the repeated movement of card to ones that have some affinity, the group will now represent a decision factor. The next step is to show the relationships among the groups (factors) in such a way that it provides a whole system view of the ensemble.



Step 6 *Show relationships among groups*. Develop a system interpretation of the ensemble of groups by making logical connections among the groups. This will require a disciplined discussion. The connections will appear as a network of groups. Follow this with an interpretation of the network with a system narrative that is consistent with the goals and the logic of the variables.

Step 7 *Review and reflect on the process and its results.*

3.3.3 Subspaces of Solution Space

The outputs of the solution space is the Cartesian product of two spaces, Eq. (3.3), In the next two sections, we show how to construct the *controllable space* and the *uncontrollable space* to obtain the *output space*.

$$(controllable\ space) \times (uncontrollable\ space) = [output\ space]. \tag{3.3}$$

3.3.3.1 Controllable Space: Alternatives Space

Decision alternatives must be managerially actionable. The ***elemental*** building blocks of the alternatives are the set of the n controllable variables $\{C_{ij}\}$ for $i = 1,2, \ldots ,n$, at each of their three levels $j = 1,2,3$.

Consider a simple example. Assume we have four controllable variables, $\boldsymbol{C_1}$, $\boldsymbol{C_2}$, $\boldsymbol{C_3}$, and $\boldsymbol{C_4}$. (**C** for controllable). For variable C_1 *(level **1**)*, we denote as $\boldsymbol{C_{11}}$; i.e. C_1 *(level **1**)* $= \boldsymbol{C_{11}}$, C_1 *(level **2**)* $= \boldsymbol{C_{12}}$, and C_1 *(level **3**)* $= C_{13}$. The same naming

Table 3.2 Controllable variables C_1, C_2, C_3, and C_4 at three levels each

	C_1	C_2	C_3	C_4
Level 1	C_{11}	C_{21}	C_{31}	C_{41}
Level 2	C_{12}	C_{22}	C_{32}	C_{42}
Level 3	C_{13}	C_{23}	C_{33}	C_{43}

convention apply for C_2, C_3, and $\boldsymbol{C_4}$. We can array this as in Table 3.2 with 4 × 3 elemental blocks from which alternatives are built.

Table 3.3 shows the *entire complete* set of actionable decision alternatives without uncertainty. It is the full factorial set obtained from Table 3.2, i.e. all possible combinations of the elements in Table 3.2. Each row of Table 3.3 represents a decision alternative, as a 4-tuple of configurations of the controllable variables, e.g. alternative 3 is represented as $(C_{11}, C_{21}, C_{31}, C_{41})$ with output $\boldsymbol{y_3}$.

Notably, Table 3.3 shows how the complexity of the variety of actionable alternatives has been ***discretized*** into a finite set. The set is still large, and can get very large very rapidly as the number of controllable variables increase. But we will show how it can reduced to a manageable set. In this case, for 4 variables at 3 levels, the full factorial is comprised of $3^4 = 81$ alternatives as shown in Table 3.3. The number of alternatives increase exponentially by the number of factors, Eq. (3.4),

$$number\ of\ alternatives = n^f \tag{3.4}$$

where n is the number of levels of the variables and f is the number of factors.

Consider another example to illustrate how this combinatorial complexity rises. For 6 variables with 3 levels each, we have $3^6 = 729$ alternatives. For 11 variables of 2 levels, we have $2^{11} = 2048$ alternatives. This volume of alternatives is too large to analyze. This is a serious challenge, we can represent the entire space of alternatives, but it is still too large for it to be practical. In the Operations Space (Sect. 4), we show how to ***uncomplicate*** this complexity.

The purpose of decision alternatives is to estimate how they will perform in order to select one that will *satisfice* the stated goals and objectives. The outputs of each alternative is shown by the column identified as **output,** $\boldsymbol{y_i} = f(alternative\ i)$ in Table 3.3. But this output is under ideal conditions **without** any uncertainty, which is not realistic. How to address this question is the topic of discussion in the next paragraph, Sect. 3.2.2.

3.3.3.2 Uncontrollable Space: Uncertainty Space

All the alternatives will operate under some uncertainties. As in the case of controllable variables, we need to ***discretize*** the uncertainty space to make it manageable. As in the case of controllable variables, we use the uncontrollable variables to represent the space of uncertainty. As a simple example, say we have three uncontrollable variables, $\boldsymbol{U_1}$, $\boldsymbol{U_2}$, and $\boldsymbol{U_3}$. (***U*** for uncontrollable). The subscript

Table 3.3 All alternatives in the controllable space, and their outputs. Under NO uncertainty

	$(C_1,\ C_2,\ C_3,\ C_4)$	$y_\alpha = f(\mathit{alternative}\ \alpha)\ 1 \le \alpha \le 81$
alternative 1	$(C_{11}, C_{21}, C_{31}, C_{41})$	$\boldsymbol{y_1}$
alternative 2	$(C_{11}, C_{21}, C_{31}, C_{41})$	$\boldsymbol{y_2}$
alternative 3	$(C_{11}, C_{21}, C_{31}, C_{41})$	$\boldsymbol{y_3}$
alternative 4	$(C_{11}, C_{21}, C_{31}, C_{41})$	$\boldsymbol{y_4}$
. . .	. . ., . . ., . . ., . . .	. . .
alternative 66	$(C_{13}, C_{22}, C_{31}, C_{43})$	$\boldsymbol{y_{66}}$
. . .	. . ., . . ., . . ., . . .	. . .
alternative 79	$(C_{13}, C_{23}, C_{33}, C_{11})$	$\boldsymbol{y_{79}}$
alternative 80	$(C_{13}, C_{23}, C_{33}, C_{42})$	$\boldsymbol{y_{80}}$
alternative 81	$(C_{13}, C_{23}, C_{33}, C_{43})$	$\boldsymbol{y_{81}}$

Table 3.4 Uncontrollable variables U_1, U_2, and U_3 at three levels each

	U_1	U_2	U_3
Level 1	U_{11}	U_{21}	U_{31}
Level 2	U_{12}	U_{22}	U_{32}
Level 3	U_{13}	U_{23}	U_{33}

Table 3.5 Entire set of uncertainties (uncontrollable space)

Uncertainties 1–9		Uncertainties 10–18		Uncertainties 19–27	
1	(U_{11}, U_{21}, U_{31})	**10**	(U_{12}, U_{21}, U_{31})	**19**	(U_{13}, U_{21}, U_{31})
2	(U_{11}, U_{21}, U_{32})	**11**	(U_{12}, U_{21}, U_{32})	**20**	(U_{13}, U_{21}, U_{32})
3	(U_{11}, U_{21}, U_{33})	**12**	(U_{12}, U_{21}, U_{33})	**21**	(U_{13}, U_{21}, U_{33})
4	(U_{11}, U_{22}, U_{31})	**13**	(U_{12}, U_{22}, U_{31})	**22**	(U_{13}, U_{22}, U_{31})
5	(U_{11}, U_{22}, U_{32})	**14**	(U_{12}, U_{22}, U_{32})	**23**	(U_{13}, U_{22}, U_{32})
6	(U_{11}, U_{22}, U_{33})	**15**	(U_{12}, U_{22}, U_{33})	**24**	(U_{13}, U_{22}, U_{33})
7	(U_{11}, U_{23}, U_{31})	**16**	(U_{12}, U_{23}, U_{31})	**25**	(U_{13}, U_{23}, U_{31})
8	(U_{11}, U_{23}, U_{32})	**17**	(U_{12}, U_{23}, U_{32})	**26**	(U_{13}, U_{23}, U_{32})
9	(U_{11}, U_{23}, U_{33})	**18**	(U_{12}, U_{23}, U_{23})	**27**	(U_{13}, U_{23}, U_{23})

notation s identical to that of controllable variables. The space of uncertainty is determined, Table 3.4.

Table 3.5 which shows the *entire complete* set of uncertainty conditions. This is the full factorial set obtained from Table 3.4, the entire set of uncertainty conditions. The complexity of the uncertainties has been discretized into a small set. For 3 variables at 3 levels, we have $3^3 = 27$ alternatives (Table 3.5).

3.3.4 Output Space = All Alternatives Under All Uncertainties

Recall that the *output space* is the Cartesian product of two mutually exclusive sets,

$$(controllable\,space) \times (uncontrollable\,space) = [output\,space] \quad \text{e.g. Table 3.5} \tag{3.5}$$

$$(controllable\,space) = (alternative_1, \ldots, alternative_a) \quad \text{e.g. Table 3.3} \tag{3.6}$$

$$(uncontrollable\,space) = (uncertainty_1, \ldots, uncertainty_u) \quad \text{e.g. Table 3.5} \tag{3.7}$$

$$\begin{aligned} &\text{thus } (alternative_1, \ldots, alternative_a) \times (uncertainty_1, \ldots, uncertainty_u) \\ &\quad = [outputs_{ab}] = matrix\,of\,all\,outputs\,under\,all\,uncertainties \end{aligned} \tag{3.8}$$

Schematically, the output matrix looks like Table 3.6:

Each matrix entry, such as ***output 32***, represents the DOE predicted output from ***alternative 3*** under uncertainty ***condition 2***. The schematic is filled as in Table 3.7. The remainder of this section is to show how to derive the outputs.

The universe of alternatives under certainty is the set {*alternative α},* where $1 \leq \alpha \leq 81$ at each of 27 uncertainty conditions. Therefore, the universe of alternatives under uncertainty is the set of 81 alternatives under the 27 uncertainty conditions. Thus the number of alternatives under uncertainty is 4^3 x $3^3 = 2187$. This set is shown as follows in shorthand in Table 3.7. We have discretized the complexity of the entire set of alternatives under the entire set of uncertainties by the Cartesian product of two discrete sets.

We have discussed three important points.

- How to represent the entire set of decision alternatives under certainty Eq. (3.8).
- How to represent the *entire set of uncertainty conditions* (Table 3.5).
- How the Cartesian product of the alternatives and the uncertainty space produce the set of alternatives within every uncertainty condition (Table 3.7).

Clearly the complexity of the output set $\{\boldsymbol{y^u}_{\boldsymbol{a}}\}$ is sizeable.

In the next section we will show how to reduce the size of this set, how to estimate the outcomes for this reduced set, and how to construct the optimally robust decision alternative (Klein 2001).

Table 3.6 Schematic of the output space

	uncertainty 1	uncertainty 2	uncertainty 3	…	uncertainty u
alternative 1	*output 11*	*output 12*	*output 13*	…	*output 1u*
alternative 2	*output 21*	*output 22*	*output 23*	…	*output 2u*
alternative 3	*output 23*	***output 32***	*output 33*	…	*output 2u*
…	…	…	…	…	…
alternative a	*output a1*	*output a2*	*output a3*	…	*output au*

Table 3.7 Complete set of alternatives set under entire set of uncertainty conditions

$y^{\alpha}{}_{j} = f(\text{alternative } i, \text{uncertainty } j)$ $1 \leq \alpha \leq 81,\ 1 \leq j \leq 27$		uncertainty **1**	uncertainty **2**	uncertainty **3**	uncertainty **4**	…	uncertainty **25**	uncertainty **26**	uncertainty **27**
alternative 1	(C_{11}, C_{21}, C_{31}, C_{41})	$\mathbf{y^{1}{}_{1}}$	$\mathbf{y^{2}{}_{1}}$	$\mathbf{y^{3}{}_{1}}$	$\mathbf{y^{4}{}_{1}}$	…	$\mathbf{y^{25}{}_{1}}$	$\mathbf{y^{26}{}_{1}}$	$\mathbf{y^{27}{}_{11}}$
alternative 2	(C_{11}, C_{21}, C_{31}, C_{42})	$\mathbf{y^{1}{}_{2}}$	$\mathbf{y^{2}{}_{2}}$	$\mathbf{y^{3}{}_{2}}$	$\mathbf{y^{4}{}_{2}}$		$\mathbf{y^{25}{}_{2}}$	$\mathbf{y^{26}{}_{2}}$	$\mathbf{y^{27}{}_{21}}$
alternative 3	(C_{11}, C_{21}, C_{31}, C_{43})	$\mathbf{y^{1}{}_{3}}$	$\mathbf{y^{2}{}_{3}}$	$\mathbf{y3_{3}}$	$\mathbf{y^{4}{}_{3}}$		$\mathbf{y^{25}{}_{3}}$	$\mathbf{y^{26}{}_{3}}$	$\mathbf{y^{27}{}_{31}}$
alternative 4	(C_{11}, C_{21}, C_{32}, C_{41})	$\mathbf{y^{1}{}_{4}}$	$\mathbf{y^{2}{}_{4}}$	$\mathbf{y^{3}{}_{4}}$	$\mathbf{y^{4}{}_{4}}$		$\mathbf{y^{25}{}_{4}}$	$\mathbf{y^{26}{}_{4}}$	$\mathbf{y^{27}{}_{4}}$
alternative 5	(C_{11}, C_{21}, C_{32}, C_{42})	$\mathbf{y^{1}{}_{5}}$	$\mathbf{y^{2}{}_{5}}$	$\mathbf{y^{3}{}_{5}}$	$\mathbf{y^{4}{}_{5}}$	…	$\mathbf{y^{25}{}_{5}}$	$\mathbf{y^{26}{}_{5}}$	$\mathbf{y^{27}{}_{5}}$
alternative 6	(C_{11}, C_{21}, C_{32}, C_{43})	$\mathbf{y^{1}{}_{6}}$	$\mathbf{y^{2}{}_{6}}$	$\mathbf{y^{3}{}_{6}}$	$\mathbf{y^{4}{}_{6}}$		$\mathbf{y^{25}{}_{6}}$	$\mathbf{y^{26}{}_{6}}$	$\mathbf{y^{27}{}_{6}}$
….	…	…	…	…	…		…	…	…
alternative 79	(C_{13}, C_{23}, C_{33}, C_{43})	$\mathbf{y^{1}{}_{79}}$	$\mathbf{y^{2}{}_{79}}$	$\mathbf{y^{3}{}_{79}}$	$\mathbf{y^{4}{}_{79}}$	…	$\mathbf{y^{25}{}_{79}}$	$\mathbf{y^{26}{}_{79}}$	$\mathbf{y^{27}{}_{79}}$
alternative 80	(C_{13}, C_{23}, C_{33}, C_{43})	$\mathbf{y^{1}{}_{80}}$	$\mathbf{y^{2}{}_{80}}$	$\mathbf{y^{3}{}_{80}}$	$\mathbf{y^{4}{}_{80}}$		$\mathbf{y^{25}{}_{80}}$	$\mathbf{y^{26}{}_{80}}$	$\mathbf{y^{27}{}_{80}}$
alternative 81	(C_{13}, C_{23}, C_{33}, C_{43})	$\mathbf{y^{1}{}_{81}}$	$\mathbf{y^{2}{}_{81}}$	$\mathbf{y^{3}{}_{81}}$	$\mathbf{y^{4}{}_{81}}$		$\mathbf{y^{25}{}_{81}}$	$\mathbf{y^{26}{}_{81}}$	$\mathbf{y^{27}{}_{81}}$

3.3.5 Base Line = Do-Nothing-Different Case = Business As Usual (BAU)

We need alternatives to find better prospects for the organization. Any improvement requires a reference point to evaluate results. It is natural and convenient to establish the reference point as the current state of the controllable variables and the uncontrollable variables. This is reasonable and practical. There is data on organizational performance and information on the uncontrollable variables. This is the current state of the decision specification; it is also the condition should the decision-makers choose to do nothing different. Taking no new action leaves the organization to run "business as usual". This is the origin for using the expression business-as-usual (BAU). It can be said that the idea of executive decisions is to improve on BAU or to confirm BAU as suitable.

However going forward, we cannot assume the uncontrollable environment will remain unchanged while doing nothing. Therefore, in addition to the base-line's specification, we need to complete four additional tasks, *viz.* specifying the: (i) current state of the controllable variables, (ii) current state of the controllable variables designing, (iii) one or more specifications of *favorable states* of uncontrollable states, and (iv) one or more specifications of *less favorable states* of uncontrollable states. *More* or *less* favorable conditions are defined relative to the actual state of uncontrollable conditions. In the paragraphs that follow, we will show how to do these tasks. We will use Tables 3.2, 3.3, 3.4, 3.5 for a hypothetical example.

Assume the four controllable variables—C_1, C_2, C_3, and C_4—are used to characterize the actual state (Table 3.3). And that, the current state is specified by C_1 at level 3, C_2 at level 2, C_3 at level 1, and C_4 at level 3, i.e. $(C_{13}, C_{22}, C_{31}, C_{43})$ specifies the actual state of the executive- management decision. This is *alternative* 66 in Table 3.3.

Specify the configuration of the *actual state* of uncontrollable variables. Hypothetically for example, consider the *set* of uncontrollable variables as described in Table 3.4. The uncertainty-state of the actual decision situation is *an* element in Table 3.5. Suppose the actual uncertainty state is represented by uncontrollable variables U_1 at level 2, U_2 at level 1, and U_3 at level 2, i.e. (U_{12}, U_{21}, U_{32}). This is uncertainty condition #11 in Table 3.5. Specification of this actual condition poses no difficulty it is self-evident by observation from the DMU. The next two tasks are:

- first is the specification of one or *more favorable* uncontrollable conditions, and
- second is the specification of one or more *less favorable* uncontrollable conditions.

More or *less* favorable conditions are relative to the actual state of uncontrollable conditions. Suppose the less favorable uncontrollable condition is (U_{11}, U_{22}, U_{31}) and the more favorable uncontrollable condition is (U_{13}, U_{22}, U_{32}). We can line up the set of uncontrollable conditions facing the BAU decision alternative from least favorable, to BAU, to most favorable as: $\{(U_{11}, U_{22}, U_{31}), (U_{12}, U_{21}, U_{32}), (U_{13},$

$U_{22}, U_{32})\}$. In summary, putting it altogether, the BAU uncontrollable situations are represented by Table 3.8.

The number of uncontrollable environments is not limited to three as shown in Table 3.8. Many more can be described. For example, in addition to those in Table 3.8, one could specify a *much more favorable* state, and a *very unfavorable state*. As a practical matter, do not recommend more than five states because it encumbers the cognitive load and makes the set uncontrollable excessively complicated. In this example, the DMU must record three results to complete the table. "Actual performance" data can be easily obtained from actual business records. The other performance data are provided by each member of the DMU working independently. It is not advisable to exert peer pressure, foment herd instincts, to produce a false convergence. The task of **each** DMU member is to fill each of the cells marked by "*enter your forecast*" with a value that represents their best professional judgment. Each DMU member is permitted and encouraged to consult their staffs, non-DMU colleagues, or subject matter experts to arrive at their forecasts. But DMU members are **prohibited** from communicating with each other. Research findings show that knowing others' preferences degrades the quality of group decisions (e.g Mojzisch and Schulz-Hardt 2010). The rule of non-disclosure of individual forecasts is supported by research.

There is no such thing as a "right" or "wrong" forecast. It is a forecast, a professionally informed judgement; it is what the literature calls "judgmental forecasting" (e.g. Fildes et al. 2009; Wright and Rowe 2011). DMU members must not automatically make symmetric intervals centered on "actual" for the "more favorable configuration" and the "less favorable configuration" of the uncontrollable environment. There is no logical reason to suppose they should be; but they can be for special and explainable situations.

The DMU facilitator ***averages*** the input for each uncontrollable environment to produce the forecasts for each of the "current," "worst," and "best" forecasts. This average represents the forecast of the DMU as a group. Averaging is a specific method of combining forecasts (e.g. Armstrong 2001; Makridakis 1989; Makridakis and Winkler 1983). Averaging of independent forecasts is recognized in the literature as a valid method of group-based judgmental forecasting. The requirement is that the forecasts must be arrived *independently* and using a systematically developed and documented procedure than can be replicated consistently (Armstrong 2001). Hibon and Evgenious (2005) are less sanguine and report

Table 3.8 BAU baseline

BAU			
Controllable variables	Uncontrollable environments		
Actual configuration $(C_{13}, C_{22}, C_{31}, C_{43})$	Less favorable configuration	Actual configuration	More favorable configuration
	(U_{11}, U_{22}, U_{31})	(U_{12}, U_{21}, U_{32})	(U_{13}, U_{22}, U_{32})
	Enter your forecast	***BAU Actual***	***Enter your forecast***

that special experiments reveal that combining is inferior to the best alternative, **but** acknowledge that "[A] limitation of this study is on how to choose among methods or combinations in an optimal way (Hibon and Evgenious 2005, 23)". This is a severe limitation. As such their findings are not actionable and thus of limited practical use. Therefore, we concentrate on the reasons that make combing effective. There are practical reasons why combining forecasts is useful. Combining reduces errors from bias and flawed assumptions. "Combining forecasts improves accuracy to the extent that the component forecasts contain useful and independent information (Armstrong 2001)." These key questions of debiasing, useful and independent information are addressed in the next Sect. 3.3.6.

3.3.6 Debiasing Social Process

Granger the 2003 Nobel laureate in economics observed that "aggregating forecasts is not the same as aggregating information . . . (Wallis 2011, 15)." Kerr and Tindale (2011) confirm the view that information exchange among group members strengthens benefits beyond averaging. Scholars' findings reveal a series of crucial points that must be considered in the forecasting social-process. The importance of non-disclosure has already been pointed out (Mojzisch and Schulz-Hardt 2010). We have also addressed the pivotal role of an able facilitator during the social process (Regan-Cirincione 1994). Schulz-Hardt's et al. (2006) work finds that group discussions that go beyond anonymous Delphi type meetings, but also encourage face-to-face discussions improve the quality of the group members' judgements. Significantly, Wright and Rowe (2011) and Russo and Schoemaker (1992) find that of dissenting discussions are very effective in forecasting group meetings. Especially when openly exercised by a heterogeneous group (Yaniv 2011). Constructive dissent, with meaningful new information and informed judgments, is useful. In fact counterfactual thinking foments creative thinking in problem solving (e.g. Markman et al. 2007).

In this section, we try to put these findings to work in a forecasting social-process geared to debiasing mental models and improving group and individual performance. We discuss what kinds of information are needed to debias mental models, what is the debiasing social process, and what are the requirements on the composition of the DMU membership. In addition to the information, we present our facilitated social process combined with information to improve the accuracy of the group's judgements. Regan-Cirincione's (1994) work shows this kind of integrated process is effective in producing forecasting quality.

We begin with counter-argumentation (Russo and Schoemaker 1992) as the central debiasing social process. Counter-argumentation is designed to mitigate the danger of group think (Janis 1992; Carroll et al. 1998), narrow framing (Tversky and Kahneman 1974; Russo and Schoemaker 1989), and false anchoring (Baron 2000). Counter-argumentation procedures reduce systematic biases by insisting on explicit, ***but*** anonymous, articulation of the reasons why a forecast derived from mental models might be correct ***and*** why it might not be correct (Fischhoff 1999; Russo and Schoemaker 1992; Arkes 2001; Koriat et al. 1980). The strategy is to search for *disconfirmatory* information in group decisions to debias and improve accuracy (Kray and Galinsky 2003). Our debiasing approach insists on counter-argumentation *without* disclosure or discussion of the *forecast figures* so that "concentering" (Roth 1995) takes place without peer pressure, which can drive a false convergence (Mest and Plummer 2003; Hanson 1998; Boje and Mirninghan 1982). Counter-argumentation also improves the DMU's effectiveness in problem solving by enriching and complementing team members' individual mental models (Mohammed et al. 2010; Mohammed and Dumville 2001; Kray and Galinsky 2003; Lerner and Tetlock 2003). Winquist and Larson (1998) show that information pooling of fresh information, which is shared, improves decision quality and the ability to conceptualize alternatives.

Emphasizing the reasons for both having strong confidence on the forecasts and its weakness, combining anonymity, and discussions on rationale and logic (rather than numbers), all together puts a premium on information, knowledge and meaning. All these are important because they can positively influence accuracy (e.g. Ashton 1985; Dawes and Mulford 1996; Winquist and Larson 1998). Another vital aspect of counter-argumentation cannot be overlooked. The diversity of the group doing the decision analysis (Yaniv 2011; Cummings 2004; Cummings and Cross 2003) is important so that rich, subtle and nuanced arguments are brought to the table. To these ends, our debiasing processes are an adaptation of Lerner and Tetlock's (2003) framework, which considers all these factors (Appendix 3.4). Leading management consultants use a similar approach to debias and enrich information exchange (Sorrell et al. 2010). Debiasing is designed to "activate ***integratively-complex*** thought that reduces biases" (Appendix 3.4). The framework: also "predicts that integratively-complex and open-minded thought is most likely to be activated when decision makers learn prior to forming any opinions that they will be accountable to an audience (a) whose views are unknown, (b) who is interested in accuracy, (c) who is reasonably well informed, and (d) who has legitimate reason for inquiring into the reasons behind participants' judgments/choices (Lerner and Tetlock 2003)."

We introduce accountability into "*integratively-complex* and open-minded" thought process by means of counter-argumentation and learning through feedback. For the BAU case, we have two forecasting rounds. Counter-argumentation is done at the end of the first round before moving to the next one. The first round includes a discussion session where the counter-arguments are disclosed (without attribution) and openly discussed. We then proceed to the second round of BAU forecasting. We ask the participants to record their individual confidence level at the end of each round because we would like to know the effect on confidence resulting from the new information disclosed during counter-argumentation. This is why complementary, heterogeneous knowledge and DMU membership is important (Mohammed et al. 2010; Banks and Millward 2000). At no time are the actual forecast figures permitted to be disclosed or discussed to anyone in the group.

Documented rationales, in support or in doubt, of individual forecasts are anonymously disclosed to the DMU. This is followed by a discussion for each documented rationale. Because the rationales are anonymous, there is less posturing and defensiveness than expected from these type of discussions. The goal is for the DMU members to learn from each other, each other's reasons, and less about the actual forecast numbers. Using the documented rationales *as a whole*, we ask that each person review, reflect, and adjust their individual forecasts in light of new information. The adjustments are done individuality, for which the no-discussion rule still applies.

Everyone is reminded that we are **not** seeking consensus numbers, but **improved judgment** in light of **new** and **complementary** information and to improve tacit knowledge (e.g. Polanyi 2009; Erden et al. 2008). There is no evaluative appraisal implied or penalty imposed just because the forecasts differ from person to person. The differences reflect distinct domain expertise and tacit knowledge each individual brings to their forecasts. The revised forecasts are used to calculate the averages, as discussed in the previous section, Sect. 3.3.5. Figure 3.6 shows typical results of this debiasing procedure.

The forecasts from round 1 (without debiasing) and round 2 (after debiasing) for the actual (or current), worst, and best uncontrollable situations (Fig. 3.7). In the current situation (the left hand panel), the mean has not changed but the variation is less. In the worst uncontrollable situation (the middle panel) the mean is not as bad as initially judged and the variation has diminished substantially. In the best uncontrollable situation (right hand panel of Fig. 3.7), the mean is not as good as initially estimated, but the variation has declined substantially. This suggests to us that debiasing has introduced new information and knowledge to each DMU member and that the judgments have improved.

We have operationalized Nobel-laureate Granger's requirement for aggregating information (Wallis 2011) and have prescribed a debiased, social process as well.

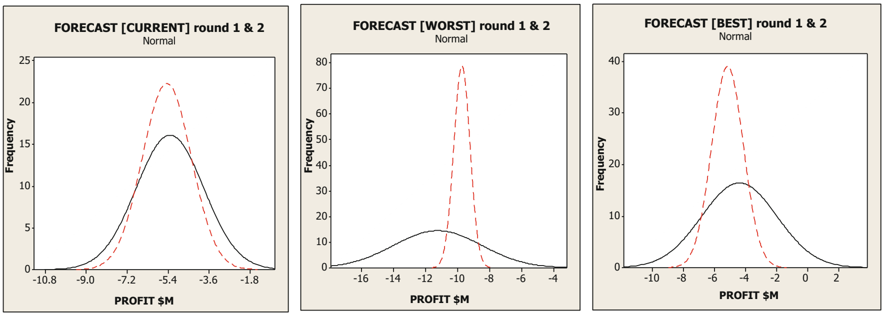


Fig. 3.7 Improved forecasts before and after debiasing

3.4 Operations Space

3.4.1 New Strategy: Gedanken *Experiments to Uncover System Behavior*

We now focus our attention on the operations space. Figure 3.8 is a schematic of this space.

The key questions in the operations space are: “How do we determine the behavior of the socio-technical organization that will implement a decision’s specifications?” The complex, messy, and wicked nature of the situation and the socio-technical systems responsible for implementing solutions, surfaces the next crucial questions: “How do we determine the system behavior of the decision specification?” What is the quality of implementation? What is the quality of the DMUs estimates? Decisions’ processes are not like technical systems, which can be *ex ante* characterized by means of the physical sciences and its equations to model them with accuracy and precision. Through very detailed and comprehensive surveys supported by interviews, a complex enterprise can be modeled. But this is a labor intensive and protracted process. The model for the ADI company, which we will use as a case study to illustrate our paradigm, has over 200 loops of interactions and over 600 variables. It took months for MIT faculty members to model, calibrate, and run simulations for analyses and to gain meaningful and useful insights. The question is then: “is there a way to obtain the same result in a substantially more efficient way?” We answer is in the affirmative. This is what this book is about. But how?

First, by eschewing the traditional thinking of developing *ex ante* analytic models. Second, by insisting on a fresh strategy. One that does not presume to know the explicit analytic equations that represent the sociotechnical system’s machinery. Unlike the conventional approach that presumes knowledge of mathematical expressions among variables to represent sociotechnical systems’ behavior, we use experiments. Using *gedanken* experiments, we *observe* and *measure* the behavior and output from the sociotechnical system. *Ex post* we infer system-behavior patterns from the outcomes of alternatives from gedanken experiments

Fig. 3.8 Schematic of the operations space

that reveal a ph**enomenological** representation of the system. Phenomenology is a scientific methodology to describe and explain observations. Appearance reveals and explains reality (Smith 2013; Otto and Wood 2001).

Using what kind of experiments? ***Gedanken*** (thought) experiments (e.g. Sorensen 1992; Brown and Yiftach 2014). *Gendanken* experiments are structured tests designed to answer or raise questions about a hypothesis *without* the need for physical equipment. But whose results can be observed and measured.

An experiment is a test (e.g. Montgomery 2001). An experiment is a well-structured and purposeful procedure to investigate a principle, hypothesis, or phenomenon. The principles, hypotheses, or phenomena can be about nature, systems, processes, philosophy, and so on. Our experiments concentrate on the behavior of corporate systems and processes resulting from potential decisions specifications. The goals of our experiments are to understand and to determine the behavior and performance of the sociotechnical systems that operationalize a decision specification.

The vast majority of experiments are performed with physical apparatus, e.g. Michelson and Morely's celebrated inquiry about the speed of light (Michelson and Morley 1887). CERN's experiments to find the Higgs boson. But many equally insightful experiments can be performed without any physical artifacts, like Galileo's gedanken experiment on the speed of falling objects, Maxwell's demon, Schrödinger's cat, Einstein's falling elevator, and so on. These are famous examples of *gedanken* experiments.

Galileo's experiment, on the question whether heavier objects will fall faster than lighter ones, is an exemplar of gedanken experiments. Contrary to apocryphal accounts, he did not drop objects from the Tower of Pisa. He supposedly arrived at his legendary scientific conclusion by reasoning. He imagined dropping a heavy and light object that are "bundled" together. If a heavier object falls faster than lighter ones, than the bundle would fall faster than the heavy object alone. But since the bundle contains a lighter object, the lighter object should slow down the fall of the bundle. The bundle cannot fall faster and slower. By the principle of the excluded middle, they fall at the same speed. With no physical equipment, he proved that heavy and light objects will fall at the same speed.

Gendanken experiments are structured tests designed to answer or raise questions about a hypothesis *without* the need for physical equipment. But whose results can be observed and measured. The experiments about such questions are framed and manipulated by "varying and tracking the relations among variables" (Hopp 2014, 250). *Gedanken experiments are performed using mental models that require experts' domain expertise and tacit knowledge* (e.g. Polanyi 2009; Erden et al. 2008). Tacit knowledge is layered on detailed cumulative understanding of the particulars, experience, failures, and effective practice. Tacit knowledge is not something that can be acquired from books, manuals and the like. Driving is tacit knowledge, heart surgery is tacit knowledge, and so is piloting an F-35 fighter jet. This kind of knowledge is acquired by doing. Which is why use of gedanken experiments us so useful to seasoned scientists and engineers. Our executive-management decision-paradigm uses gedanken experiments, as well as, real tests, for confirmatory and disconfirmatory data to analyze outcomes and execution quality.

3.4.2 Operations Space: Conceptual Framework

Regardless of the type of experimental assets that are used, physical or intellectual; given the objectives of our investigation, the fundamental questions that need to be addressed are:

- What kind of experiments do I need?
- What is a sufficient and comprehensive number of experiments?
- How will the findings improve my understanding of the problem?
- Is there a science to address this?

The science to address these questions is called **Design of Experiments (DOE)**. DOE answers these questions by first positing that a system or a process can be represented by a simple, abstract, and uncomplicated construct shown in Fig. 3.9.

The input variables of the system or process, $\{C_1, \ldots, C_p\}$ are managerially controllable by the experimenter and $\{U_1, \ldots, U_q\}$ are managerially uncontrollable. The response, output, is given by $\boldsymbol{y}_{\boldsymbol{\alpha}} = f(C_1, \ldots, C_p, U_1, \ldots, U_q)$. In our use of the DOE, the experiments are *gedanken* experiments about decision alternatives. The gedanken experiments are about sociotechnical systems and processes and the *organizational units* to implement the decision specifications committed by the decision-maker. The arrows pointing up represent the methods and mechanisms used by the organizational units to execute and implement. The key methods are DOE, Measurement System Analysis (MSA) (AIAG 2002), debiasing procedures, evaluation methods for decision outcomes and implementation quality.

DOE is an experimental strategy to determine the kind of experiments and the sufficient number required to systematically make inferences and predictions about the behavior of a system. DOE allows the experimenter to determine the *phenomenological behavior* of the system/process. The idea is to use the set of responses from the experiments to fit a relationship over the design space of controllable and uncontrollable variables (also called factors) (Otto and Wood 2001).

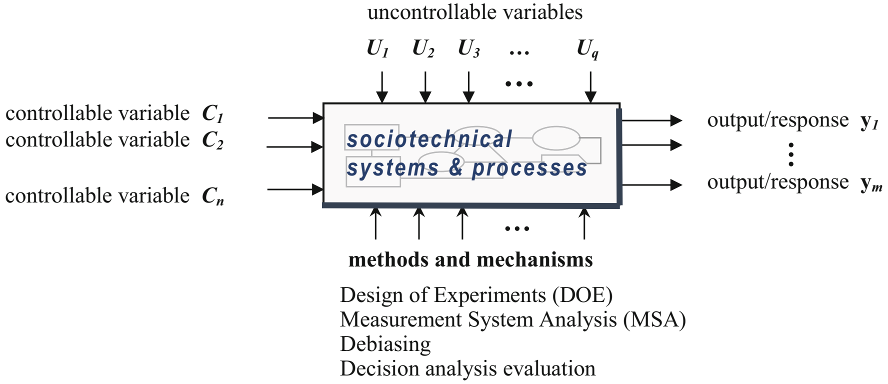


Fig. 3.9 Schematic of *gedanken* experiments for executive-management decision

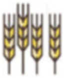
“A well-organized experiment, followed by thorough data analysis … can provide answers to the following important questions:

- Which are the most important factors affecting the performance characteristics?
- How do the performance characteristics change when the factors are varied?
- What is the joint influence of factors on the performance characteristics?
- Which is the optimal combination of factor values?” (Vucjkov and Boyadjieva 2001).

DOE presents methods to answer the questions of the kind of experiments that can be constructed, the ways to analyze them, and how to make reasoned and informed predictions about the output ***y***. A ***key*** feature of the DOE methodology is that it provides methods to determine the **smallest number** of experiments that will satisfy the criteria of sufficiency, comprehensiveness, and ability to predict outcomes and variances over the entire space of alternatives under uncertainty.

3.4.3 Design of Experiments (DOE)

The genesis of modern experimental methods is recent. We follow Montgomery (2001), Wu and Hamada (2000) to punctuate the historical development of DOE into stages of progressively more sophisticated methodologies and increasing applications in different domains of inquiry. (Appendix 3.1 shows a sample of typical engineering problems studied using DOE.) We extend this progression by including our executive-management decision paradigm as the most recent new advance in DOE. We will discuss the reasons why this is a frame-breaking and challenging undertaking.



Stage 1 is the agricultural era. As the inventor of the DOE methodology (Fisher 1966, Box 1978), Fisher’s interest was in producing high yield crops under different controllable and uncontrollable variables of water, fertilizer, rain, sunshine, and other factors. He systematically formulated experiments, which specified crop treatments with different combinations of variables at different values. Some plots were fertilized others not, some were irrigated more intensely than others, and so on. Of course, they were all subjected to many different uncontrollable conditions; such as rain, sunshine, and so forth. As one would expect, the set of possible treatments became very large, and the variety of uncontrollable conditions were many. The combinatorial explosion of controllable and uncontrollable factors grew very large. (His term, “treatments”, is till used today as a synonym for “experiments”.) To address this complexity, Fisher devised methods to reduce the number of experiments to merely a fraction of the total possible experiments. And to analyze experimental results, he created the Analysis of Variance (ANOVA) as a new statistical method to study the joint effect many

factors. Fisher also articulated the renown experimental principles of randomization, replication, and blocking. His work stands as a landmark in original and practical thinking.

Stage 2 is the industrial era ushered by Box and Wilson (1951), statistician and chemist, respectively. They recognized that unlike protracted agricultural experiments; chemical and process types of experiments can produce results with much greater immediacy. Learning from immediate results, they were able to rapidly plan an improved next experiment. Armed with this insight and more sophisticated statistical methods, they developed the Response Surface Methodology (RSM). RSM is a sequential procedure. The objective is to move incrementally from the current operating region to an optimum. The investigator begins with simple models, and as knowledge about the solution space improves, more advanced models are used to explore the regions of interest and to determine the extremum. Box and Wilson's (1951) innovation was to demonstrate the efficacy of Fisher's method in another domain of inquiry.

Stage 3 is the product and manufacturing quality era. Taguchi (1987, 1991) introduced the DOE and the concept of *robustness* for use in product design and manufacturing. A product or a process is robust when:

- the performance, its response or output, is highly insensitive to uncontrollable or difficult to control environmental factors even they are not removed,
- the performance is insensitive to variations transmitted from uncontrollable variables of the exterior environment.

Using Taguchi's innovations in DOE methods, robustness is achieved through *robust product design* (e.g. Phadke 1989; Taguchi and Clausing 1990; Fowlkes and Creveling 1995; Vucjkov and Boyadjieva 2001; Otto and Wood 2001). The design engineer specifies settings of controllable variables that drive the mean response to a desired value, while simultaneously reducing variability around this value. It is rare that both of these objectives can be met simultaneously; the designer must make an artful compromise. Taguchi defined the signal-to-noise ratio heuristics that simplify this task. He further simplifies the task of designing treatments by providing another innovation, the specifications of a comprehensive set of pre-defined treatments in the form of orthogonal arrays, also called *Taguchi arrays*. These arrays are sample subsets of the entire set of experiments from which one can predict the outcome of any experiment. *These arrays vastly reduce the number of alternatives that need to analyzed and considered. It is a breakthrough complexity-reduction mechanism.*

We saw in Sect. 3.1, the number of alternatives rises as the exponent of the number of factors, and by including uncertainty, the complexity escalates further. Table 3.9 shows the growth of combinatorial complexity and the dramatic efficiency of the Taguchi arrays sampling. *Using these arrays, the one can predict the results of any other alternative in the entire space*. For example, with 10 variables,

Table 3.9 Sampling efficiency of Taguchi arrays

Total variables	Mix of variables	At number of levels	Number of combinations	Sufficient sample size	Sampling efficiency %
4 6	4 6	3 levels 5 levels	$3^4 = 81$ $5^6 = 15,625$	9 25	88.889 99.840
8 = 1 + 7	1 7	2 levels 3 levels	$2^1 + 3^7 = 2189$	18	99.178
10 = 1 + 9	1 9	2 levels 4 levels	$2^1 + 4^9 = 262,146$	32	99.988
11 15	11 15	2 levels 2 levels	$2^{11} = 2048$ $2^{15} = 32,768$	12 16	99.414 99.951
16 = 3 + 13	3 13	3 levels 2 levels	$2^3 + 3^{11} = 1,594,331$	36	99.998
13 = 1 + 12	1 12	2 levels 5 levels	$2^1 + 5^{11} = 48,828,127$	50	99.999

Table 3.10 Nine experiments suffice to predict the full factorial of 81 experiments

	Variables
$L_9(3^4)$	$(C1,\ C2,\ C3,\ C4)$
alternative 1	$(C11, C21, C31, C41)$
alternative 2	$(C11, C22, C32, C42)$
alternative 3	$(C11, C23, C33, C43)$
alternative 4	$(C12, C21, C32, C43)$
alternative 5	$(C12, C22, C33, C41)$
alternative 6	$(C12, C23, C31, C42)$
alternative 7	$(C13, C21, C33, C42)$
alternative 8	$(C13, C22, C31, C43)$
alternative 9	$(C13, C23, C32, C41)$

one of which is specified at 2 levels, and 9 of which are specified at 4 levels, a sample set of 32, as defined by a Taguchi array, suffices to predict outcomes over the entire space of 262,146. Sampling efficiency is, therefore, $1-[(32)/(262,146)] = 99.998+\%$. We will use this approach to address the combinatorial complexity of alternatives in Chap. 9. Table 3.9 presents more detail.

Consider the first entry in Table 3.9. In this case, we have 4 controllable variables at 3 levels each. The full factorial set consists of $3^4 = 81$ experiments. However, with a sample of 9 experiments, we can predict the outcomes for the entire 81 experimental constructs (Table 3.10). The sampling efficiency is $[1-(81/9)] = 88.889\%$. This sample of 9 experiments is known as the $\mathbf{L_9(3^4)}$ array. **L** stands for Latin square, or orthogonal array, 3 is the number of levels of the variables, and the superscript 4 stands for the number of variables.

These ideas have been successfully applied in a wide variety of engineering applications, e.g. Wu and Wu (2000), Clausing (1994), Phadke (1989) and Taguchi et al. (2000). Specific examples of applications are in Appendix 3.3.

Stage 4 is what this book is about. Leveraging the aforementioned achievements, we apply DOE to the practice of executive-management decisions. But we must do more than that. We must do so in a complementary, meaningful and insightful way. This is a challenging undertaking. For example, in each of the previous stages, scientists and engineers have taken the lead in the innovations of DOE. To inform them, they had the singular advantage of well-established science, its laws, and theorems for sense making, framing, and problem solving.

The practice and the discipline of executive-management does not have these advantages to nearly the same extent. The problems and opportunities facing executive-management tend to be ill structured, messy, and wicked. The field of executive-management decisions is a sociotechnical discipline. The interplay between social and technical variables create a set of unique dynamics. We must integrate and synthesize findings from thinkers in complex systems, cognitive psychology, organizational theory, economics and managerial practice. To understand and appreciate the significance of DOE in decision theory and practice, we must first develop some strong intuition about the methodology. This the subject of the remainder of this chapter.

3.4.3.1 DOE Foundations

DOE has three pillars: Analysis of Variance (ANOVA), regression analysis, and the principles of DOE (e.g. Vucjkov and Boyadjieva 2001; Wu and Hamada 2000).

ANOVA is a statistical method to quantitatively derive from a multivariate experimental data the relative contribution that each controllable variable, interaction, or error together make to the overall measured response. Common practice is to present the results of an experiment using an ANOVA table as shown below for two factors A and B (Table 3.11) (Montgomery 2001).

The second pillar is regression analysis. Regression analysis is a powerful method for model building because experimental data can often be modeled by a

Table 3.11 Analysis of Variance table for two-factor fixed effects model

Source	DOF	Sum of squares	Mean square	F
A	$a - 1$	SSA	$MSA = SSA/(a - 1)$	$F = MSA/MSE$
B	$b - 1$	SSB	$MSB = SSB/(b - 1)$	$F = MSB/MSE$
A × B	$(a - 1)(b - 1)$	SSAB	$MSAB = SSAB/(a - 1)(b - 1)$	$F = MSAB/MSE$
Error	$ab(n - 1)$	SSE	$MSE = SSE/(ab)(n - 1)$	
Total	$abn - 1$	SST		

general linear model (also called the regression model). Given response (output) $\boldsymbol{y}$ is related to p variables $x_1, \ldots, x_p$ as $\boldsymbol{y} = \Sigma \boldsymbol{\beta}_i x_i + \varepsilon$. If we have N observations $y_1, \ldots, y_N$, then the model takes the linear polynomial form of $y_i = \beta_0 + \beta_1 x_1 + \ldots + \beta_p x_p + \varepsilon_i$, with $i = 1, \ldots, N$. These N equations are then $\boldsymbol{y} = \boldsymbol{X} \boldsymbol{\beta} + \boldsymbol{\varepsilon}$ in matrix form. $\boldsymbol{X}$ is the $N \times (p + 1)$ *model matrix*. Since the experiment gives us only a sample, we want $\hat{\boldsymbol{y}} = \boldsymbol{X}\widehat{\boldsymbol{\beta}}$ and from the least squares estimate we obtain $\widehat{\beta} = (X'X)^{-1} X'y$ and using the R^2 statistic we can determine the proportion of total variation explained by the fitted regression model $\boldsymbol{X}\widehat{\boldsymbol{\beta}}$. And using the F statistic we can get the $\boldsymbol{p}$ values for the explanatory variables $x_1, \ldots, x_p$. (e.g. Vucjkov and Boyadjieva 2001; Wu and Hamada 2000). (We will discuss this topic in more detail in the Results Space, Sect. 5 and show how it is used in case study applications in later chapters.)

The third pillar is the set of principles first formulated by Fisher (1966). They are randomization, replication, and blocking. Randomization is a fundamental principle of any statistical analysis. It refers to both the allocation of experimental assets, as well as, the time and sequence in which treatments are performed. Randomization minimizes the impact of systematic bias that may exist. Replication is a distinct concept about repeated measurements of a single experiment. It refers to performing the same experiment and taking measurements for each. Replication permits us to determine repeatability and reproducibility of experiments. Blocking is a way to control for factors that are not considered critical to the response of the experiment, e.g. the time or day when the experiment is performed or the supplier of materials.

3.4.3.2 Advantages of DOE

There are many practical attributes that make DOE useful and practical. The salient ones are discussed next. *Demonstrably Effective* DOE methods are widely researched, reviewed in refereed journals, and documented in the literature. Wu and Hamada (2000) present 80 examples in their book. Frey et al. (2003) identify a very wide variety of applications in engineering and science. Antonsson and Otto (1995) use Taguchi methods of DOE in product design. Clausing (1994) based on his experience in Xerox presents examples how Taguchi methods was used at different phases of the product development life cycle. Fowlkes and Creveling (1995) do the same based on their experiences in Kodak. Taguchi et al. (2000) and Wu and Wu (2000) present data, models, and analysis from numerous successful industry experiments. Appendix 3.1 contains a sample of DOE applications in engineering with pointers to references.

Addresses Key Difficulties DOE's statistical methods overcome many difficulties facing an experimenter. The key difficulties are noise, complexity, interactions, and causation versus correlation (Box et al. 2005). Noise is a major source of uncertainty. DOE clearly separates controllable variables from uncontrollable variables (noise variables) to analyze the effect of the interactions among the controllable and aleatory variables on the output. The ANOVA table reports the factor interactions (Sect. 5.2). To address complexity, accumulated empirical evidence has distilled three very practical principles for the analysis of factorial effects; they are the *hierarchy, sparsity*, and *heredity* principles (Wu and Hamada 2000). *Hierarchy* means that the n factor effects dominate $n + 1$ factor interactions, $n \geq 1$. S*parsity* asserts that the number of important variables in a factorial experiment is small. This is important because DOE naturally reduces complexity. *Heredity* is the observation that for an interaction to be significant, at least one of its parent should be significant. For causation and correlation, "interplay between theory and practice" must come together (Box et al. 1978). Experimenters must rely on domain knowledge working principles to construct relationships among variables.

"Black-box" Approach A distinctive DOE advantage is its phenomenological approach to the analysis of systems and processes. The systems under investigation are considered as a "black box" and provided the inputs and variables are known, we can characterize the behavior of the system, *ex post*, by analyzing its output. The ability to view systems phenomenologically as a black-box combined with the ability to consider the effect of uncontrollable variables gives us the ability to make predictions about the performance of complex systems. And very significantly, we can design and build systems or processes to be robust against noise, i.e. against the effect of uncontrollable conditions. These black-box"benefits are particularly useful when the experimenter may not know or be able**,** *ex-ante*, express the behavior of the product or system with equations. Using DOE methods the experimenter can, *ex-post*, empirically derive a transfer function that represents the behavior of the system over the solution space. All these are significant and practical advantages in the study and solving challenging executive-management decision situations.

3.4.3.3 New Idea: DOE for Executive-Management Decisions

Applications of DOE for management decisions made at senior-corporate executive levels is barely visible in the literature. The role of experiments in business looks narrowly limited to product screening concepts and product testing during the early phases of product development. This is useful and traditional. To our knowledge, these methods do not explore the entire solution space under all uncertainty conditions; the large majority of "what-if" questions remain a mystery. Work on a problem of optimal scheduling of earth-moving equipment using simulations with a queueing model is reported (Smith et al. 1995). There the objective is to find the optimal setting of variables to optimize their output. They do not appear to exploit uncontrollable variables, so the system effects under uncertainty remain largely unexplored. Marketing scholars test a variety of the mix of product, price, promotion, and place (Kotler and Keller 2009) for consumer products (Almquist and Wyner 2001). But the use of uncontrollable variables is not discussed and therefore the effect of uncertainty is indeterminate. Thomke (2001, 2003a, b) argues that experiments using prototypes, computer simulations, and field tests of service offerings should be integrated into a company's business process and management system. We impose the following challenging requirements to extend and complement, to a new level, the usefulness of these ideas. The design decision alternatives must be:

- the result of explorations of the *entire* solution space anywhere in the *entire* space of uncertainty, i.e. uncontrollable conditions,
- robust under uncontrollable conditions even when these conditions are not removed,
- artefacts of technical and social processes, which have been systematically designed, and
- have been subjected to debiasing procedures.

These requirements are new and novel to executive-management decisions and address a significant void in research and the practice.

A goal of this research is to address this void. There is an abundance of research literature on DOE applications in engineering, manufacturing, and the sciences, but their absence, in managerial applications, is conspicuous. This can be explained by the fact that the traditional applications are in disciplines rooted in the sciences, engineering, or operations research. Experimenters, in these disciplines, have the benefit of the laws of physics and their analytic equations to guide them in identifying variables and framing their experiments. Students of corporate decisions do not have these advantages to nearly the same extent, which is why the science of DOE is so new and practical for executive-management.

3.4.3.4 Our Use of DOE

Our strategy is to approach executive-management decisions as engineers of complex sociotechnical systems. We use product development as analogous to engineering decisions. The former is about physical products, the latter is about intellectual artifacts. Like engineered products, executive-management decisions must be systematically planned, designed, and operated to perform to specifications. These considerations and the advantages of DOE, motivate us to use DOE to frame our executive-management decision-decisions and design decision alternatives. To address uncertainty, the DOE methodology unambiguously distinguishes controllable and uncontrollable variables. It also provides us with methods to analyze their interactions and effects on the system that generates the output.

3.5 Performance Space

3.5.1 New Strategy: Robustness, Repeatability, Reproducibility, Reflection

There are four key questions in the performance space (Fig. 3.10). One, the structure of the decision specifications. Two, the production quality of the

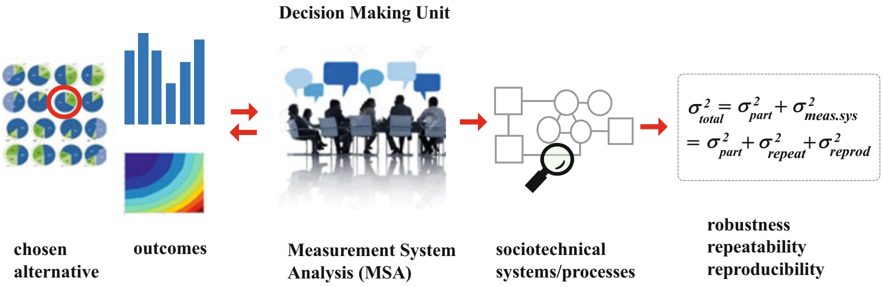


Fig. 3.10 Schematic of the performance space

sociotechnical processes that enact decision specifications, i.e. the consistency and trustworthiness of the production system. Three, quality of the input data and the forecasting quality from the DMU. And four, the ability to learn from good and bad outcomes by reflecting on the experiences throughout the life cycle. The machinery we will use to answer these questions are the ANOVA statistics, DOE main effects and standard deviations response tables, and Gage RR statistics Measurement System Analysis (MSA).

3.5.2 *Analyzing Data: Analysis of Variance (ANOVA)*

Our gedanken experiments uses of a number of controllable input-variables that interact with a number of uncontrollable variables. DMU, adjunct experts, members and their organizations identify these variables. The questions of interest are:

- which controllable variables are most important? What are the intensities of their contributions to the outcomes?
- do the controllable variables explain sufficiently the observed outputs? I.e. is there additional important information that was missed?
- are we learning from what we are doing and from the results we are getting?

ANOVA is a statistical method to quantitatively estimate the % contribution that each controllable variable, interaction, and error makes to the outputs (responses) that are being measured (e.g. Box et al. 1978; Montgomery 2001; Levine et al. 2001). The intensity of each contribution is determined by the relative contribution to the variation of each controllable variable, interaction, and error to the total variation observed from the measurements. Variation is obtained from the ***sum of squares*** analysis and they are reported in an ANOVA table (e.g. Table 3.12).

Knowing the % contribution, each controllable variable or interaction makes to the output, is important because it gives the decision-maker insight into the relative importance of each controllable factors to the output. In our field experiments (Part III of this book) a senior executive noted, "[I] always thought this factor was

Table 3.12 Example of ANOVA table

Source	DF	Seq SS	Adj SS	Adj MS	F	P
r&d	2	712	712	356	8.63	0.003
Yield	2	21,686	21,686	10,843	262.82	0.000
cogs	2	20,733	20,733	10,367	251.28	0.000
price	2	58,059	58,059	29,030	703.65	0.000
yield**cogs*	2	257	257	128	3.11	0.072
Error	16	660	660	41		
Total	26	102,107				
S = 6.42305, R-Sq = 99.35%, R-Sq(adj) = 98.95%						

important, but for the first time, I am told how important. And with numbers no less." In our Japanese experiment, we found that one variable, which the decision-maker agonized intensely about, turned out to have negligible effect on the final result. Knowing the % contribution of the interactions is significant because if the interactions are small, it informs the decision-makers that they can think about the controllable variables additively. The allocation of company resources to the implementation of corporate decisions can now be made in a way that is consistent with the contribution that a controllable factor can make to the outcome.

A typical ANOVA table is, for example, Table 3.12 taken from our case study in Chap. 6.

"Source" is the column that identifies a controllable variable, interaction, or error. The controllable variables are all present here, *r&d, yield, cogs, price*. The term *yield*cogs* is the interaction between these two variables.

DF (or *DOF*) means degrees of freedom. One can think of *DF* as the number of equations needed to solve for unknowns. The number of equations represents their capacity to solve for the variables. Similarly, *DF* represents the capacity of a variable (or an experimental design) to produce additional information. Statisticians estimate a statistic by using different pieces of information, and the number of independent pieces of information they use to calculate a statistic is called the degrees of freedom. For controllable and uncontrollable variables with *n* levels, the *DF* is *n-1*.

Sum of Squares Total (*SST*) represents the total variation among all the observations around the *grand mean*. The sum of squares, *SS*, due to a factor *A* (*SSA*) represents the differences the various level of factor *A* and the grand mean. *Seq SS* measures the *SS* when each variable is considered in the *sequence* they are listed under the column with the heading of "Source".

Adjusted SS (Adj SS) measures the amount of additional variation in the response that is explained by the specific variable, given that all other variables have already been considered. Hence, the value for the *Adj SS* does not depend on the order in which they are presented in the *Source* column. The *Seq SS* and *Adj SS* are identical when the model is *balanced*. Balance is a combinatorial property of the model. For any pair of columns in the array that is formed for all the experiments, all factor-level combinations occur an equal number of times (e.g. Wu and Hamada 2000). By definition, orthogonal arrays are balanced, so the *Seq SS* and the *Adj SS* columns display identical values. This will be the case for all our experiments because we will be using orthogonal arrays exclusively. Our orthogonal arrays are always balanced. We note that the *SS's* for *yield*cogs* is small relative to the other variables. Its contribution to the outcomes is very small, 227/102,107 = 0.0022.

(*Adj MS*) = (*Adj SS*)/(*DF*) for a particular variable. For example for *r&d, Adj MS* = ½ × *712*. It is the variance of the measurements for a particular variable. We obtain its % contribution through a simple division of its *Adj MS* by the sum of the individual elements.

F(A) is: *F(controllable variable A) = (Adj MS of variable A)/(Adj MS error)*. This is also called the *variance ratio* and used to test the *statistical significance* of the variable A.

- For $F < 1$, the experimental error is bigger than the effect of the variable. The effects of the variable cannot be discriminated from the error contribution. The particular variable is therefore statistically insignificant as a predictor of the output. In Table 3.12 all variables are statistically significant with $p < 0.05$, they are *good* predictors of the output. If $p << 0.05$, then the variables are *strong* predictors of the output being studied.
- For $F \sim 2$, the controllable variable has a modest effect on the output.
- For $F > 4$, the controllable variable effect is much stronger than the effect of error and is therefore statistically significant and a good predictor of the output.
- For $F > 5$, the controllable variable effect is dominates the effect of error and is therefore statistically very strong predictor of the output.

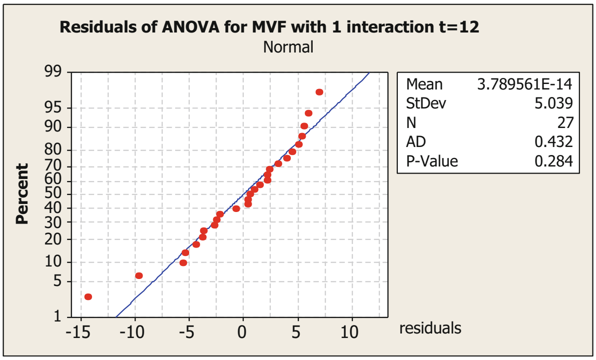
R-Sq (R^2 or R-squared) is *the percent of variance explained* by the model. It is the fraction by which the variance of the errors is less than the variance of the dependent variable. Or, how good the fit, of the data points is for the regression line, or how well the controllable variables explain the outputs.

R-Sq(adj) or (R^2 adjusted) is the *standard error of the regression* rather than the standard deviation of the errors. *R-Sq(adj)* compares the descriptive power of regression models that include many predictors. Every predictor added to a model increases *R-Sq* and never decreases it. Adding more **useless** variables to a model, *R-Sq(adj)* will decrease, but adding **useful** variables, adjusted R-squared will increase. In our example, it does not appear that we have useless variables.

It is good practice to examine the *residuals* from the ANOVA model to convince ourselves that they are random normal with a mean of zero. A residual is simply expressed by the equation: *residual = [(observed value)−(predicted value)]*. Ideally the residuals are always zero, but there are always aleatory factors that cause observed values to diverge from predictions. Although their presence is inevitable, we would like them to be randomly distributed. This indicates that they are not carriers of input information from factors that have not been considered. Random normal residuals increase our confidence in the validity of the choice of controllable and uncontrollable variables, as well as, how they represent the sociotechnical system behavior.

Showing the residuals graphically is a simple and effective way to analyze the distribution of the residuals. We like the half-normal plot as in the plot of residuals

Fig. 3.11 A statistically significant residual plot



in Fig. 3.11. The x-axis shows the range of the values of the residuals. The sloping diagonal line is a logarithmic plot of a cumulative normal distribution with mean zero and standard deviation (SD) of the residuals. The dots are the residuals. If all the residuals lie on the line, they are normally distributed. Or if they are *close*. *Close* can be determined by the “fat pencil” test. In other words, if the residuals are covered within the diameter of a “fat pencil,” the distribution can be judged to be normal. This is MIT’s Roy Welsch “fat-pencil” test. The box in the chart shows some statistics that can tell us more definitively whether the residuals are normal with mean zero. In this case, for a sample of 27 numbers, the mean is 3.789561×10^{-14}, which is a very small number—close to zero. The standard deviation is acceptable given the Anderson-Darling (AD) statistic, we reject the hypothesis that they are not random. The value $p > 0.05$ supports this fact. We conclude that the residuals are normal. This may appear confusing, but it becomes clearer when one considers that the null hypothesis H_0 is that the residuals are normal, so that is $p > 0.05$.

3.5.3 Analyzing Performance: Response Tables

From the ANOVA data, we can determine whether we have chosen the appropriate variables and the extent to which they contribute to the intended outcomes. In addition, we know that at the scale they are chosen, whether we have not omitted any other key variables. The next questions are:

- Can we predict the outcomes of designed alternatives? For any “what-if?” question. For any alternative, under any uncertainty conditions? If so, how?

The answers are affirmative and we will show how this is accomplished. In addition to the ANOVA table, using our orthogonal arrays, we are able to obtain the Response Tables and the Tables for the standard deviations. For example Table 3.13, which we will discuss in detail in Chap. 6. Here we sketch how the Response Tables are used to design an alternative.

Table 3.13 Response tables for variables' means and standard deviations

Response table-means					Response table-St deviations				
Level	r&d	Yield	*cogs*	Price	Level	r&d	Yield	*cogs*	Price
1	759.7	720.9	782.6	690.7	1	105.1	102.0	104.2	98.8
2	746.4	749.4	753.4	753.4	2	100.8	100.2	104.4	101.9
3	742.0	777.9	712.1	804.0	3	101.2	104.8	98.3	106.3
Delta	17.8	57.0	70.6	113.3	Delta	4.32	4.63	6.11	7.52
Rank	4	3	2	1	Rank	4	3	2	1

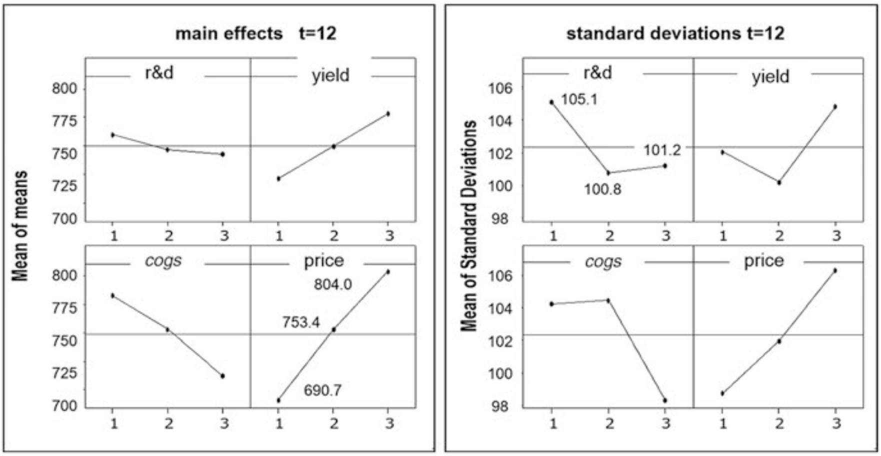


Fig. 3.12 Graphs of response tables for variables' means and standard deviations

We focus on the LHS of the Table 3.13, the response table for the output Market Value-of-the-Firm, MVF. Under the "Level" column, listing levels "1", "2", and "3" for the controllable variables are shown. For example, *cogs* at level 2 is determined to have value 753.4. In this example, level 2 is the existing operating condition, the (BAU) level. The controllable variables are expenditures for *r&d,* manufacturing *yield,* cost to the company of the goods sold *(cogs)*, and *price* at which they are sold.

Delta is the maximum distance between any two levels; for example for the variable *yield*, 70.6 = (782.6−712.1). *Rank* is simply an ordering of *Delta* from high to low. Rank tells us which variable has the greatest influence on the output. In this case, it is *price* with a *Delta* = 113.3.

The standard deviations are calculated from the output data, for each variable at a level, to obtain the response table for the standard deviations. We get the RHS plots in Fig. 3.12.

We can design alternatives to meet any specification, by inspection of Table 3.13 data on the RHS and LHS. For example, suppose that *r&d* is not a problem, and the objective is to maximize *yield*, have the lowest *cogs,* and raise *price*; the alternative can be specified as:

- ***C((r&d(level-1), yield(level-3), cogs(level-3), price(level-3)),*** or more simplified as
- *(r&d-1, yield-3, cogs-3, price-3),* or even simpler as *C(1,3,3,3).*

  In this case *price(level-3)* produces a salutary positive effect on profit—the higher price combined with the lower cost, i.e. hitting both the "top-line" and the cost-line. This is an aggressive strategy. But we must ask: what is the risk? The ***C*** *(r&d-1, yield-3, cogs-3, price-3)* strategy implies *standard deviations* ***SD****(r&d-1, yield-3, cogs-3, price-3)* for those controllable variables. In other words, the decision specification *C(1,3,3,3)* will result in the highest standard deviations for controllable levels *r&d*, *yield* and *price* (right hand panel of Fig. 3.12). Higher standard deviations means a large spread in the outcomes. This means more risk.

Suppose we design a decision-specification that is less aggressive, i.e. C *(2,3,3,2).* We elect *r&d-2* because from the upper left hand panel of Fig. 3.12, we observe that the impact of *r&d* is low on the outputs. This is shown by Delta in the *r&d* column of Table 3.13. We keep *price* at level-2 because we choose to only have lower *cogs* and exert its effect on profit and *cogs* has the lowest SD. Compared to the *C(1,3,3,3)* alternative, the standard deviations, for *r&d* and *price,* are less in alternative *C(2,3,3,2).* Alternative *C(2,3,3,2)* is less risky than *C(1,3,3,3).* It is robust, which is a less risky decision and which still optimizes *yield* and *cogs.* It is the better decision.

Using orthogonal arrays, we can predict the outcomes of any ***specific alternative*** under any ***uncertainty condition***, e.g. for the Business-As-Usual (BAU), the do-nothing-different, behavior of the firm, under *nine different uncontrollable* (uncertainty) conditions. We show DOE predicted output of *market-value-of-the-firm (MVF)* for BAU under these nine uncontrollable uncertainty conditions (Fig. 3.13). As expected the BAU in the *current environment* is bracketed by the best *SD (2 2,1)* and *worst environments SD(1,1,2).* (This example comes from Part II.)

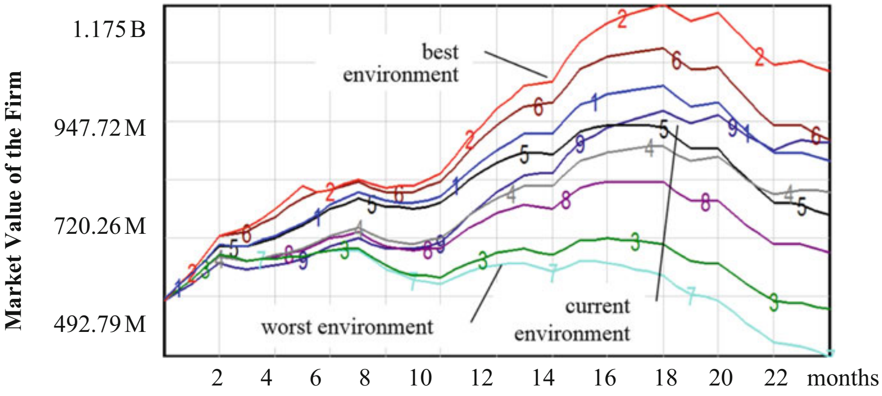


Fig. 3.13 Predicted MVF for *BAU(2,2,2,2)* under nine uncertainty conditions

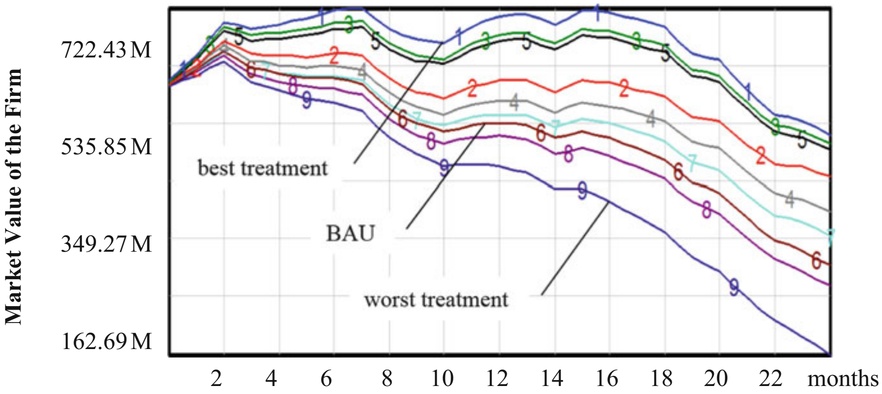


Fig. 3.14 Predicted market-value-of-the-firm using nine alternative decision alternatives, including BAU, under single worst uncertainty condition

Using orthogonal arrays, we can predict the outcomes for a ***range of alternatives*** under a ***specific condition***. For example, we now illustrate the case of *nine* alternatives (including *BAU*) under a *single* environment—the worst. The DOE predicted output of nine alternatives for raising the *market-value-of-the-firm (MVF)* under the worst environment *SD(1,1,2)* shown in Fig. 3.14. The best alternative is specified as *C(1,3,1,3*) because it maximizes MVF. The worst alternative is specified as *C (3,1,3,1)* it produces the lowest *MVF*. As expected the BAU is bracketed by the best and worst alternatives. (This example comes from the case studies in Part II).

We find the transfer function and can also plot the graphical relationship between two interacting variables, e.g. Fig. 3.15.

Firmvalue(12)=659–6.27r&d+34.7yield–33.9*cogs*+56.4 price–3.43yield**cogs*

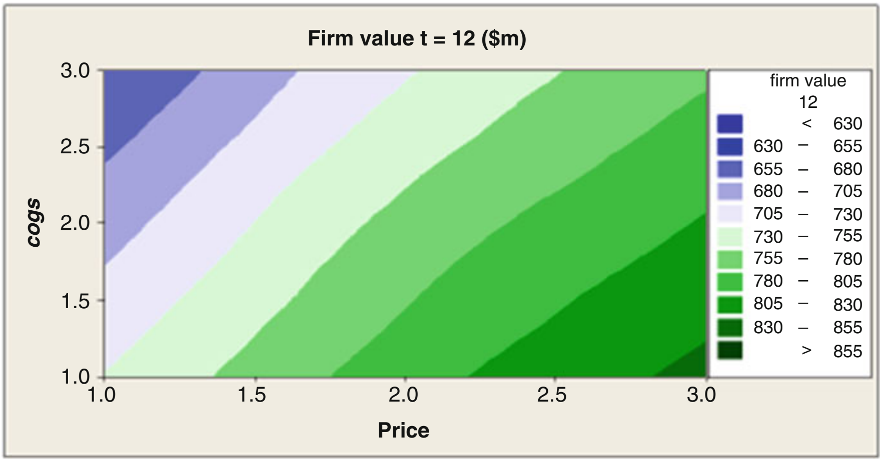


Fig. 3.15 Surface plot of predicted market-value-of-the-firm using as function of *price* and the *cogs* (cost of goods sold)

3.5.4 *Analyzing Sociotechnical System Quality: Gage R&R*

The discussions in Sect. 5.1 have centered on the use of DOE methods to construct decision alternatives (DOE experiments/treatments) and predict performance. Experiments depend on data. How do we know the data are “good enough”? What is good enough? Why or why not? What can we learn from this additional knowledge? Why is it important? These are the questions we explore and discuss in the context of executive-management decisions. The discussions are grounded on the science and practice of Measurement Systems Analysis (AIAG 2002).

Good-enough means that the data are *accurate* and *precise*. “Accurate” means that the data is located where it is supposed to be relative to a reference value. The reference point is the intended output. “Precise” means that repeated readings under different conditions produce data are close to each other. Accuracy and precision can be determined by the statistical property of variation. Given that variations will be present, we need to know the sources of these variations. Knowing the origins of variations, we can think about how to take corrective action, if necessary. Who and what are contributing to these variations? The variation can be inherent in the data itself, the people who are taking the measurements, or they can be due to measuring instrument quality. Gage R&R (Gage Repeatability and Reproducibility) methods (e.g. Breyfogle 2003; Montgomery 2001) from Measurement Systems Analysis (e.g. AIAG 2002; Creveling et al. 2003) give us the machinery to perform for this analysis.

The genesis of Measurement System Analysis (MSA) is in manufacturing for the production of physical objects. MSA is a statistical method to assess the performance of a *measurement system*. The concept reflects its roots in manufacturing. A **measurement system** is defined as:

- “the equipment, fixtures, procedures, gages, instruments, software, environment, and personnel that together make it possible to assign a number to measured characteristic or response (Creveling et al. 2003)”.

Gage R&R is a MSA method to study the components’ variability in a measurement system (e.g. AIAG 2002; Montgomery 2001). Gage R&R is a widely used in engineering and production management (Wang 2004; Foster et al. 2011). We will show that the concept of a measurement system, conceptually remapped to the engineering of executive-management decisions is very meaningful and useful. All this is somewhat abstract, so we will sketch the key ideas using Fig. 3.16, explain the statistics, and discuss the mapping to decision engineering. To make these ideas more intuitive, we begin by discussing the Gage R&R idea in a hypothetical manufacturing production environment.

Consider the manufacturing line of bolts (Fig. 3.16) as a direct analogy of a DMU forecasting outputs of decision alternatives, and the orthogonal arrays as DMU productions. The measurement in question is the diameter of the bolts. Variation in the diameter is an indicator of the quality of the production system, the people, and the measurement instruments. These variations need to be

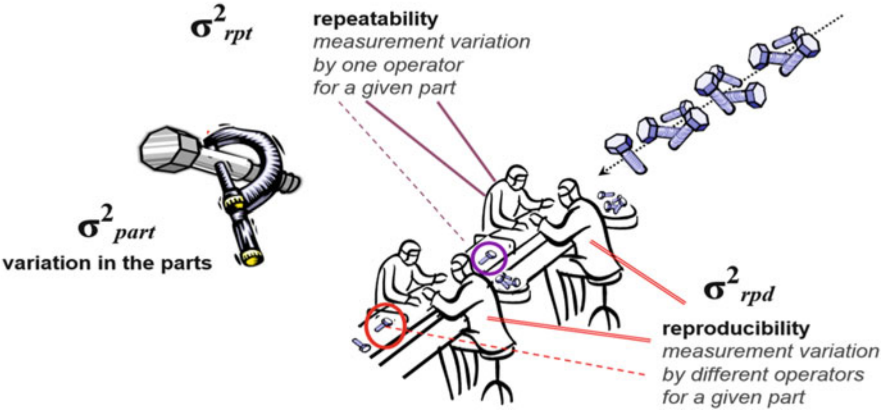


Fig. 3.16 Sources of variability for measurements

understood and interpreted to determine the quality of the ***production system.*** There are three sources of variations, they are:

- *Part-part* is the variability in measurements across different parts from the same batch. In this example, this is the variation in the diameter measurements of the bolts. Ideally, we want this variation to dominate all the remaining variations. In other words, the variations introduced by people and the measuring instruments are to be small.
- *Reproducibility* is the variability in measurements obtained when parts are measured by different operators. That is to say, for a given part, are different people making the measurements able to reproduce a measurement?
- *Repeatability* is the variability in measurements obtained when parts from the same batch are measured by the same person, i.e. is an operator able to repeat the measurement value for a given bolt?
- *Gage R&R* is the sum of reproducibility and repeatability. This sum is the overall measurement variation.

The sources of variations in measurements are mathematically related as shown in Fig. 3.17.

A simple sum expresses this relationship.

$$\sigma^2{}_{total} = \sigma^2{}_{part} + \sigma^2{}_{meas.sys.} = \sigma^2{}_{part} + \sigma^2{}_{rpt} + \sigma^2{}_{rpd}. \tag{3.9}$$

3.5.5 MSA and Executive-Management Decisions

What does MSA have to do specifically, in detail, with executive-management decisions? A lot. Recall that **we consider an organization's sociotechnical**

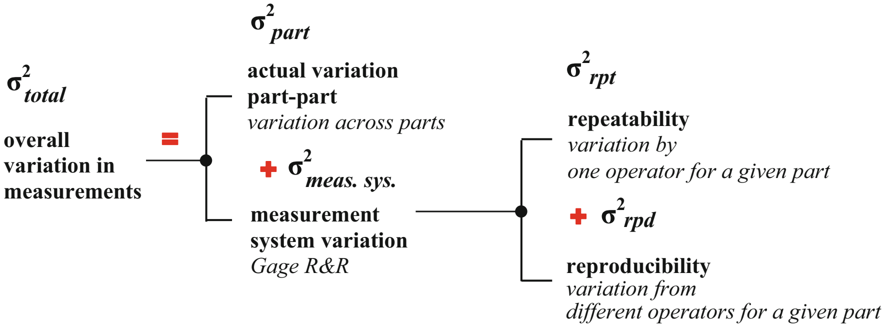


Fig. 3.17 Graphical illustration of the various variations' relationship

Table 3.14 Adaptation of gage R&R to DOE-based decision analysis

Manufacturing model	Mapping	Our DOE decision analysis paradigm
Parts	←→	Decision alternatives
Measurements	←→	Forecasts of decision alternatives' outcomes
Operators	←→	Participants making the forecasts

systems as a decision factory, a manufacturing production system. A *decision* specifies *how* an organizations and associated sociotechnical systems must behave so they will generate the intended outcomes in the *outcomes space*. Which is why we consider organizations as production or manufacturing systems. They are factories of sociotechnical systems and machinery designed to recognize meaningful opportunities and problems, to analyze, engineer solutions, execute, and gain additional knowledge from its outputs. We measure the quality of this decision-specification execution system using Gage R&R.

The analogy is an isomorphic mapping (Table 3.14). The fidelity of the analogy is remarkably high. Decision specifications, the intellectual non-physical artefact, is mapped to parts, physical artefacts. Measurements become forecasts of decision outcomes. Operators who are doing the measuring with instruments are mapped to the DMU who are making the forecasts of outcomes.

ASQC and AIAG provide guidelines for measurement system statistics (AIAG 2002). A useful and accepted AIAG guideline is that the Gage R&R variation should be <10% and the part-part should be >90%. This makes sense for a mass production environment where the ideal is to have identical parts, i.e. without any variations so that the variations are all isolated in the measurement system. Specifically, the AIAG and ASQ guidelines stipulate that $\sigma^2_{part} = 90\%$ and that the rest be equally divided between σ^2_{rpt} and σ^2_{rpd}, i.e. 5% each. The 90-5-5 are indicators of a quality manufacturing line (Fig. 3.18). It is important to note that these guidelines are based on decades of manufacturing experience of American industry, which without exaggeration has produced billions of parts. The heuristic has a strong and a long history of empirical evidence. Therefore, we can, with confidence, adopt this quality heuristic for measuring the executive-management sociotechnical systems.

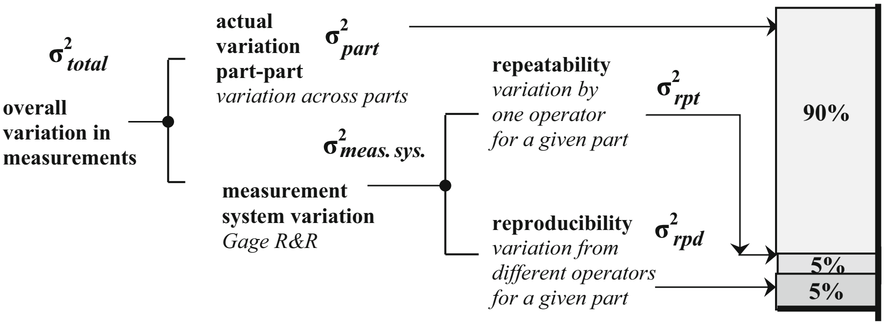


Fig. 3.18 AIAG recommended distribution for measurement system quality

However, this 90-5-5 GR&R distribution sets a very high bar for executive-management decisions. This is discussed next.

The AIAG and ASQ standard is defined on the assumption that the parts are identical, but because people, technical systems, and processes are imperfect, there are variations in the final measurement. MSA seeks to determine the sources of these variations to enable management to take corrective action (Eq. 3.9). Our approach reverses the logic. We start with "parts", i.e. gedanken experimental results. Unlike manufacturing, these "parts" are specifically designed to be different. We then ask, does our measurement system detect this intentional variation? In other words, is σ^2_{part} *very large* as it must be by design? And are σ^2_{rpt} and σ^2_{rpd} small, i.e. the DMU members and their sociotechnical systems capable? But we are not satisfied with this only.

As another test of the DMU and their sociotechnical capability of producing quality forecasts, we designed special *verification* experiments: does our measurement system detect the variations of a DMU member for different forecasts? And does the measurement system pick the variations from different DMU members for the same forecast? In other words, do σ^2_{rpt} and σ^2_{rpd} data reveal these facts? If the data to all these questions support repeatability and reproducibility, then there is support for the quality of the sociotechnical system.

3.5.6 Reflection and Learning

Reflection is thinking about experiences *ex ante*, *ex post* or *ex inter*, directed at learning for better decisions for the next decision situation and experience. To us "experiences" are the DMU's work leading to the outputs and *ex post* reviews, as well as, discussions of the in-process outputs and end-process outputs. "Reflection is not a casual affair" (Rogers 2002, 855). It is not wooly or undisciplined rumination. "Reflection is a systematic, rigorous, way of thinking, with its roots in scientific inquiry" (Rogers 2002, 845).

Why reflect at all? Reflecting is an inherent human quality—to learn from experiences, to improve subsequent experiences. Knowledge must be experienced. Survival drives this instinct. The possibilities of improved effectiveness are strong and natural drivers that motivate reflection and learning. Schön's (1983) segments reflection into reflection-**in**-action and reflection-**on**-action. Reflection-in-action is learning by doing, *ex inter* learning. Reflection-on-action is *ex post* learning. Reflection is not navel-gazing, it requires systematic disciplined processes, close cousins of the scientific method. Dewey (1933), Rogers (2002) and Moon (2013) discuss various strategies for systematic reflection. Reflection can be taught. While solitary reflection is useful, carried out in a sociotechnical community environment is far more effective. It stimulates personal and organizational learning (e.g. Kolb 1984, McLeod 2013).

Without reflection, two malevolent laws of organizations begin to take root. Phil Kotler (1980) names them as the Law of Slow Learning and the Law of Fast Forgetting. Without reflection, people increasingly do things by rote, numb to the changes and uncertainties in the exterior environment. As a result, they add less and less to the organization's body of effective knowledge. This is organizational slow-learning. Lack of reflection makes people think less and less about business processes and forget that processes were predicated on epistemological and ontological assumptions about their effectiveness. This is organizational fast-forgetting. He, as does Kolb (1984), argues that these two laws are perniciously mutually reinforcing in the absence of reflection.

3.6 Commitment Space

The hallmark of decisive executive is their ability to cross the Rubicon. Executives must commit themselves to a course of action (Fig 3.19). In Sect. 1.62 we discussed decisiveness as a principle of executive decision-making. And in Appendix 1.5 we summarized the 15 types of indecisiveness and indecisions. Our paradigm, facilitates commitment, by making the outcome more immune to uncontrollable conditions. Besides decisiveness, commitment requires the following:

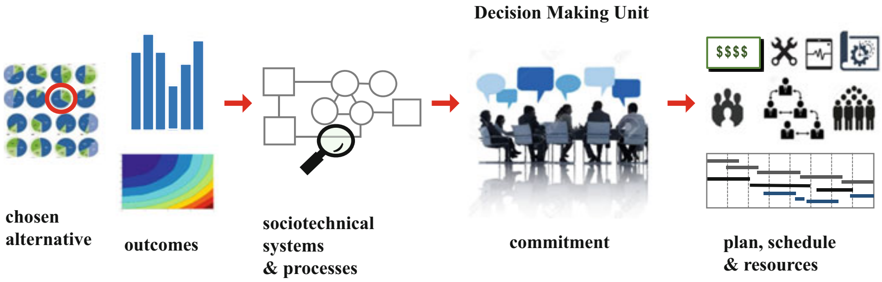


Fig. 3.19 Schematic of the commitment space

- Concurrence from the executive to whom the executive must answer to.
- A Plan with milestones and work products that mark the achievements of milestones.
- Consistent with robustness, it must contain risk analyses that include uncontrollable variables.
- Resources, funds, physical assets (plant, equipment), and people to execute.
- Interlock with organizations for which there are upstream and downstream dependencies.
- Required financial information.

3.7 Chapter Summary

- The processes of executive-management decisions take place in five sociotechnical operational spaces. They are the Problem Space, the Solution Space, the Operational Space, the Performance Space, and the Commitment Space. Collectively, they form the five phases of the executive-management decision life-cycle all directed at the singular goal of designing robust decisions and sociotechnical systems that support its implementation and execution.
- The Problem Space deals with sense-making of the decision situation triggered by a problem or opportunity. The trigger, frequently as a surprise, signals the presence of a new decision situation. The situation needs to be interpreted for significance and meaning. The operating principle is abstraction to reduce cognitive load of the DMU. The principal processes are to understand the decision situation using an uncomplicated, but accurate, representation of the problem/opportunity. The goal is to cultivate complementary and consistent mental models by the DMU. This enables the appropriate framing of the decision situation and the specification of goals and objectives.
- The Solution Space concentrates on the design of decision alternatives. This is a very challenging and creative part of the decision life-cycle. The operating principle is to make the goals and intended outcomes actionable by the sociotechnical organizational systems. The goals are to design actionable solutions that are robust. The design processes must address the entire set of possibilities in the solution space, under any uncertainty conditions.
- To systematically design alternatives requires identifying the essential variables. Essential variables are either managerially controllable variables or managerially uncontrollable variables. Managerially controllable variables are those which directly influence the intended outcomes and which can be manipulated by executives. Uncontrollable variables are those that managers cannot control. The uncontrollable variables shape the uncertainty conditions under which the decision will operate. Uncontrollable variables must not be omitted because they interact with the controllable variables to affect intended outcomes.
- The normative axiom of “There Is No Free Lunch” applies to the controllable variables. The spirit of this axiom must be reflected directly in the set of

controllable variables. Otherwise, exercising all controllable variables to the fullest benefit would entail no cost and there would be no need to make decisions.

- A fundamental sociotechnical process is debiasing forecasts and aligning mental models. We prescribed a social process that includes counter-argumentation that encourages dissent based on information, not actual numerical quantities. The process results in DMU members' mental models that are complementary, more complete, and aligned. The goal is not for the DMU to have identical mental models. The process helps improve the decision deliberations throughout the decision life cycle.
- The Operations Space deals with the execution of decision-specifications. The operating principle is to enable unconstrained explorability, i.e. the ability to explore the entire solution set under any uncertainty condition. We can estimate the performance of alternatives by experiments to reveal a phenomenological model of the sociotechnical system. This strategy is grounded on the DOE methodology. The experiments are *gedanken* experiments. In our paradigm, the fundamental objective of decisions is robustness.
- The Performance Space concentrates on the quality of the implementation and execution of the decision specification. Recall that we consider the sociotechnical system, which implements and executes decisions, as a production system, the manufacturing arm. The key measurements are robustness, repeatability, and reproducibility. The measurement science is Gage repeatability, and reproducibility (Gage R&R).
- The Commitment Space addresses the need for a decisive executive that will commit scare resources at the time decision making is required.
- The innovation of our operational approach is to depart from conventional strategies. We eschew the traditional way of thinking, which insists on *ex ante* analytic models. We do not presume to know *a priori* the explicit mathematical equations that represent the decision's sociotechnical machinery. We adopt a fresh strategy. We use *gedanken* experiments rather than equations and probabilities to infer a **phenomenological** representation of the system. The inference is drawn from the results and data of the *gedanken* experiments. The system behavior is revealed *ex post*, not specified *ex ante* using equations about presumed system behavior. This is a phenomenological approach. Phenomenology is a scientific methodology to describe and explain observations. Appearance reveals and explains reality.

Appendix 3.1 Keeney's Techniques for Identifying Objectives

The table below is taken directly from Keeney's (1996) article on this subject. This is not a recipe for finding the objectives for a decision problem, but it is an approach to explore the thinking of the decision maker.

Type of Objective	Questions
Wish list	• What do you want? What do you value? • What should you want?
Alternatives	• What is the perfect alternative, a terrible alternative, some reasonable alternative? • What is good about each?
Problems and shortcomings	• What is right or wrong with your organization? • What needs fixing?
Consequences	• What has occurred that was good or bad? What might occur that you care about?
Different perspectives	• What are your aspirations? • What limitations are placed upon you?
Strategic objectives	• What are your ultimate objectives? • What are your values that are absolutely fundamental?
Generic objectives	• What objectives do you have for your customers, employees, your shareholders, yourself? • What environmental, social, economic, or health and safety objectives are important?
Structuring objectives	• Follow means-ends relationships: why is that objective important, how can you achieve it? • Use specification: what do you mean by this objective?
Quantifying objectives	• How would you measure achievement of this objective? • Why is objective A three times as important as objective B?

Appendix 3.2 Smith's Approach to Conceptualizing Objectives

The table below is an extension from Smith's article (1989) on conceptualization of objectives. All eight conceptualizations are different types of "gaps." To show what we mean, we restate his examples as a "gap statement." Discovering corporate gaps is where we begin in our field experiments with our executive interviews. Simultaneously we try to learn as much as possible about the conditions and historical situations that led to these identified gaps. From this we distill corporate objectives we want to study. Then the background of the gap becomes what we call "the decision situation," which gives the context of the corporate problem and objectives senior executives want to achieve. This is a way to **frame** a decision situation.

Example	Description	Conceptualization	Gap Statement
"Sales are $150,000 under budget."	Comparing existing and desired states	Gap Specification	Same
"It‘s tough competing, given our limited experience in this market."	Identifying factors inhibiting goal achievement	Difficulties and Constraints	"The differences between our experience and what is required are ...

(continued)

Example	Description	Conceptualization	Gap Statement
"We need to convince management that this is a profitable market."	Stating the final ends served by a solution	Ultimate Values and Preferences	"We need to show +x % more profitability to our management."
"This year's sales target of $5.2 million must be met."	Identifying the particular goal state to be achieved	Goal State Specification	"Current sales are $x M, a shortfall of $Y M from target of $5.2 M."
"We have to hire more salespeople."	Specifying how a solution might be achieved	Means and Strategies	"We are short of +xx sales people."
"The real problem is our ineffective promotional material."	Identify the cause (s) of the problematic state	Causal diagnosis	"Our promotional material is ineffective in the following areas because ...."
"Our product is 6 years old; our competitors out-spend us on advertising; etc."	State facts and beliefs pertinent to the problem	Knowledge specification	"Our product is 6 years old; competitors out-spend us on advertising by x% per y unit sales ...; etc."
"Since the market isn't growing, we're in a zero-sum game with our competition."	Adopting an appropriate point-of-view on the situation	Perspective	"We need to gain share of x% from our competitors ..."

Appendix 3.3 Eight Analytic Structures

von Winterfeldt and Edwards (2007) specify eight mathematical structures to model the system behavior to predict and analyze variables that have an influence the outputs. These approaches are not limited to mathematical structures. They are also very effective in qualitative analyses as well. Our descriptions that follow are presented in this spirit.

Means-Ends Networks

This process can start at any level of a problem or opportunity, say at level n. To build the means-ends chain, ask the question: "why?" *Viz.* why is this objective important? Itemize the reasons and now you have the $n - 1$ level of the network. Next from the n level, ask the question: "how?" Namely, how will this objective be accomplished? Itemize the answers and now you have the $n + 1$ level of the network. Proceed iteratively, up or down or both, until you have found the appropriate level at which to address the opportunity/problem. Clearly the process can produce very complex networks.

Objectives Hierarchies

Objectives hierarchies are simple two-column tables. On the left hand column list your itemized list of objectives. On the right hand column, for each objective, list the measures to achieve the objective. For example, for the objective to: "Improve customers' service economics", the right hand column can show, for example, "reduce consulting fees." Or "provide the first 50 h of consulting for free". Complete the table and you have an objective hierarchy.

Consequence Tables

Consequence tables are also two column tables. On the left hand side list the fundamental objectives and the right hand side specify the measures. (This is almost identical to Objective hierarchies.) Complete the table in this manner and you have a consequence table.

Decision Trees

Decision trees begin with a *decision node*, N_0, normally depicted by a square. Emanating from the N_0 node are the various links identifying alternative decisions, say d1, d2, and d3, that can be made. Each of these links terminate in a *chance node*, normally identified by a circle. To each d1, d2, d3 link, a probability can be assigned. Links emanate from each of these circles to potential outcomes with an associated payoff. Suppose that from d1 we have 2 links to outcome o11 and o12; from d2 we have outcomes 021, 022, and 023. And from d3, we have outcome o31 and o32. The expected value of the outcome o32 is the product of the probability of d3 and payoff o32. This a schematic description of a decision-tree of 3 layers. A decision tree becomes very bushy when it has many levels.

Influence Diagrams

Influence diagrams are the inventions of Howard (2004) who coined the term "decision analysis". An influence diagram is graphical representation of the decision in question. The diagram is represented with the following elements: *decision* nodes as rectangles, the *outcomes* and their value represented as octagons or rectangles with rounded corners, and *functional arrows* to show the *variable*-nodes on which values depend. Clearly, a functional arrow must exist between a decision (rectangle) and outcomes (octagon or rounded-corner rectangle). Using these geometric illustrations a network that represents the causal relationships of a decision can be illustrated.

Event Trees

Event trees are built from the "bottom up". The consequences of an event are identified in a step-wise feed forward successively branching out as in the decision tree approach. Event trees are often used to determine probabilities of failures and other undesirable events. This a "bottom up" approach.

Fault Trees

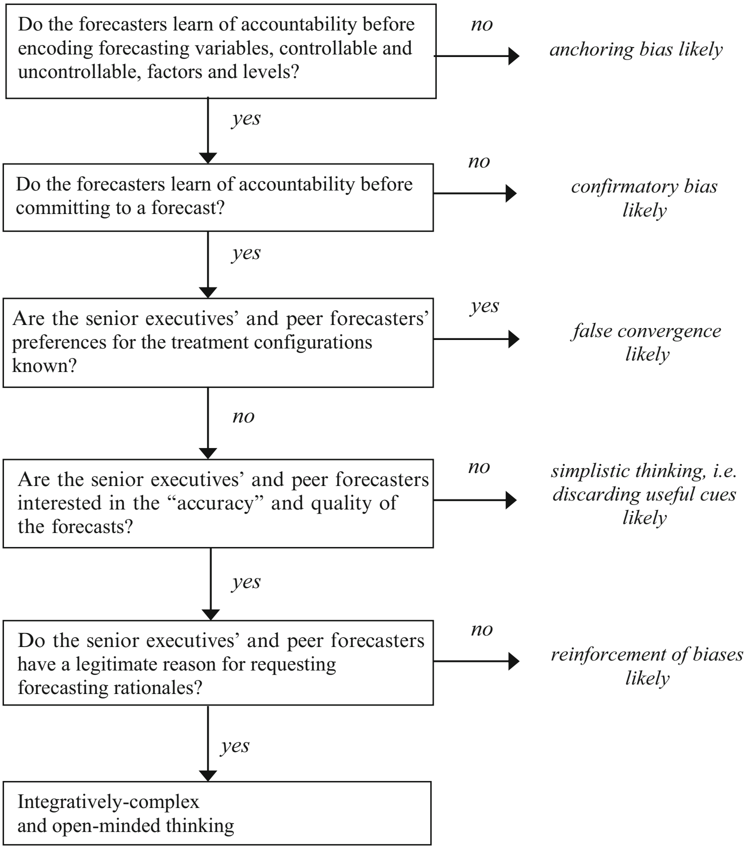
This is a so-called "top down" approach. This is the opposite approach of event trees, which uses a "bottom-up approach". The idea of a fault tree is to start with a *fault*. A fault can be understood as an engineering failure or a serious deleterious sociotechnical outcome. The fault tree is constructed starting with fault and identifying the reasons leading to the fault. Reasons can be conjunction or disjunction. The process proceeds iteratively down using the same logic.

Belief Networks

A belief network is a directed acyclic network/graph, with an associated set of probabilities. The graph consists of nodes and links. The nodes represent variables. Links represent causal relationships between variables. In general, a belief in a statement/hypothesis S, involving variables, that depend on some prior related knowledge K. Our belief in S, given we know something about K, forms a belief function P(S|K). Bayes theorem give us a way to determine the value of this expression. Thus associated probabilities and prior knowledge gives us a way to reason about uncertainty. Modeling a problem this way involves many nodes that are linked, forming a Bayesian Belief Network.

Appendix 3.4 Debiasing Logic

This debiasing procedure is from Lerner and Tetlock (2003).



Appendix 3.5 Examples of Engineering Applications Using DOE

Engineering problems	Reference
• Chemical vapor deposition process	Phadke (1989)
• Tuning computing systems	Phadke (1989)
• Design of accelerometer	Antonsson and Otto (1995)
• Paper feeder w/o misfeeds and multifeeds	Clausing (1994)
• Waste water treatment plant	Clemson et al. (1995)
• Camera zoom shutter design	Fowlkes and Creveling (1995)
• Capstan roller printer	Fowlkes and Creveling (1995)
• Numerically controlled machine	Wu and Wu (2000)
• V-process casting Al-7%Si Alloy	Kumar et al. (2000)
• Development of a filter circuit	Wu and Wu (2000)
• Gold plating process	Wu and Wu (2000)
• Optimization of inter-cooler	Taguchi et al. (2000)
• Replenisher dispenser	Taguchi et al. (2000)
• Warfare Receiver System	Taguchi et al. (2000)
• Body panel thick variation	Roy (2001)
• Tensile strength of air bag	Roy (2001)
• Electrostatic powder coating	Roy (2001)
• Chemical reaction experiment	Wu and Hamada (2000)
• Task efficiency	Wu and Hamada (2000)
• Injection molding shrinkage	Wu and Hamada (2000)
• Carbon electrodes study	Frey et al. (2003), Frey and Jugulum (2003)
• Clutch case study	Frey et al. (2003), Frey and Jugulum (2003)
• Medical serum	Nalbant et al. (2007)
• Multicycle chemical process	Montgomery (2001)
• Yield of chemical process	Montgomery (2001)
• Impeller machine for jet turbines	Montgomery (2001)
• Medical serum	Jahanshahi et al. (2008)

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Part II
Verifying Functionality

We have two goals for Part II. First is to rigorously frame the question: Does Our Paradigm Work? This the subject of Chap. 4. Chapters 5 and 6 are tests of functionality of our prescriptive paradigm. We have made an effort to make Chaps. 5 and 6 self-contained to minimize cross referencing between chapters. Part II is comprised of three chapters:

Chapter 4—Does It Work? Metrology for Functionality and Efficacy
Chapter 5—Verifying Functionality: Maximizing Value of the Firm (MVF)
Chapter 6—Verifying Functionality: Maximizing Annual Operating Income

Chapter 4
Does-It-Work? Metrology for Functionality and Efficacy

Abstract We will unpack this question very systematically and rigorously. First, we make clear that this question cannot not be addressed as if discussing a light bulb, a used car, or a radio. To answer "does it work" in a meaningful and thoughtful way, we adopt the approach used by pharmaceutical companies. Demonstrating that a drug works is a stringent process, which is also regulated by unforgiving laws. A drug works if its developers can verify that it is *functional*. The science must be valid. Then its *efficacy* must be verified with people. The science and the statistics must be valid. *A drug works if and only if both functionality and its efficacy are verified.* This the standard we seek. Second, verification requires instruments, a measurement system, and processes that specify how the instruments are to be used and how measurement data are to be analyzed and interpreted. Simply stated, *a metrology* must exist. We need a metrology for our paradigm. Regrettably, in spite of our best efforts, we are unable to find a metrology for prescriptive decision paradigms. As a result, we developed a metrology and measurement instrument. To our knowledge *this is a first in this field and very meaningful contribution.* We invite scholars to research this subject and add to the body of knowledge of metrology in the praxis of decision theory.

4.1 Introduction

This chapter is an introduction to Part **II**. In Part **I**, we showed the conceptual and technical rigor, as well as, the distinctive and practical nature of our paradigm. We described our paradigm, distilled first-principles and framed the five phases of our executive decision life cycle and presented prescriptive procedures for each of the five spaces of the executive-decision life-cycle. We grounded our methodology on engineering design-thinking, systems-development methods and proven sociotechnical practices. We discussed how to methodically design decision-specifications that are robust even under noisy operating environments. Robustness means that a decision's outcomes remain largely unaffected even when uncontrollable uncertainty conditions cannot be removed. To design robust decision-specifications, we specified a process to systematically identify the key managerially controllable and uncontrollable variables. Then we prescribed how to use them to construct alternative decision-specifications. Decisions and their outcomes are

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invariably influenced by uncertainty conditions; they cannot be eliminated. To address this difficulty and to mitigate their negative impact, we showed how to specify uncertainty regimes using uncontrollable variables. We showed how to minimize the negative impact of uncontrollable variables by robust engineering-design methods. We exploit the interactions between controllable and uncontrollable variables in a positive and productive way. We presented a new and innovative way to measure and analyze the quality of the socio-technical system that implements and executes decision specifications. We use the manufacturing-engineering methods of gage repeatability and reproducibility (Gage R&R). Putting all this together, we have characterized and represented, in detail, the technical and social subsystems of our executive-decision paradigm. And to operationalize our paradigm, we systematically presented detailed and actionable prescriptions.

However, we have not yet applied, nor exercised, our prescriptions in either simulated or real world settings. At this point it is natural to wonder whether our paradigm and its methods "work". *Work* is the central theme of this chapter. We will argue that the question is a false dichotomy if posed as "does it work?" or "not work?" To this end, we will first present a definition for "it works" and then we will discuss how to systematically determine and measure the extent to which a complex sociotechnical artefact like our executive-decision paradigm and its methods "work", "not work", why and how to make it "work" better.

4.2 Framing the Question as Readiness

4.2.1 Readiness as Ready-to-Work and Ready-for-Work

The question "Does it work?" is superficial if posed with the naïve mental model reserved for traditional products like a mouse for a PC, a chainsaw, a radio, a used car, and the like. That perspective is wrong for complex sociotechnical artefacts of the artificial (Simon 2001); such as, technologies, complex sociotechnical systems, solutions to messy and wicked problems, their methodologies and practices. For example,

- "Does stealth technology work?"
- "Does the F-35 work?"
- "Does Total Quality Management work?"
- "Does Design For Six-Sigma (DFSS) work?"

Whether such complex systems, methodologies, or technologies "work" cannot be understood as a binary attribute. "It works" is neither univariate, unidimensional, nor categorical. "Does it work?" cannot be understood, framed, or addressed using the light-bulb on/off-switch mental model. The question is inappropriate when posed as a false dichotomy.

Our goals are to unpack and understand the question of "Does it work?" We will discuss our findings and their implications and to formulate a way to systematically answer "does it work?" with more than a "yes" or a "no". We propose to methodically determine and evaluate the conditions under which a complex artificial artefact works, why it works, how well it works, for *whom* it works, the conditions under which it *will* or *will not* work, and how to improve how it works. We will conclude whether such artefacts work, or not, is not a categorical attribute. Namely, there are specific conditions under which a complex artefact will work; there are other conditions under which the same artefact will only work marginally as well, and under yet different conditions possibly work much better. How to characterize these different conditions, in a domain neutral language to facilitate precise communications, are the challenges we will be addressing.

Critically important is also the question of "Who's asking whether it works?" Is it the creator or developer of the artefact, or is it a DMU or a user who is considering whether or not to use the artefact? It may work for the former, but not for the latter. The former must convince itself that the artefact meets its design specifications. The latter must separately convince itself that the artefact is effective for their specific application, in their operating environment. Use of the artefact must be valid for both (e.g. Borsboom et al. 2004; Borsboom and Markus 2013; Messik 1989; Golafshani 2003). There is more to "does it work?" than meets the eye. The question is tightly packed with meaning and nuance. This is especially true for nontrivial artefacts of the artificial, such as executive-management decisions. For example a company executive will undoubtedly wonder "will this decision to turn around this profitless firm to produce the results I need? If not, how can I make it better? And then how much better?" Or an executive, about to implement a new company-wide business process based on new IT technology, needs to feel confident that he has identified the most critical factors of the project and that he is well prepared to undertake the implementation. And therefore, the question of "will it work?" is not a yes or no, but "is my organization ready to take on this project? How to improve my firm's capabilities to make it ready?"

Or consider the following decision-situation and the required decision-specifications. In the 1990s IBM was experiencing losses amounting to billions of dollars. Declining competiveness and dismal financial performance were proof of a serious crisis. IBM was losing both its position as the dominant industry leader, as well as, its role as the choice vendor in the market. I was assigned to a task force, among many others, that was studying the myriad of issues related to reverse this grim situation and considering restructure the company to recover its former supremacy. The concept was to transform IBM into a holding company of separate and independent product and service companies. To make this a reality, IBM had many task forces in motion with a wide range of ostensibly ***ready-to-work*** proposals and decision-specifications. Investment bankers were beating a path to IBM and knocking down its doors. And even names were being proposed for the new independent subsidiaries. Meanwhile, the market was impatient and remorseless. Earnings continued to plunge into deep negative territory.

At the nadir of its losses, IBM's board of directors appointed Lou Gerstner as the new CEO. Very quickly, he announced that the putative prescription, to break up

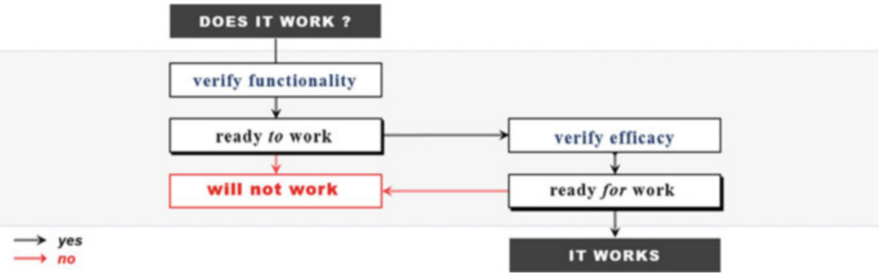

Fig. 4.1 Framing the concept of "It Works"

IBM into independent units, was a very bad idea. Gerstner judged the proposed solution was not ***ready-for-work,*** if ever. To him the idea failed 'sense-making' (Weick 2001). To Gerstner, the proposals were all solutions to the wrong problem. He had a very different mental model, from the rest of IBM's senior executives, for the reasons of IBM's decline. Namely, IBM had lost touch with its customers and had become unresponsive to their needs. From its origins as a market driven company, it had become internally focused and sluggish. Not one to mince words, he described the proposed prescriptions as: "barreling toward a strategy of disaster" (Gerstner 2009, p. 17). This example starkly illustrates the fact that whether a decision-specification "works", or not, requires two independent judgements. One from its creators and the other from a DMU representing a potential user who has unique needs to address, under specific situations, for a specific application, in a specific disciplinary domain. A judgement formed by the creator of the artefact, and from a DMU or user, imply fundamentally different pragmatics. They mean entirely different things.

"It works" is a composite verdict of two orthogonal judgements about a designed decision and its specification. One verdict is about *functionality*; the other is about *efficacy* (Fig. 4.1).

Functionality means that we, as creators and designers of our executive-decision paradigm and its methods,[1] can legitimately claim that our methodology will perform as intended. We must show that our methodology is ***ready-to-work***. This implies that an executive, from firm x, who commits to design and implementation of an executive-decision, its design and its specifications using our methodology will have a decision design that functions to specifications. It will function because our methodology is grounded on demonstrably *valid* concepts, solid principles and rational methods, not on chance design, anecdote or guess work. A methodology that can also tell him the quality of its sociotechnical system and to what extent is the decision production system responsible for poor outcomes.

For functionality, we must have *verified* and proven to ourselves that **our** methodology meets **our** engineering design specifications. The onus is on us, as the original engineers and designers of this methodology, to do so. We must present legitimate and valid claims of functionality to a DMU, or a user. This is not unlike a

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[1] Henceforth, we will frequently call our paradigm and its methods simply as our "methodology".

new medication, for which a manufacturer in good faith claims the drug will work because it has passed required certification tests. On the other hand, ***efficacy*** means that a DMU, or a user, has rendered, on its own, an independent verdict of efficacy and made a commitment to use. *Viz*. a user, has implemented a decision specification using our methodology for a specific application in a specific operating environment. The user has systematically acquired a body of useful information confirming or refuting the functionality and performance claimed by the artefact's creators. A user must convince itself, and the DMU, of the efficacy of our methodology, i.e. the application using our methodology is ***ready-for-work***. We summarize by stating the following principles for our methodology:

- **Readiness** is at the center of ***ready-to***-*work* and ready-***for***-*work*. Our methodology "**works**" if and only if it is ***ready-to***-*work* **and** ***ready-for***-*work.*
- **Functionality** is necessary and sufficient to demonstrate our methodology is ***ready-to***-*work*. The presumption is that it meets all design specifications, i.e. it will function as designed.
- **Efficacy** is necessary and sufficient demonstration that our methodology is ***ready-for***-*work*. The presumption is that it is ready-to- work, **and** it is effective **for me**.

We now know the "what" of readiness. The "how" remains to be addressed. Namely, "how" do you demonstrate readiness? What are the tools to measure the extent of readiness and confirm readiness? These are the questions we will concentrate in the next two Sects. 4.2.2 and 4.2.3.

4.2.2 Measurement Readiness: Metrology, Instruments, and System-Measurands

Readiness is at the crux of "it works". Measuring readiness is not like using a ruler, handling an ohmmeter, or simply standing on a weight scale. All of which are accomplished in one undemanding move. In contrast, measuring readiness is a systematic and disciplined sociotechnical process. It involves organizational procedures, skilled professionals, technical equipment, and a measurement system grounded on science and engineering. We need a **metrology** for readiness (BIPM et al. 2008). *Regrettably, the science of metrology appears absent in the domain of decision theory and analysis.*

We define *metrology for readiness* as the science and practice of measuring the functionality and efficacy of our methodology. Our metrology includes systematic processes to take measurements for readiness, equipment, norms and conventions to interpret the obtained measurement numbers, and a discipline-neutral *lingua franca* for senior-executives and technical professionals to communicate goals, status and progress on measurement plans and progress. Our *metrology for readiness* is a

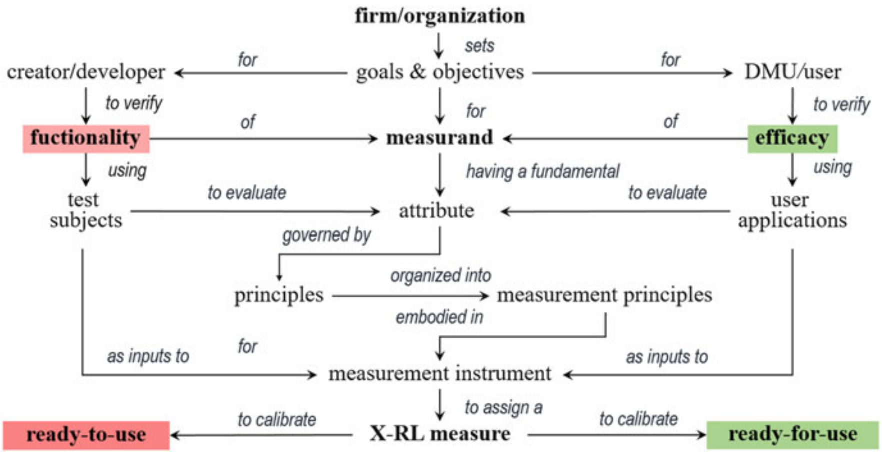

Fig. 4.2 Conceptual architecture of a readiness metrology

dynamic sociotechnical system. Its conceptual architecture is illustrated by Fig. 4.2. In the paragraphs that follow, we present a vocabulary to describe its key components and their roles. We will use simple examples to help build intuition about the concepts we will be discussing.

1. **Measurement**. Measurement is a process or experiment for obtaining one or more quantities about attributes of outcomes or **values** that can be ascribed to our executive-decision paradigm and its methods. The attributes of interest are functionality and efficacy. Measurement presupposes a description of the functionality and efficacy attribute commensurate with the *intended* use of the measurement result, a measurement procedure, and a measurement quantity. The readiness measurement is intended to inform us or a user to what extent the functionality or the efficacy of our methodology can be trusted. And therefore inform us or a user what remedial actions must be undertaken to improve readiness.
2. **Measure**. A measure is the assignment of a numerical value that represents the intensity of the *readiness* attribute of our methodology. Our methodology is the **measurand**. What is a measurand? For example, consider an A4 sheet of paper being measured for length. The A4 sheet is the *measurand* and the measure of length is 297 mm. The *measurement unit* is a millimeter.
3. **Measurand**. In our case, the methodology that is the subject of measurements is not a simple "dumb" artefact like a resistor. The resistor is *passive* to the agent making the measurement and using an ohmmeter. (It is passive at this scale of abstraction, use and observation. Actually no object is passive. Even a resistor depends on atomic-level behavior of its material to effect a behavior in an ohmmeter.) More complex measurands, like a car engine being measured for power, requires fuel to make the engine run in order to take measurements. Different fuels will produce different engine performance, e.g. torque. The combination of engine and the fuel form a ***system measurand***. The measurement

unit is newton-meters, for example. Similarly, the combination of our methodology together with an experimental test case qualifies as a *system measurand.*

4. **Measurement unit**. Measurement unit is usually a scalar quantity defined and adopted by convention that will be used as a consistent basis for comparison. For our methodology, the measurement for readiness is an **ordinal** number we call ***readiness level-n,*** where $n \varepsilon \{1,2,3,4,5\}$. Level-1 is the lowest readiness level and level-5 is the highest. Level-1 requires that the concept of executive-decisions to be articulated and explained, that the fundamental sciences are identified and justified, and the scale and scope of applicable executive-decisions to be described and specified. Level-1 readiness is the ground we already covered in Chaps. 1 and 2. In Sect. 4.4 of this chapter, we will discuss in detail the other readiness levels.
5. **Measuring instrument**. A measurement system is an artefact used for making measurements, alone or in conjunction with supplementary artefact(s). A ruler is a simple instrument. The twin Laser Interferometer Gravitational-wave Observatory (LIGO) detectors form a system instrument. A market survey interview and questionnaire is a more complex measuring instrument. An instrument can be physical, non-physical or a mixture of both. The exact and precise specification of our measuring instrument for our methodology will be discussed in detail in this chapter. At this point, we need more terminology and concepts.
6. **Measurement procedure**. A measurement procedure is intended for *people* to implement. The procedure is a recipe that is documented in sufficient detail to enable a DMU, organization, agent or user to take a measurement that are attributable to the extent of readiness of an executive-decision paradigm and its methods.
7. **Measurement principle**. A measurement principle is a phenomenon that serves as the basis for a measurement. For example, to determine a car's speed on a freeway, police use a pointing device that uses the Doppler Effect to measure speed. The Doppler Effect is the measurement principle. For our executive-decision paradigm and its methods the measurement principle for *ready-to-work* is *functionality*, and the measurement principle for *ready-for-work* is *efficacy*. Principles are made operational and discernible by measurement methods within an instrument.
8. **Measurement method**. An *instrument* implements, by design, a logical organization of operations during a m**easurement** according to **measurement principles** to obtain a readiness *measure* for an executive-decision paradigm and its methods. Note that a measurement method is intrinsic to the instrument. In contrast, a measurement procedure is extrinsic, it is intended for people to implement.
9. **Measurement system**. A measurement system is the sociotechnical composite comprised of the organization, their knowledge, data bases, formal and informal procedures, and instruments.

4.2.3 Base-Measurand and System-Measurands

We now turn out attention to the concepts of *base-measurand* and *system-measurand*. We illustrate the idea of a base-measurand and system-measurand in Fig. 4.3. The one system-measurand on the left is delimited by the red dashed-lines. This is the system-measurand that we use as designers and engineers of our methodology for the purpose of measuring the readiness extent of ready-to-use. The measurement principle is functionality, i.e. our methodology functions according to our design specifications as demonstrated by test subjects. The other system-measurand is on the right, of Fig. 4.3, delimited by the green dashed-lines. It depicts the system-measurand of a specific DMU/user of our methodology. The user's goal is to measure the extent of ready-for-use. In this case, the measurement principle is efficacy. The purpose is to test efficacy. This means that our methodology is useful and effective according to applications' needs in their usage environment. The two system measurands overlap. This overlap forms the *base operand* used by us as either the creators/developers of the methodology to test functionality or by a user to test efficacy.

The overlapped area, base-measurand, is our methodology. The base measurand has been extensively addressed in Chaps. 1, 2 and 3. The Introduction to this chapter has provided a terse summary of these chapters.

Each system measurand, though using the same base-measurand, employs a **different** type of experimental objects and artefacts to determine readiness. As the creators and developers of our methodology, we use test-objects to verify the *functionality* of our methodology. The other is, as users with application for the DMU/user, we use other objects for tests of *efficacy*. In general, the functionality subjects are distinct from the efficacy test subjects. They can be same, but the goals will be different, for functionality or efficacy. Whatever the case may be, the results are input to the measurement instrument to determine the extent of

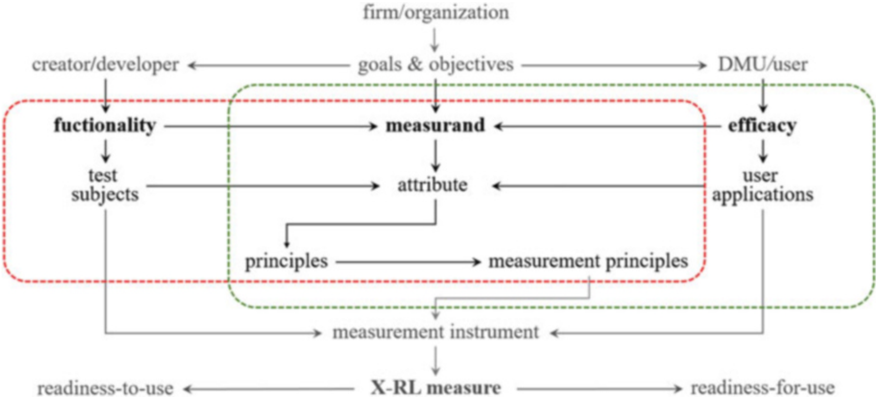

Fig. 4.3 Two system-measurands

readiness *to-work* or the readiness *for-work*. We can think of this instrument as an *ordinal thermometer* for readiness.

The remainder of this chapter concentrates on these two moving parts of the machinery to confirm readiness of our methodology—the system measurands and the measurement instrument. We will first address the issues of test subjects to demonstrate our paradigm is *ready-**to**-work* and *ready-**for**-work*. We will follow with a detailed discussion on the issues of our readiness measurement instrument.

We now turn our attention to the system-measurand for functionality, the red dashed-line box on the left of Fig. 4.3. For its test subject, we will argue the need of a *surrogate*. A surrogate is an artefact that is used in place of a real company, to test our paradigm and its methods. We will discuss the necessary qualifications, for the surrogate, we need to prove functionality. Our surrogate is a system dynamics model (Sterman 2000) of a real company. Justification for using this model will be extensively argued. This will be followed with a comprehensive discussion of our readiness *measurement instrument,* its principles, methods, and procedures. Our instrument adopts concepts from the lean technology-readiness framework (Tang and Otto 2009, Appendix 4.2). We adopt the following key concepts: a readiness framework based on the idea of robustness, and the idea of a *lingua franca* that enables straight forward, exact, and a *lingua franca* for domain-discipline neutral communications about readiness. The lexicon and semantics (Carlile 2004) are neutral in the same sense that a kilogram is a meaningful measurement unit for mass, whether for a rock, an electron, or a person.

4.3 Measuring Ready-to-Work

Readiness is a modern concept (Mankins 1995, 2009; DuBos et al. 2008). The notion of readiness has its roots in technology. The term readiness was specified as the extent to which a technical system, and particularly, a new technology was sufficiently understood, characterized, and demonstrated to be effective in a variety of ***use-environments***. The central idea was to be able to describe a technology's maturity level so that it simultaneously communicated the level of risk, of testing and verification at different stages of its maturation and adoption. The goal was to enable engineers and businesses to adopt technology with fewer surprises and less risk than was heretofore practical. Readiness demands another layer of intellectual rigor from engineers, developers and users of technology.

4.3.1 System Measurand for Ready-to-Work

Testing our paradigm for *readiness* requires appropriate sociotechnical test subjects. The ideal test subjects are real world companies or organizations. Businesses or groups that have challenging decision-situations, as well as, executives willing to engage in realistic experiments in their organizations. Executives willing to construct systematic experiments to investigate the conditions that will make their decision-specifications effective. Executives with organizations that will collect test data and information to determine the reasons and the *extent* to which their decision-specifications can resolve their messy and wicked problems. This is typical (and demanding) work required to assemble evidence that will support or refute whether our methodology is ready-***to***-work.

However, because we are concentrating on messy and wicked decision-situations (e.g. Cherns 1976; Rittel and Webber 1973), we cannot expect executives to eagerly turn their companies into experimental test objects of a new paradigm. Their reluctance is understandable. Macro-economists cannot expect to conduct experimental tests of novel and untried economic policies with national governments.[2] For the same reasons, without solid and convincing evidence that our methodology is ready for real-world problems, we should be very cautious and prudent about experimenting with companies. Given this hurdle, we need to start testing with an artefact that behaves like a real firm. An artefact that can serve as "a case study with the participants on the inside (Jones 1998)" for "computational experiments to explore the implications of varying assumptions and hypothesis (Bankes 1993)". We need a high fidelity model, a facsimile of a company to simulate our decision specifications, to collect data, and evaluate inferences.

In short, we need a *surrogate*. A "surrogate" is a model that is used*, in place of* an actual and costly experiment, to simulate the behavior of a company. The idea is to simulate and analyze the behavior of the surrogate as if it were a real company. The goal is to obtain data from the surrogate and make inferences that are expected to be valid in a real company. This idea is not new. For example, software models are used to simulate nuclear explosions. In a wind tunnel, a miniature model airplane is used as a surrogate for a real aircraft in flight. A surrogate is distinct from a prototype. The airplane model in the wind tunnel is not a prototype. A prototype is a *real* embodiment, albeit low fidelity, highly abbreviated, low cost, and frequently crude. Nevertheless, it is a *real* functional embodiment used during the early stages of system development to test working principles and demonstrate concepts. As system development progresses, higher fidelity, more functionally complete and rugged prototypes are used until the prototype is a near embodiment of the final product. A surrogate is not intended to undergo this kind of chrysalistic evolutionary process. Nevertheless, a surrogate must be a sufficiently accurate facsimile; otherwise data, findings, and inferences are not convincing. Or worse, wrong.

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[2] Although the propensity, of politicians to do so, is not negligible. For example, the New York Times (3-29-2016) opines "The move to raise the statewide minimum wage would make California a guinea pig in a bold economic experiment."

4.3.2 Criteria for Our Surrogate in the System Measurand

A useful surrogate must satisfy four criteria. It must: address key functions of the firm; include key managerially controllable and uncontrollable variables; be endowed with fine-grained details and; enable capturing data at different points in the simulation process.

- *Address key functions of the firm.* Because we are studying decision analysis at the executive-management level, the surrogate must not omit key functional areas of a company (e.g. Chandler 2004). It must include key business processes from the major functions of the firm, e.g. research, planning, marketing, product and system development, manufacturing, finance, accounting, sales, distribution, and services. As a corollary to multi-functional coverage, the surrogate must include their interactions to reveal key emergent properties.
- *Include managerially controllable and uncontrollable variables.* Firms are surrounded by an external environment, from which many actors are exerting forces that influence the firm's behavior and performance. "Firms, if not all organizations, are in competition for factor inputs, competition for customers, and ultimately, for revenues that cover the costs for their chosen manner of surviving (Rumelt et al. 1994)." It follows that a surrogate must include key internal and controllable, as well as, external and uncontrollable variables in its representation. These variables form the bedrock of our representation framework of our Operations Space (Sect. 3.4.2). For example, a firm's total r&d expenditures is a controllable variable set by management. In a free market economy, aggregate industry-demand is an uncontrollable variable. Demand is determined by competitors and customers pursuing their independent interests. Except for monopolies, illegal cartels, industry demand cannot be influenced by a few parties. The interactions between controllable and uncontrollable variables must be represented in the surrogate to investigate their influence on the system behavior and impact on intended outputs.
- *Be endowed with fine-grained details.* By definition, an executive-manager (Sect. 1.1) must have a depth of control that extends at least three layers deep. Therefore, a surrogate model must enable us to drill-down to study the detailed relationships of key variables. It must also provide a view up their current organizational level. This is necessary to understand the structure, functions, and constructs of the operational processes and composite variables in the overall context of the enterprise (eg. Cherns 1976; Clegg 2000; Rittel and Webber 1973). For example, for Cost of Goods Sold (*cogs*), we would like to know the proportion of contribution of parts, manufacturing labor, manufacturing overhead, and warranty. Or for example, we would like to explore the effect of manufacturing yield on cost and price and on competitors.
- *Enable capturing data at different points of the simulation process.* All decisions are about today's commitments and future expectations (e.g. March 1997). Therefore, the temporal dimension of outcomes is inextricably and inexorably entangled in any decision alternative and its outcomes. The surrogate must

permit us to sample values of controllable and uncontrollable variables for any point in the model's operational processes. For example, the investment effects on production will not be immediately discernable. There is a time lag between action and effect. A surrogate must permit the capture of such performance data to analyze the behavior of the sociotechnical system.

4.3.3 Criteria for Our Surrogate: System Dynamics Model of ADI

ADI is a leading manufacturer of integrated circuits and electronics products (ADI, Inc., 2015). It reported revenues of \$3.4 B for the fiscal year 2015. ADI is a substantial enterprise of >9000 employees with a customer base >100 K. Our surrogate is a system dynamics (Sterman 2000) model of this company. The surrogate was developed by Sterman et al. (1997) of MIT. The surrogate covers the years 1985 through 1991. In 1991, ADI's revenues were only \$538 M. ADI is very successful now, but in 1990 it faced many serious problems. The surrogate emulates ADI's behavior during this turbulent period. We will simulate a wide variety of decision-specifications as experiments that operate in this volatile environment. For ADI, this period of time was fraught with uncertainties. Our surrogate model is a non-trivial test vehicle. We are keenly aware that simulations do not guarantee performance in the real world. However, effective simulation is a necessary step before we experiment in the real-world.

The ADI system-dynamic model meets our criteria for a surrogate of a real company (Sect. 4.3.2). The surrogate model must address:

- *Address key functions of the firm.* The ADI model uses 620 equations to represent 85 enterprise business processes. A top-sheet system-description (Fig. 4.4) shows twelve business processes that are modeled by the ADI surrogate. The key corporate functions, of interest to us, are included in the system dynamics model. The entire system dynamics model is described in a document that is over 400 pages in length.
- *Include managerially controllable and uncontrollable variables.* The architecture of the ADI system dynamics (SD) model (Fig. 4.4) clearly identifies and describes in great detail the controllable and uncontrollable variables. Table 4.1 shows examples of those variables as reported by Sterman et al. (1997).
- *Fine-grained details.* The SD model is too large to present in its entirety. In this paragraph, we limit our attention to the outcome of Expected *A*nnual ***O***perating ***I****ncome* (AOI) (Fig. 4.5). We will design decision-specifications for this outcome in Chap. 5. Clearly AOI is an accumulation. Therefore, it is represented by an integral of a net flow given by *Change in Exp OP Income*.

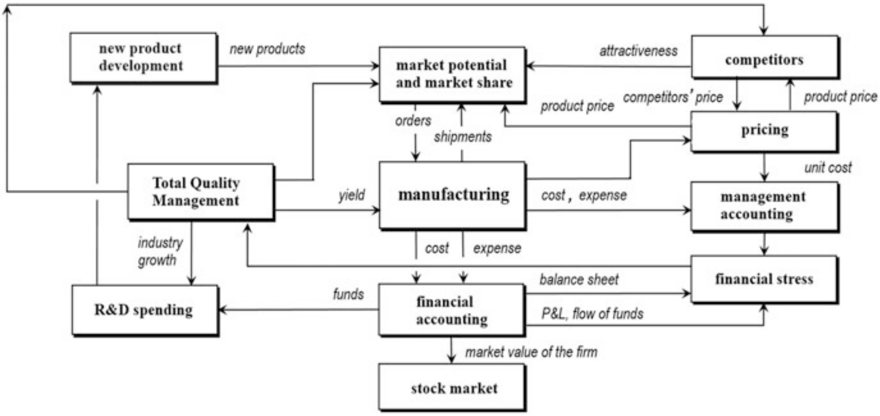

Fig. 4.4 System overview of ADI SD model

Table 4.1 Examples of endogenous and exogenous variables

Managerially controllable variables		Managerially uncontrollable variables
• Unit sales • Sales revenues • Cost of goods sold • Operating income • r&d budget	• Cumulative products introduced • Manufacturing yield • Manufacturing cycle time • On time delivery • Market value/cash flow	• Competitors' product price • Inflation • Industry demand • Yield of SP 500 • Competitors' improvements

$$Expected\ Annual\ Operating\ Income = \int (change\ in\ Exp\ OP\ income)dt + AOI_0 \tag{4.1}$$

We will also test the outcome of Indicated *Market Value of the Firm* (MVF) in Chap. 5 also using the ADI system dynamics model. The MVF flow depicts the following analytic relationships:

$$indicated\ \ MVF = \max[(value\ \ of\ \ growth + PV(earnings)), 0] \tag{4.2}$$

$$PV\ \ of\ \ earnings = PV[\boldsymbol{f}(expected\ \ annual\ \ operating\ \ income)/discount\ \ rate] \tag{4.3}$$

$$value\ of\ growth = (\exp.annual\ earnings \times effective\ growth\ value)/discount\ \ rate. \tag{4.4}$$

Equation (4.2) states there are two determinants of MVF: PV (present value) of earnings and value of growth. PV is a function of the discounted value of earnings and discount rate. Value of growth, is exogenous and uncontrollable, equation (4.4).

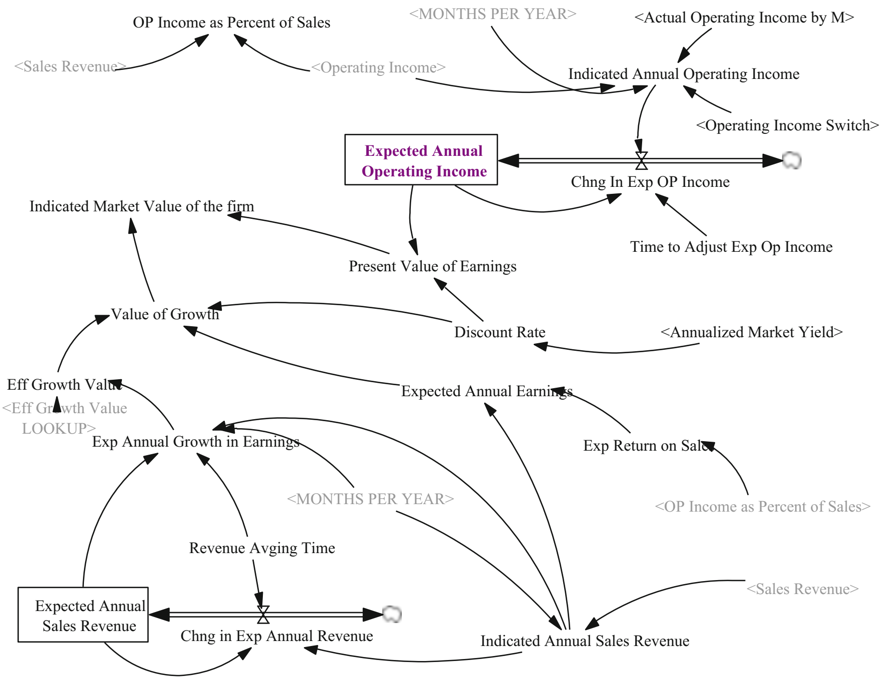

Fig. 4.5 SD stock and flow model for Expected Annual Operating Income (AOI)

This is investors' figure of merit assigned to ADI's earnings. Overall, the details of the model are impressive. There are 210 loops (a loop is a complete circuit of arrows in the same direction) that include the variable MVF. A sample of 50 loops shows that each loop contains >20 variables. There are 85 flow charts like Fig. 4.5, each one representing a key part of the ADI enterprise model. The ADI surrogate model is very detailed. The number of variables is 620, and their interactions are thoroughly represented.

- *Enable capturing data at different points of the simulation process*. Figure 4.6 is an example of the data generated by the SD model. The graphs display a snapshot of ADI's expected Annual Operating Income (AOI) during a 24 month period under three different regimes: manufacturing yield is higher by 10% relative to current yield level, manufacturing yield is at the current yield level, and manufacturing yield is at a diminished yield of 90%. Yield differences of 10% in IC manufacturing are non-trivial. It is not unlike yield of a savings account; 10% is significant. 10% higher manufacturing yield requires substantial effort. And 10% lower manufacturing yield is indicative of serious problems. The ±10% envelope shown is a meaningful representation of the space of possibilities. Graphs like Fig. 4.6 are also useful to evaluate construct, internal, and face validity, e.g. Figure 4.6 shows there is a meaningful, causal, and temporal relationship between manufacturing yield and expected AOI. As

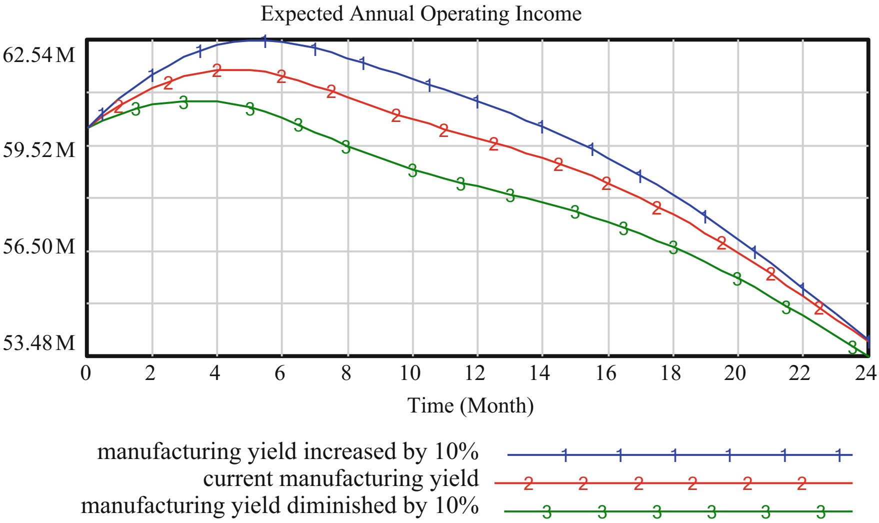

Fig. 4.6 Snapshot of AOI under different yield regimes

manufacturing yield increases, AOI increases (line 1 in blue). This causal relationship between dependent and independent variables is consistent with domain knowledge, i.e. manufacturing performance improvements lead to improved profits. Note that the effect of yield drop is more pronounced than an equivalent increase in yield. But there is a time delay between action and its maximum impact, 6–12 months later. The surrogate model includes hundreds such streams to represent the relationships between and among variables.

4.3.4 *Quality of Our Surrogate: System Dynamics Model of ADI*

Verisimilitude of the ADI system dynamics surrogate is high. A full analysis and discussion is discussed in the paper by Sterman et al. (1997). Data are summarized (Table 4.2) to support the model's quality. The discussion below is a summary from the original paper.

Majority of the *MAPE* numbers are in the single digits, and $0.70 \leq R^2 \leq 0.99$ is very good. The fit of **unit sales, revenue, cost of goods sold, r&d budget,** and **cumulative new products introduced** are excellent, also in bold text in Table 4.2. Operational performance—*manufacturing yield, outgoing defects, manufacturing cycle time,* and *on time delivery (OTD)*—have more variation than the aggregate measures, so the *MAPE* tends to be slightly larger, but $0.74 \leq R^2 \leq 0.91$ is very good. Model fits for share price and market value/cash flow are fair, with $MAPE = 0.13$ and 0.19 respectively, and $R^2 = 0.81$ and 0.82 respectively, and low

Table 4.2 Historical fit of model, 1985–1991

Variable	*MAPE*	Theil inequality statistics			R^2
		Bias	Unequal variation	Unequal covariation	
Unit sales	**0.04**	0.11	0.12	0.77	**0.94**
Sales revenue	**0.03**	0.01	0.08	0.91	**0.94**
Cost of Goods Sold (*cogs*)	**0.05**	0.08	0.08	0.80	**0.92**
Operating income	0.18	0.11	0.25	0.64	0.70
R & D budget	**0.07**	0.19	0.01	0.81	**0.91**
Cumulative products Introduced	**0.04**	0.00	0.50	0.50	**0.99**
Manufacturing yield	*0.10*	*0.16*	0.00	*0.84*	*0.82*
Outgoing defects	*0.22*	*0.06*	0.01	*0.92*	*0.91*
Mfg. cycle time	*0.13*	*0.11*	0.02	*0.87*	*0.82*
On time delivery (OTD)	*0.05*	*0.31*	0.05	*0.64*	*0.74*
Market value/cash flow	0.19	0.16	0.02	0.82	0.82
Share price	0.13	0.21	0.00	0.79	0.81

MAPE = Mean Absolute Percent Error between simulated and actual variables. [*smaller is better*]
Theil inequality statistics—Bias, unequal variation, and unequal covariation. They show the fraction of the mean square error between simulated and actual series is due to:
Bias ≡ unequal means [*smaller is better*]
Unequal variation ≡ unequal variances [*smaller is better*]
Unequal covariation ≡ imperfect correlations [*bigger is better*]
Unequal variation ≡ unequal variances [*smaller is better*]
R^2 ≡ percent of variance explained by the model [*bigger is better*]

bias and unequal variation error. The second largest error is in operating income, $MAPE = 0.18$ and $R^2 = 0.70$. Operating income is the small difference of two large numbers (revenue less cost), so small errors in either create much larger percentage errors in income. "Overall the model's ability to replicate Analog's experience . . . from the factory floor to the financial markets, is good." (Sterman et al. 1997).

4.4 Measuring Readiness with an Instrument

> *If you cannot measure it, you cannot improve it. Lord Kelvin*[3]

> *If you cannot measure it, you cannot control it. J. Grebe*[4]

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[3] http://www.eecs.qmul.ac.uk/~andrea/dwnld/SSPE07/AC_SSPE2007.pdf. Downloaded 10 April 2017.

[4] Morrow (Morrow 2012, p. 207).

4.4.1 Weaknesses of the Traditional Readiness Measurements: Build-Break-Fix

Readiness is at the core of "does it work?" *Readiness* as a property that is correlated with the reasons and conditions under which an artefact is effective, the degree to which it is effective and ***for whom***. In other words: *is it ready-**to**-work? How well, and **for** whom?* In Sect. 4.3, we discussed at length that testing for *readiness* requires appropriate test subjects.

In this section, we make the case for requiring *a measuring instrument* to determine *the extent* to which, our executive-decision paradigm and its methodology meet the *functionality* requirements of executives facing messy and wicked situations. The traditional product and system development approach, to demonstrate that an artefact "works", is by testing alpha and beta prototypes, (e.g. Pahl and Beitz 1999; Otto and Wood 2001; Dym et al. 2013), engaging in comprehensive field tests, (e.g. Booth 2009; Dolan and Matthews 1993; Cole 2002) and using models of various types (e.g. Viana and Haftka 2008; Forrester et al. 2008). However, these methods are not without their limitations.

The first limitation is the asymmetry of risks. It is tacitly accepted that the developer of the artefact determines that "it works". For simple products and systems, users can take the producers' word at face value. However, a DMU, or user, of complex systems, bears disproportionate risks for deficient efficacy. To mitigate this risk, the practice is to test, observe and experience, first-hand, an artefact's behavior and its performance under a wide variety of operating conditions. Hence, it is common practice for users and DMUs to insist on acceptance tests to ensure that complex systems will perform effectively for their application in their specific operational environment. The observation from US astronaut Alan Shepard vividly exemplifies the asymmetric risks borne by users. He famously noted that: "It's a very sobering feeling to be up in space and realize that one's safety factor was determined by the lowest bidder on a government contract."

The second limitation is the lack of a common language, i.e. *a lingua franca*. Complex sociotechnical systems operate under a wide variety of uncertainty conditions that are difficult to describe and communicate. Over a century, probability theory has evolved to address this difficulty. This has proven to be very useful, but also omits helpful semantic information. Limiting oneself to probabilities is like saying that the human eye can detect electromagnetic wavelengths from about 390 to 700 nm. This is very precise, but absent are descriptions that the wavelengths range from the ultraviolet to the infrared, with other colors in between. The notions of hue, saturation and brightness are absent and therefore not communicated. Probabilities, though precise, do not provide a textured, nuanced or ***semantically*** rich *lingua franca* to communicate about the ***meaning*** of readiness to executives. A domain neutral *lingua franca,* which includes a vocabulary, semantics and measures, is required.

The third limitation is the absence of a readiness framework that systematically organizes concepts and principles to inform, communicate, prepare and prove readiness, functionality, and efficacy. We think this gap has impeded the clarity and precision about readiness, functionality, and efficacy and practices for their rigorous evaluation. A conceptual framework that overcomes the above limitations is needed. Fortunately, the US National Aeronautics and Space Administration (NASA) comes to rescue with a solution.

4.4.2 New Concept of Readiness. Measurements: Verification in Five Decision Spaces

Perhaps inspired by Alan Shepard's remark, and certainly very determined to tackle the limitations in Sect. 4.4.1, NASA introduced Technology Readiness Levels (TRL) as an assessment framework and instrument Appendix 4.1. The NASA TRL instrument seeks to satisfy two major technical and management goals:

- guide systems developers validate candidate for potential adoption,
- help users adopt technologies with more confidence, less risk, and fewer unhappy surprises.

NASA's TRL framework as an instrument, with prescribed readiness measures, is a very useful and important conceptual and managerial contribution to the development, management and diffusion of technology-intensive-complex systems.

To measure readiness, the NASA TRL specifies an ordinal scale of 1 through 9 (Appendix 4.1). The ordinal scales are anchored on precise and discipline-neutral definitions for readiness. Level-1 is the lowest level of readiness. Level-9 indicates the most thoroughly demonstrated level of readiness. Level-2 through Level-8 are intermediary levels. The US Department of Defense now requires proof of TRLs for all its acquisition programs for weapons systems (DOD 5000 2002; Graettinger et al. 2002, Appendix 4.1). The 2013 US GAO assessment of its weapons-systems portfolio, consisting of 80 major programs, reports that 50 programs were ahead of the cost estimates, while only 30 were behind. These results suggest the beneficial effects of the TRL's (GAO 2014).

We adopt the TRL concept to assess, measure, and evaluate our paradigm. The TRL's spirit, conceptual framework, and measures are very consistent with our needs. Because the TRL idea is about technology, we must first convince ourselves that our paradigm can be considered as a technology. We now argue the case for our executive-decision management paradigm as a technology. Our arguments are founded on Arthur's (2009) definition of technology as having three meanings:

1. "…technology is the *means* to fulfill a *human purpose*." "Means (noun)" and "human purpose" imply human intention and processes designed to achieve goals and objectives. Means (noun) is an intentional and goal-oriented rational process that applies scientific knowledge to transform matter, energy, information, and intangibles into an embodiment that "fulfills a human purpose". Technology means (verb) design and engineering.

2. Technology is "the assemblage of practices and components" that include the science, physical products, as well as, procedures, sociotechnical practices, and the like. For example, in the pharmaceutical industry, biology, painstaking and exacting development processes, meticulous filings for approval, certification of Class 1, 2, 3, 4 laboratories, laws about testing on humans, and ethical practices are all part and parcel of the pharmaceutical technology.
3. Technology is "the collection of devices and engineering practices available to a culture". "The totality of the means employed by a people to produce with the objects of material culture (*op. cit.* Arthur)" is technology. For example, the immense cost of billions of dollars just to build and equip an electronics fabrication plant, has created the practice of outsourcing fabrication. This practice frees companies to concentrate on design innovations rather than fabrication. All these are distinctive "collection of devices and engineering practices" of what we call "the high tech culture" of microelectronics. Hence the term "Silicon Valley culture" is a uniquely accurate appellation for that region in California.

We add a fourth and fifth corollary to the above:

4. Technology is also the *resultant* artefact from technology processes, components, and practices, whether the artefact is physical or non-physical. Arthur (*op cit.* Arthur) writes about the steam engine as a technology exemplar. It follows that the computer, DRAM, the internet, the recipe for making heavy water, the canonical decision making model (e.g. Baron 2000; Bazerman 2002; Bell et al. 1988) are all technologies. The 2016 *MIT Technology Review* discusses ten breakthrough technologies (MIT 2016). They include reusable rockets, robots teaching robots, and conversational interfaces. As in the case of the steam engine, they are technologies. Embodiments resulting from technology processes and practices **are** technologies.
5. Technology belongs to the sciences of the artificial (Simon 2001, and Chap. 1 of this book). Sciences of the artificial are about man-made objects (physical or non-physical), their conception, design, implementation, and operations. Technology uses the natural sciences and mathematics as tools, but its goals are distinct. Science seeks to understand nature. Technology uses what it knows about nature to build purposeful manmade objects.

In conclusion, our paradigm, and its methods for executive-management decisions, as an ensemble, is a technology. Therefore, a *NASA-like TRL* would be very meaningful and helpful for us. However, we also need to understand recent thinking about some of its inadequacies, and research to mitigate known limitations.

4.4.3 Specifications of Our Readiness Measurement Instrument

The NASA TRL, as defined needs to be updated to address three apparent deficiencies.

First, the TRL is predicated on the **build-test-fix** mental model of system development (Tang and Otto 2009). This is a tinkerer's approach to product development: improve an artefact by trial-and-error. Engineers are driven by results. They are impatient and have a strong sense of urgency. This makes them inclined to improve TR levels and push for early releases of hardware, software, and systems often before they are ***ready***. This triggers *cycles* of build-test-fix in the laboratory and the field. This is inconsistent with modern engineering methods to design and develop complex systems and technology. Such *build-test-fix* cycles during systems development are now well documented to be inefficient and wasteful (Tang and Otto 2009; Kaplan et al. 1995).

Second, NASA TRL is silent on new principles and practices for design and development of technology intensive systems. TRL is silent on *lean principles* (e.g. Ward and Sobek 2014; Oppenheim 2004; Browning 2000) and for *six-sigma* (e.g. Creveling et al. 2002; Goh 2002; Koch et al. 2004; Brady and Allen 2006; Yang and El-Haik 2003; Pyzdek and Keller 2003). Lean principles state that, with inevitable exceptions, which does not add to customer value is waste.[5] Lean practices focus on waste reduction and elimination. Six Sigma seeks to improve design of artefacts and sociotechnical processes by statistical methods rather than anecdotes, platitudes and guesswork. Lean and six-sigma are significant steps to reduce build-text-fix cycles.

Third, the TRL appears biased to physical products, though software readiness levels are defined. TRL should have more emphasis on intangible artefacts; such as, methods, algorithms, and socio-technical services; for they are also technologies. Recent Manufacturing Readiness Levels and the Services Readiness Levels are steps in this direction (Tang and Otto 2009). Their focus is on robustness to reduce build-test-fix rework cycles. We adopt and adapt these key ideas for our framework and instrument for readiness (Table 4.3). This is Table 3.1 from Chap. 3, we have Table 4.3, the X-RL for e**X**ecutive-decision **R**eadiness **L**evels. We have identified the tasks required for a systematic process. Recall that our systematic process is consistent and extends the canonical form to include operationalizing the decision specification and adds the requirement for the capability to design and predict the outcome of any hypothetical what-if decision.

Our readiness instrument puts together ideas from the work of practitioners and scholars. First, we have taken the NASA idea of technology readiness and adopted it to represent decision readiness. Second, we have adopted of *robust design* over the *build-test-fix* approach to designing by trial and error. Third, we have adapted

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[5] Lean acknowledges that necessary work, which does not add to customer value, is indeed pervasive, e.g. filing tax reports.

Table 4.3 Readiness level specifications for executive decisions

Process phases	Our systematic process	
X-RL1 Characterize **Problem space**	Sense making—uncomplicate cognitive load	☑
	Frame problem/opportunity and clarify boundary conditions	☑
	Specify goals and objectives	☑
	Specify essential variables Managerially controllable variables Managerially uncontrollable variables	☑
X-RL2 Engineer **Solution space**	Specify subspaces of solution space Alternatives space and uncertainty space	☑
	Specify entire solution space	☑
	Specify base line and uncertainty regimes Do-nothing case and choice-decision Estimate base line and dispel bias	☑
X-RL3 Explore **Operations space**	Specify Sample orthogonal array	☑
	Do-nothing case and choice decision-alternative	☑
	Predict outcomes	☑
	Design and implement robust alternative Design and implement any what-if alternative	☑ ☑
X-RL4 Evaluate **Performance space**	Evaluate performance: analyze 4R Robustness, repeatability, reproducibility Reflect	☑ ☑ ☑
X-RL5 Enact **Commitment space**	Decisive executive Approval of plan Commit funds, equipment, organizations	☑ ☑ ☑

☑ indicates required for readiness

the idea of systematic design from Pahl and Beitz (1999), Otto and Wood (2001) to the design of decisions. Finally, we remain consistent with our life-cycle view of executive decisions, not only as *events* or only intense analysis, but as synthesis and production. This life-cycle approach places proper emphasis on synthesis, redresses the bias to analyses, and stresses the importance of committing to action and implementation.

X-RL1 is the lowest level of readiness. And X-RL5 is the highest level of readiness, wherein the executive responsible and accountable for the decision demonstrates visible action. Action means that scarce and costly resources are allocated, an action plan is specified, and finally the organizations are mobilized. Mobilization implies getting concurrence from the senior executive to whom he is responsible and accountable lining up dependencies he needs for success, and preparing his own organization for action. Success in X-RL5 is the *sine qua non* for readiness, whether ready-to-work or ready-for-work.

4.5 Measurement Procedures for Ready-to-Work

> *… if the result confirms the hypothesis, then you've made a measurement. If the result is contrary to the hypothesis, then you've made a discovery.* (E. Fermi[6])

4.5.1 Proof of Functionality: Two Cases Using ADI Surrogate

We framed the question of "does it work?" as readiness, Fig. 4.1. Recall that for a complex sociotechnical system, "it works" has two meanings. One is that the creators and developers have demonstrated the artefact is ready-to-work with evidence of functionality. This is the responsibility of the creators and developers of the executive-decision management paradigm. Two is that a user, independently, in turn, has convinced itself that the artefact is ready-for-work with evidence of efficacy.

Functionality means that the paradigm and its methods meet its design specifications as an engineering artifact of the artificial. This requires five levels of verification, as shown on the left-hand side of Table 4.3. They cover the familiar five spaces of the executive-decision life cycle. Proof of functionality is necessary and sufficient to have successfully performed all tasks of the systematic process. Proof of functionality for any X-RL level, it is necessary and sufficient that all tasks at that level are performed successfully.

In Chaps. 5 and 6, we will use the ADI surrogate to show how our paradigm and methodology will satisfy the ready-to-use criteria (Fig. 4.7). X-RL5 will not be able to be demonstrated since we are using a surrogate, but we will do so in Chaps. 7, 8 and 9. In Chaps. 5 and 6, the decision-situation will be framed as the management survival from hostile takeover and the goal as retaining control of the firm. The objectives are specified as maximizing the Value of the Firm (MVF) in Chap. 5 and maximizing Operating Income (AOI) in Chap. 6. The controllable variables and the uncontrollable variables will be specified for the analyses and syntheses. We will use experiments of different resolutions, *viz*. full-factorial models, intermediate-sample size models, and a low-fidelity coarse model. We will compare and contrast the results and infer lessons we can apply with real world executive decision-situations.

4.6 Measurement Procedure for Ready-for-Work

> *What's good for the goose is good for the gander.* (Folk wisdom)

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[6] http://www.u-s-history.com/pages/h1624.html. Downloaded 10 April 2017.

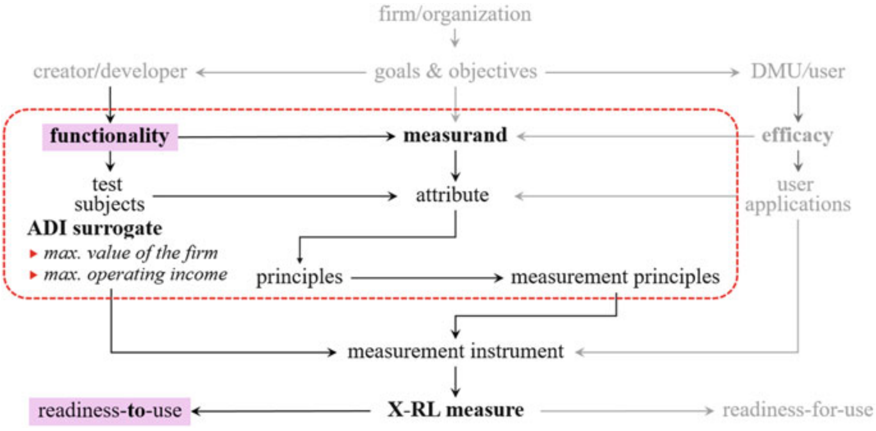

Fig. 4.7 Chapters 5 and 6—Validation with ADI surrogate to simulate a company's operational environment

4.6.1 *Proof of Efficacy: Three Global Enterprises*

We have discussed at length the issue of the question "does it work?" as one of readiness (Fig. 4.1). We have argued that for a complex sociotechnical system, readiness has two distinct meanings. The first derives from the creators and developers who have demonstrated the artefact is *ready-to-work* with evidence of *functionality*. This is the responsibility of the creators and developers of the executive-decision management paradigm. The second meaning derives from the user. She has convinced herself (and a DMU) that the artefact is *ready-for-work* with evidence of *efficacy* (Fig. 4.2, right-hand path). Efficacy means that our paradigm and its methods will prove to be effective for a user's application. This means that our methodology of the systematic process is effective **to use** for their application. The presumption is that we have verified the functionality of the methodology. To prove efficacy the presumed functionality of the concepts constructs, and operations of the paradigm have to be proven as being effective for the user's application. That is to say that the paradigm and its methods is ready for use and therefore the user's application is ready to be used (Fig. 4.8).

We will use real world companies and organizations to show how our paradigm and methodology will satisfice ready-for-use conditions. We will report these case studies in Chaps. 7, 8 and 9. In Chap. 7, the decision-situation is about the turnaround of a $600 M global electronics contract-manufacturer that has over a dozen manufacturing plants around the world. The decision situation in Chap. 8 is about a professional services engagement by a Japanese service company for a leading Japanese car manufacturer. Both the service provider and the manufacturing company are leaders in their industry. This engagement is politically sensitive, both the CEO's of the service provider and the manufacturer sit on each other's board and both consider this a showcase project to prove their good judgement in

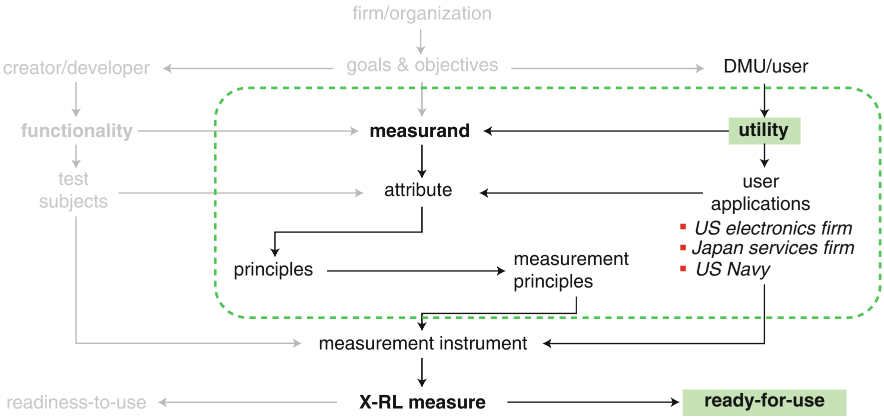

Fig. 4.8 Chapters 7, 8, and 9—Validation with real-world users in their operational environment

high technology projects. Chap. 9 deals with a US military establishment, the US Navy. The nature of the decision-situation is about military hardware, the time horizon is decades in length, and the scope of impact is national security. The decision-situation has all the hallmarks of being messy, wicked, as well, as of near immutability. This Naval case study is particularly challenging. There are over 1.3 trillion possible decision alternatives to choose from.

4.7 Chapter Summary

Our executive-decision management paradigm and methodology is a complex sociotechnical methodology of the artificial. Whether such a sociotechnical artefact "works" is not something that can be answered with a "yes" or "no" as if it were a light bulb.

- For sociotechnical artefacts "it works", means that it is *ready*-***to***-*work* and *ready*-***for***-*work*. The key concept is *readiness*.
- *Ready*-***to***-*work* is validation of ***functionality***. It means that we as creators and developers of the methodology have evidence that it is effective as stipulated by our systematic decision process.
- *Ready*-***for***-*work* is validation of ***efficacy***. It means that a DMU or user have sufficient evidence that our methodology is effective for their application use in their operational environment.
- If and only if the functionality and efficacy conditions are both verified, can it be said that the artefact "works".
- For us, to verify that our executive-decision paradigm and methodology "works" and *ready*-***to***-*work*, it must execute every step of our systematic decision process (Table 4.3), which in their entirety cover the executive decision life cycle.

- To verify *ready-**to**-work*, we run simulations using a surrogate. A *surrogate* is a high fidelity model of a real company used *in place of* the actual company for experimental purposes. The surrogate we use has detailed models of 85 business processes of a real company. All together the model is represented with >620 variables. The surrogate's operational verisimilitude is very high, which is required for the analyses and syntheses work ahead of us.
- *Ready-**for**-work* means that a DMU, or user has convinced themselves that our executive-decision methodology is effective for a specific application, in their specific operational environment. Use of the application must also satisfy the same aforementioned series of progressively stringent validation stages. *Ready-for-work*, it must execute every step of our systematic decision process (Table 4.3), in their entirety cover the executive decision life cycle.
- To measure the extent of readiness, i.e. how *ready-**to**-work* and *ready-**for**-work,* we use our framework of E**X**ecutive-Management-Decision **R**eadiness **L**evels, X-RL (Table 4.3) as our "calibration thermometer".

Putting all this together, we have introduced a **readiness metrology** for the evaluation of any decision management process. We have precise definitions for **measurement, measure, measurand, measurement unit, measuring instrument, measurement procedure, measurement principle, measurement method, and measurement system**. Moreover, this is not just a list of definitions, but a conceptual structure for the evaluation of sociotechnical artifacts of the artificial. In other words, a metrology.

This is an original contribution to the field of prescriptive paradigm verification.

Appendix 4.1 NASA Definition of Technology Readiness Levels

TRL 1 Basic principles observed and reported. Transition from scientific research to applied research. Essential characteristics and behaviors of systems and architectures. Descriptive tools are mathematical formulations or algorithms.

TRL 2 Technology concept and/or application formulated. Applied research. Theory and scientific principles are focused on specific application area to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.

TRL 3 Analytical and experimental critical function and/or characteristic proof-of-concept. Proof of concept validation. Active Research and Development (r&d) is initiated with analytical and laboratory studies. Demonstration of technical feasibility using breadboard or brassboard implementations that are exercised with representative data.

TRL 4 Component/subsystem validation in laboratory environment. Standalone prototyping implementation and test. Integration of technology elements. Experiments with full-scale problems or data sets.

TRL 5 System/subsystem/component validation in relevant environment. Thorough testing of prototyping in representative environment. Basic technology elements integrated with reasonably realistic supporting elements. Prototyping implementations conform to target environment and interfaces.

TRL 6 System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space): Prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application.

TRL 7 System prototyping demonstration in an operational environment (ground or space): System prototyping demonstration in operational environment. System is at or near scale of the operational system, with most functions available for demonstration and test. Well integrated with collateral and ancillary systems. Limited documentation available.

TRL 8 Actual system completed and "mission qualified" through test and demonstration in an operational environment (ground or space). End of system development. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. Verification and Validation (V&V) completed.

TRL 9 Actual system "mission proven" through successful mission operations (ground or space). Fully integrated with operational hardware/software systems. Actual system has been thoroughly demonstrated and tested in its operational environment. All documentation completed. Successful operational experience. Sustaining engineering support in place.

Source: https://esto.nasa.gov/files/trl_definitions.pdf. downloaded January 20, 2016

Appendix 4.2 Lean TRL Definitions

L-TRL 1 Basic principles observed and reported. Equations are observed describing the technology physics.

L-TRL 2 Technology concept and/or application formulated. Noise factors identified. Control factors identified. Measurement response identified.

L-TRL 3 Technology performance behavior characterized. Range of control factors identified. Range of noise factors identified. Measurement response identified. Measurement system GRR baselined. Basic concepts demonstrated.

L-TRL 4 Technology Nominal Performance validated. Integration of basic technological components to establish they work together and produce the range of performance targets necessary. Integration uses "ad hoc" hardware in the laboratory. Transfer function equation predicts a validated nominal response. Measurement system GRR complete and capable.

L-TRL 5 Technology Performance Variability validated. Integration of basic technological components with reasonably realistic supporting elements to test technology in a simulated environment. Robustness work on the technology components is complete. The sum of squares response variation impact of each noise factor varying is predicted in a validated transfer function equation.

L-TRL 6 Supersystem/system/subsystem interactions in relevant environment are demonstrated. Test representative prototype system in a stress test laboratory or simulated environment. Develop and validate scalable transfer function equations for the entire product as a system with the new technology. Equations include prediction of sum-of-squares performance variation and degradation for the entire product with applied off-nominal variation of the noise factors.

L-TRL 7 Product System Demonstrated Robust in representative environment. Technology prototype transferred to a product commercialization group, and they scaled it to fit within their real product application as an operational system. Demonstration of an actual full-product prototype in the field using the new technology. Transfer function equations for the particular product system instantiation are completely verified. A limited set of remaining control factors are available to adjust the technology within the product against unknown-unknowns. Technology is as robust as any other re-used module in the product.

L-TRL 8 Product Ready for Commercialization and Release to Manufacturing Full Production. Technology has been proven robust across the noise variations of extreme field conditions using hardware built with the production equipment purposefully set up and operated at their upper and lower control limits. Transfer to manufacturing is a non-event to the development staff if L-MRL processes are in place.

L-TRL 9 Experienced Customer Use. Product in use by the customer's operational environment. This is the end of the last validation aspects of true system development. The performance of the product and the technology perform to customer satisfaction in spite of uncontrollable perturbations in the system environment in which the product is embedded or in other external perturbation. Transfer to the customer is a non-event to the engineering staff if L-TRL and L-MRL processes are in place.

Source: Tang and Otto (2009)

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Chapter 5
Verifying Functionality: Maximizing Value of the Firm (MVF)

Abstract Macro-economists cannot expect governments or central banks to use them as test objects for their theories. Likewise, we cannot expect firms to submit themselves as test subjects to verify the functionality of our prescriptive paradigm. Therefore we simulate with a surrogate of a real company. The surrogate is system dynamics model of ADI, a high technology electronics firm. The model has over 620 equations to represent ADI's operational behavior of its functional areas and the firm's interactions with its external environment. The model's documentation covers over 400 pages. This chapter models the decision to Maximize the Value of Firm (MVF). The goal is to shield ADI from "vulture hunters". High market value will make it costly to buy control of the firm. As such, MVF is directed at forces exterior of ADI. Best effort has been made to attach the data for the simulations as appendices and all the calculations are shown and illustrated.

5.1 Introduction

In the previous chapter, we argued that our methodology ***works***, if and only if, it can simultaneously satisfice two necessary and sufficient conditions, *viz.* it is ready-**to**-work for users ***and*** ready-**for**-work by a user for a specific class of decision situations. Ready-to-work needs to be demonstrated by us as creators of the methodology. We have to demonstrate its *functionality,* Fig. 5.1.

We have to show that the methodology ***works*** as intended by us, as engineers of the executive-decision methodology, as an intellectual artefact. Separately, users need to independently satisfy themselves the methodology *works* for them. Namely, that the methodology is ready-for-work. Users require evidence of the *efficacy* of the methodology. This requirement is natural given the complex sociotechnical nature of executive decisions and the scope of their potential impact. The methodology must work for them, i.e. users must convince themselves it is ready-**for**-work.

We will use the ADI surrogate (Fig. 4.4, Chap. 4) as a test object to produce evidence that our methodology is *ready*-***to***-*work* by demonstrating that it will satisfy the X-RL conditions (Table 5.1). In this ADI simulation, we play the role of a DMU. As a rump DMU, we will apply and evaluate our systematic decision life-cycle process.

In the previous chapter, we discussed the reasons why we need a company surrogate, how to select one, and why we selected the ADI system dynamics model

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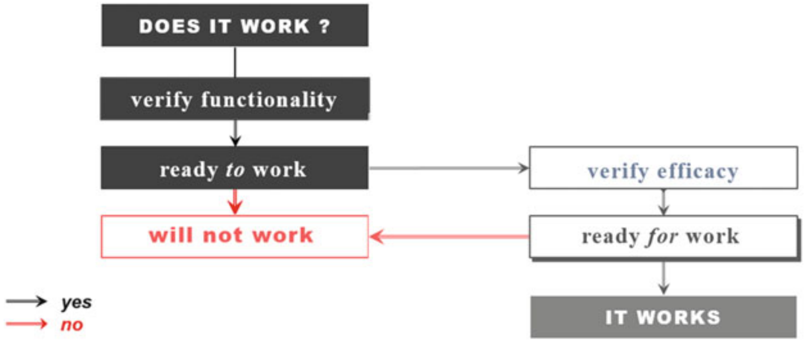


Fig. 5.1 Functionality is a necessary condition to demonstrate methodology *works*

Table 5.1 Readiness level specifications for executive decisions

Readiness level	Our systematic process		Strategy
X-RL1	Characterize	Problem space	Sense making
X-RL2	Engineer	Solution space	Engineer experiments/alternatives
X-RL3	Explore	Operations space	Explore entire solution and uncertainty spaces
X-RL4	Evaluate	Performance space	Measure robustness, repeatability, reproducibility
X-RL5	Enact	Commitment space	Commit plan with approved resources

to play this role. Using the ADI surrogate as test object, we will verify the readiness of our methodology for the design of a specific executive-decision specifications (Fig. 5.2). We will demonstrate that our methodology will meet the X-RL specifications for *functionality*. Using the ADI surrogate to simulate the ADI system behavior, we test our methodology to meet the corporate objective of *maximizing the market value of the firm* (MVF), at every phase of the decision life-cycle. In the next chapter, we will be demonstrating the functionality of our methodology for a different objective, to *maximize ADI's annual operating income* (AOI).

This chapter has eight sections. We begin with an introduction, Sect. 5.1. A section is devoted to each of the five phases of the executive decision life-cycle—the Problem, Solution, Operations, Performance, and Commitment Spaces (Table 5.1). The objective is to systematically determine the extent of X-RL readiness at each phase of our methodology. The overall findings are discussed in the Chapter Summary.

Section 5.2 covers Characterizing the Problem Space. We apply our methodology to characterize the decision situation adhering to our principles of abstraction and uncomplicatedness to develop a tractable mental model for an executive decision. We verify the *functionality* of our methodology for this crucial step. Given the non-trivial nature of the decision situation and the systematic processes we use to verify our characterization; this section is lengthy but necessary. We

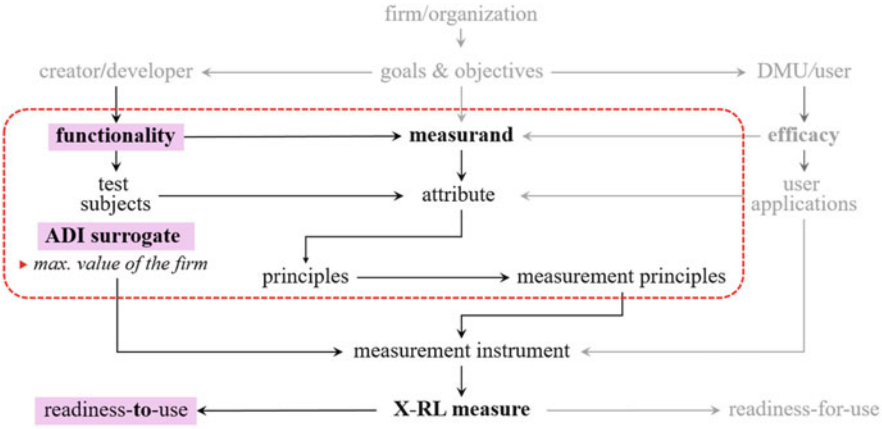


Fig. 5.2 Functionality is a necessary condition to demonstrate methodology *works*

introduce a notation, a short hand intended to avoid long and unwieldly descriptive sentences. We will demystify the notation so that it can be decoded at a glance.

In Sect. 5.3, Engineering the Solution Space, we identify the essential variables, develop the problem solving constructs used for the Solution Space and the representations for the whole spectrum of uncertainty conditions. We discretize the uncertainty space into a discrete and spanning set of *uncertainty-regimes*. This is a fundamental process because it makes the entire uncertainty space tractable. Sections 5.2 and 5.3 establish the analytic base-line for the work in subsequent sections.

Section 5.4 covers Exploring the Operations Space. We use a structured set of *gedanken* experiments and three sets of structured sets of experiments of different resolutions and fidelity, for our analyses of the Solution Space. We show a procedure for constructing and exploring any hypothetical decision alternative with the ability to determine a risk profile represented by standard deviations. We collect data for the evaluations needed in the Performance Space, Sect. 5.5. We analyze the architecture of the experimental sets to determine the additional utility of more complex models.

The Analysis of the Performance Space is highly abbreviated because the authors are acting as a rump DMU. Because we are playing the role of a DMU, we do not have a quorum to evaluate two of the 3R's. We can address Robustness, but defer Repeatability and Reproducibility to Part III where we report on customer engagements. Although note that all the simulations, for different decision specifications under different uncertainty conditions, assume that the ADI executives have committed to those different decision alternatives. Section 5.6, the Commitment Space, is similarly abbreviated for the same reasons. Section 5.7 closes this chapter with a summary of the key learning from the simulations studies.

5.2 Characterizing the Problem Space

> In the dynamics of social systems … near decomposability is generally very prominent. This is most obvious in formal organizations, where the formal authority relation connects

> each member of the organization with one immediate superior and with a small number of subordinates. (H.A Simon 2001, 200)

5.2.1 Sense-Making and Framing

In 1987, ADI launched a TQM initiative and concentrated its efforts on the firm's technically-intensive functions. The results were dramatic improvements in product quality and manufacturing. Yield doubled, cycle time was cut by half, product defects fell by a factor of ten, and on-time delivery improved from 70% to 90%. People worked very hard to achieve these impressive results. However, operating profit and stock price continued to plunge. Specifically, operating profit fell from $46 M to $6.2 M. The stock market had lost confidence in ADI. Price per share dropped from $24 to $6 during the period of 1987–1990. And, unprecedented in ADI's history, people were laid off and manufacturing jobs were transferred overseas, long before it became expedient and fashionable. Management had lost credibility with the ADI workforce. The firm's financial crisis threatened Ray Stata, founder and CEO of the firm, with a hostile takeover from raiders in Wall Street. An ADI senior manager observed "... with its [low] market value, ADI could have been acquired for about 3 years' cash flow from operations." Ray Stata is reported to have remarked "... there was something about the way we were managing the company that was not good enough (Sterman et al. 1997)".

5.2.2 Goals and Objectives

No entrepreneur wants to lose control of their business. We can assume that Stata does not want the firm to be acquired on the cheap. Moreover, for Stata, it is critical that he demonstrates his ability to turn around ADI. He urgently needs to improve the performance of its key business functions and restore confidence and morale of its workforce. Ray Stata's decision situation is thus framed as specified in Table 5.2.

The goal is to mount a defense against the threat of ADI being taken over by outsiders. The first objective is to maximize the market-value of the firm (MVF). A high market-value makes ADI less affordable to raiders. It also serves to increase the stockholders' confidence in the current management. So that if it comes to a proxy fight, stockholders will be more favorably inclined to retain the current management. The second objective is to restore trust and confidence in ADI's

Table 5.2 ADI's decision situation

Problem	• Threat of hostile takeover • Loss of confidence in ADI management
Goal and opportunity	• Turn around the company • Retain control of the firm
Objectives	• Maximize market value of the firm, MVF • Maximize operating profit

management by improving operating profit. Operating profit reflects management's ability to control cost and expense. Cost is an indicator of engineering and manufacturing effectiveness; and expense is an indicator of operational efficiency and effectiveness of the other functions of the firm (e.g. Brealey and Myers 2002). Operating profit **puts these two measures together.** As such, it is a good proxy that reflects the quality of the firm's management.

5.2.3 The Essential Variables

Much more important is an understanding of what are the key variables in shaping system equilibrium and what policy variables can have an effect on that equilibrium (H.A. Simon 1997, 113). Essential variables are the key controllable and uncontrollable variables that satisfice to represent the ADI sociotechnical system for analyses. They are consistent and meaningful given the scale and level of abstraction of the problem (Chap. 3, Sect. 3.3.2).

5.2.3.1 Controllable and Uncontrollable Variables

For the controllable variables, we concentrate on the key business functions, which are fundamental and typical in high technology companies. They are r&d, manufacturing, engineering, and finance. We assume that a senior functional-executive is in charge of each function. This is reasonable given the specialized disciplinary knowledge and the operational experience required to manage each of these technically intensive domains. To each of them, we can pose the questions about ways to maximize the Market Value of the Firm (MVF). Specifically:

- What are the key variables you can control?,
- What is the range of controllability for those variables?,
- What are the key secular variables that you cannot control?, and
- Can you describe their plausible scope and range of behavior?

We begin with the managerially controllable variables. Consistent with the scale and level of abstraction, in which we are considering our problem, we identify the following controllable variables.

- For r&d, the key controllable variable is the *r&d budget*. More r&d, for a high technology company. More r&d% is expected to be better,
- For manufacturing it is *manufacturing yield*. Scrap and rework are considered the bane of manufacturing; therefore higher yield is better,
- For engineering it is the cost of goods sold *(cogs)*,
- For finance it is *product price*. The ability of a firm to command a premium price, while holding costs and expenses down, is considered the hallmark of good management. Clearly, lower *cogs* is better.

Table 4.3 in Chap. 4 shows that these variables have a very good statistical fit in the ADI surrogate model. $R^2_{r\&d} = 0.91$ for *r&d*, $R^2_{yield} = 0.82$ for *manufacturing* *yield*, $R^2_{\text{defects}} = 0.91$ for defects, and for *product price* $R^2_{\text{price}} = 0.70$. These data strengthen our belief that these variables are well chosen.

We now turn our attention to the key uncontrollable variables. We concentrate on the most influential variables that management cannot control, either extremely difficult or prohibitively costly to control, and whose behavior have a direct and strong impact on our chosen objectives. *It is the behavior of these variables that generate the uncertainty conditions under which the controllable variables will operate*. These variables collectively can characterize the key external uncertainty conditions facing ADI in its efforts to maximize the value of the firm (MVF). In the documentation of this case, Sterman et al. (1997) point us to three major uncontrollable variables.

- First is the *long term growth of industry-demand*, which can "raise or lower all boats" in the industry. In a free market, unless one has a monopoly or a dominant industry position, industry-wide demand is not something that is controllable. At best they can influence in minor ways through advertising, rebates, and other costly ways. ADI's revenues and profit alone indicate ADI does not fit the profile of a monopoly or dominant player in the market.
- The second uncontrollable variable is the *rate of ADI orders*. By virtue of its product line and position in the supply chain, ADI has very limited influence on the rate or volume of customer orders. ADI is not a consumer product company. Its market is an *industrial market* (e.g. Anderson and Narus 1999). ADI is an original equipment manufacturer (OEM), a commodities supplier of electronic components that are delivered as parts to many other product manufacturers. Demand for ADI's components is derived from the sales of the final products of the manufacturers, such as computers, components for consumer products, medical equipment and the like. ADI's ability to control industry demand for final products is infinitesimally small.
- Finally, the third uncontrollable variable is the *attractiveness of competitors' products*. As a relatively small industrial player among many in a free market, ADI has no control over competitors' products functionality, performance, price, quality, fulfillment or services capabilities. ADI cannot control *competitors' product attractiveness*. It is an uncontrollable variable.

5.2.3.2 Levels for Controllable Variables and Uncontrollable Variables

Next we set the levels that bracket the range of managerial controllability for the controllable variables (Table 5.3). In practice, these are set by a DMU through discussions, until a general consensus is reached. Playing the role of a DMU, we specify three levels to demarcate the ranges of controllability. We set level 3, at which there is an improvement from the current level of operations. In all cases, except for *cogs,* more is better, so that an increase is expected to improve the output of MVF. For example, we would expect that all things being equal, an increase in the *products' prices* will increase the MVF since it can boost revenues. Whether this is a sustainable approach is influenced by uncontrollable factors, which we will be

Table 5.3 Controllable variables and levels

Controllable factors	Level 1 (%)	Level 2	Level 3 (%)	Characteristic
r&d budget	−10	Current level	+10	More is better
IC yield	−15	Current level	+15	More is better
cogs	−10	Current level	+10	Less is better
Product price	−10	Current level	+10	More is better

investigating. Increasing *cogs* will make the product less competitive; it will pressure profit margins and price. Higher *cogs* will not improve the outcome of MVF.

Except for *cogs*, the +xx% represents our assumption for the maximum improvement that can be achieved with a very strong effort. The best level for *cogs* is assumed to be at −10%. Again except for *cogs*, the −xx% represents our assumptions for the maximum declines that are tolerable to management. ±10% is non-trivial. For example, a 10% gain of an investment portfolio is not an achievement that can be attained automatically. In this chapter, we will test the behavior of ADI under each of these assumptions. *Current level* is the as-is operational level, with **no** changes. This level is also referred to as Business-As-Usual (BAU) throughout this chapter.

Superficially, it may appear that a useful approach is to drive all the controllable variables to their levels that maximize the objective. But this is not feasible because the *r&d Budget* variable serves as a regulating factor. The managerial cross-functional interactions, in the DMU, are unlikely to make indiscriminate outcome maximization, with profligate resource expenditures, practical or feasible. For example, to lower cost of goods *(cogs)*, one has to invest in manufacturing, this raises r&d expenditures and puts pressure on expenses. These issues will naturally come to the DMU's attention. Compromises will have to be made. The principle of No Free Lunch (Sect. 3.3.2.2) will assert itself during the managerial competition for funds and people.

The levels for the uncontrollable variables are based on the maximum and minimum *plausible* values of the uncontrollable variables. They are our assumptions about the best and worst cases, which must be realistic. Domain expertise and competent judgment are required to set these upper and lower bounds. For example, for a pharmaceutical startup, demand for a new product can be extraordinary or it can be negligible. This is reasonable and logical given the high failure rates of new drugs. However, for a mature product in a mature market, these suppositions are not reasonable. For a mature product in a mature industry, incremental and momentum growth is more logical. Unlike the controllable variable levels, which specify the limits of managerial action, the levels for the uncontrollable variables represent **secular** conditions, which are plausible as most favorable or most unfavorable to the firm (Table 5.4).

With three uncertainty, uncontrollable variables, each at three levels, ADI faces $3^3 = 27$ full factorial potential distinct scenarios of uncertainty that are distinct from its current condition.

Table 5.4 Uncontrollable variables and levels

Uncontrollable factors	Level 1	Current state	Level 3	Characteristic
Industry growth rate	Current − 25%	Current	Current + 25%	Fast is better
ADI orders rate	Current − 25%	Current	Current + 25%	High is better
Competitors' attractiveness	Current − 25%	Current	Current + 25%	Lower is better

5.2.4 Notation

To simplify our narrative of the variables and their levels, we prescribe the following notation. A specific configuration of $\boldsymbol{n}$ factors with $\boldsymbol{k}$ levels, we use a $\boldsymbol{n}$-tuple where each entry is an integer representing a level $\leq k$. For a specific configuration of our four controllable factor-levels, we use a 4-tuple. For example, (2,1,2,2) means factor1 at level 2, factor2 at level 1, factor3 at level 2, and factor4 at level 2. For 3 uncontrollable factors, a 3-tuple denotes a specific configuration. For example, the (2,1,2,2) decision alternative at the uncertainty condition of (1,2,3) is written as ((2,1,2,2),(1,2,3)). And occasionally also as ((2,1,2,2),(123)).

5.2.5 The Business-As-Usual (BAU) Situation

The BAU situation, the current condition, is ((2,2,2,2),(2,2,2)) in the current uncertainty regime. The current uncertainty regime is the "center point" of the uncontrollable space hypercube (Table 5.5). Given the definition and the level specifications for the uncontrollable variables, we surmise that for ADI the best environment is (3,3,1), i.e. *industry demand* is high, *ADI orders* are strong, and *competitors' products* are unattractive and weak. Similarly, we posit that the worst environment is (1,1,3) when *industry demand growth* is weak, *ADI orders* are weak, and c*ompetitor products' attractiveness* are strong. We will test these assumptions in this chapter.

Table 5.5 Values for the BAU state and the current environmental condition

Controllable factors	BAU	Numeric value
r&d budget	Level 2	$28.47 M
Manufacturing yield	Level 2	20%
cogs	Level 2	$11.28 M
Product price	Level 2	$17.38

Uncontrollable factors	Condition	Numeric value
Growth in demand	Current level	2%
ADI orders	Current level	1.487 M
Competitors' products attractiveness	Current level	4.955e-005 (this is an index)

5.2.6 Validity of the Essential Variables

Validity is defined as “how accurately the account represents participants’ realities of the social phenomena and is credible to them” (Criswell and Miller 2000; Borsboom and Markus 2013; Borsboom et al. 2004). This implies the criteria of face validity, construct validity, internal validity and external validity (Yin 2013; Hoyle et al. 2002; Johnson 1997; Golafshani 2003). To these ends, we will test the sensitivity of MVF with respect to our controllable and uncontrollable variables. We test for the presence of causal linkages between the MVF outcome (the dependent variable), and the independent variables (our uncontrollable variables). We examine whether these linkages behave as we expect, given our domain knowledge and understanding of the decision situation. And finally, we use statistics to determine whether there is support for the constructs and the narratives of the sociotechnical system behavior, i.e. does it all really make sense?

5.2.6.1 MVF = *f* (single controllable variable)

We now show the behavior of the dependent variable, MVF, **under the current BAU situational condition** as a function of the independent variables (the controllable variables). We express this condition as MVF((2,2,2,2),(2,2,2)) or MVF ((2,2,2,2),(222)). The objectives, for the analyses are to determine whether there is a causal linkage between the dependent variable and the independent variables. And also to assess whether the observed behavior is consistent with our understanding of the problem and our domain knowledge of the situation. Note that MVF ((2+,2,2,2),(222)) is the situation in which the first controllable variable is changed to level 3, while the others remain unchanged.

Figure 5.3 plots MVF((2,2,2,2),(222)) versus *product price* as a function of time. With no changes in *product price*, MVF behaves as shown (graph #3). MVF is in monetary units of $M. A 10% increase in *product price*, MVF((2,2,2,2+),(222)) grows as in graph #1. A 10% fall in *product price*, MVF((2,2,2,2−),(222)) behaves as shown in graph #2. Graphs #2 and #3 are everywhere dominated by graph #1. *Price* has a very pronounced and immediate impact on MVF. Note that a decline is price has a more pronounced effect on MVF. This behavior is predicted by Prospect Theory (Kahneman and Tversky 2000).

We show plots for the other controllable variables. MVF((2,2+,2,2),(222)) rises as *manufacturing yield* rises (Fig. 5.4); or as *cogs* declines (Fig. 5.5), MVF ((2,2,2,2−),(222)) increases. *Manufacturing yield* improvements dominate current and decline in yield, as one would expect. Clearly *product price* has a stronger influence on MVF than *manufacturing yield.*

The story for *r&d* expenditures is consistent with ADI’s problem of this case, described in Sect. 5.2.1 and illustrated with Fig. 5.6. *r&d* has made ADI technically excellent, but unable to produce financial performance. The result is a decline in MVF. An effective business strategy is more complicated than simply better technology.

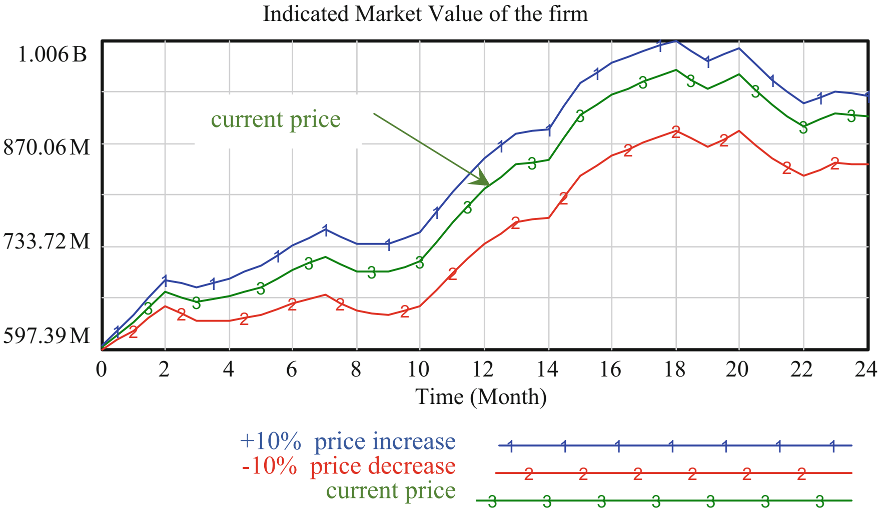


Fig. 5.3 MVF((2,2,2,2±),(222)) with higher, current, and lower price

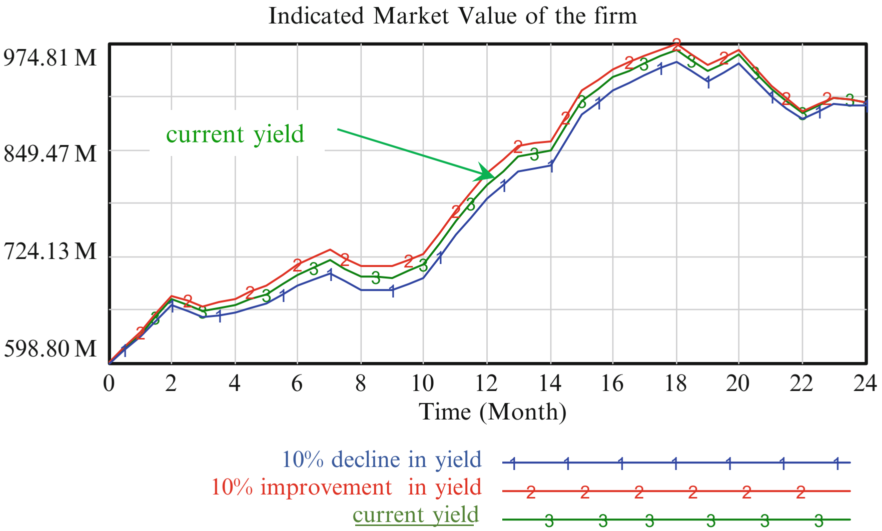


Fig. 5.4 MVF((2,2±,2,2),(222)) with higher, current, and lower manufacturing yield

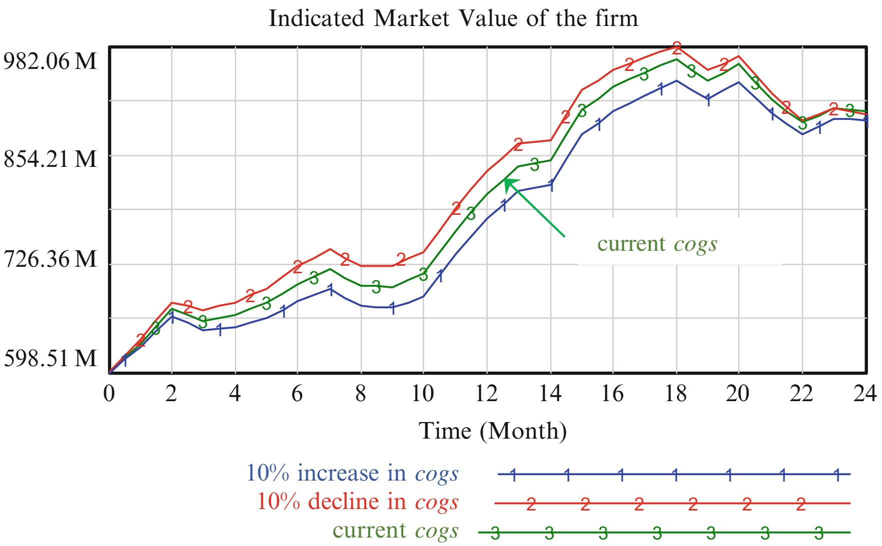


Fig. 5.5 MVF((2,2,2±,2),(222)) with higher, current, and lower *cogs*

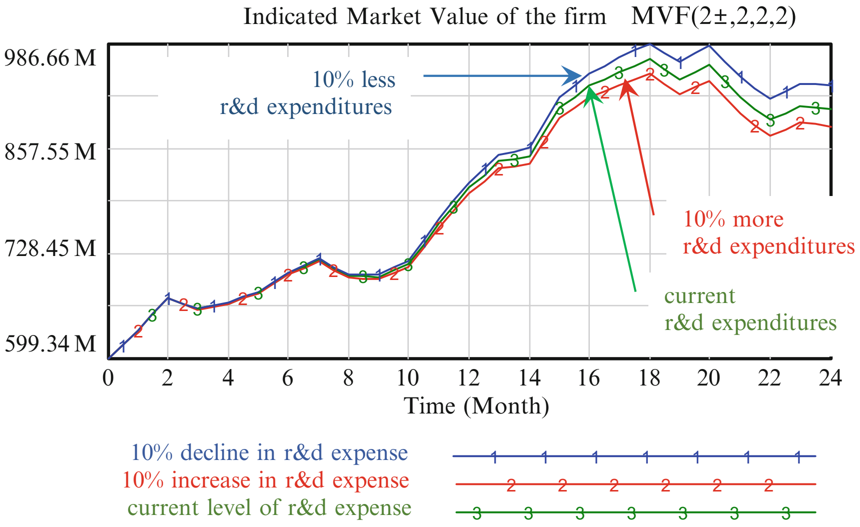


Fig. 5.6 MVF((2±,2,2,2),(222)) with higher, current, and lower r&d expense

Finding

For **MVF((2±,2±,2±,2±),(222))**, our controllable variables (*r&d budget, manufacturing yield, cogs, and product price*) influence the dependent variable, MVF, variable in the direction that is consistent with our understanding of the decision situation. MVF fluctuates in the opposite direction of *cogs*. Higher product costs reduces MVF. In the long run (t > 6) MVF moves in the opposite direction of *r&d*. This shows that for ADI's current strategy, all things being equal, *r&d* just depletes funds.

5.2.6.2 MVF = *f* (single uncontrollable variable)

In the previous Sect. 5.2.6.1, we have shown the change of MVF as a function of ***controllable*** variables, one variable at a time. We now turn our attention to the behavior of MVF as a function of ***uncontrollable*** variables, one variable at a time. The goal is now to determine whether there are causal linkages between the dependent variable MVF and our uncontrollable variables. For BAU under different uncontrollable conditions, we write MVF(BAU,(2±,2±,2±)), as appropriate. Note that BAU is short-hand for (2,2,2,2).

Figure 5.7 plots MVF(BAU,(2±,2,2)) as a function of time versus the uncontrollable factor, *growth of industry-demand*. Graph #3 shows MVF(BAU,(2,2,2)) with current *industry-demand growth* "as is". For 30% stronger *industry-demand*, MVF(BAU,(2+,2,2)) rises (graph #2). The "rising tide" indeed raises ADI's MVF. But for MVF(BAU(2−,2,2)) when *industry-demand growth* is diminished by 30%, MVF declines (graph #1). Beyond t = 4, graph #1 is everywhere dominated by graphs #2 and #3. The dependent variable MVF behaves as one would expect for changes in *industry-demand*. Its effect is not immediate, there is clearly discernable delay.

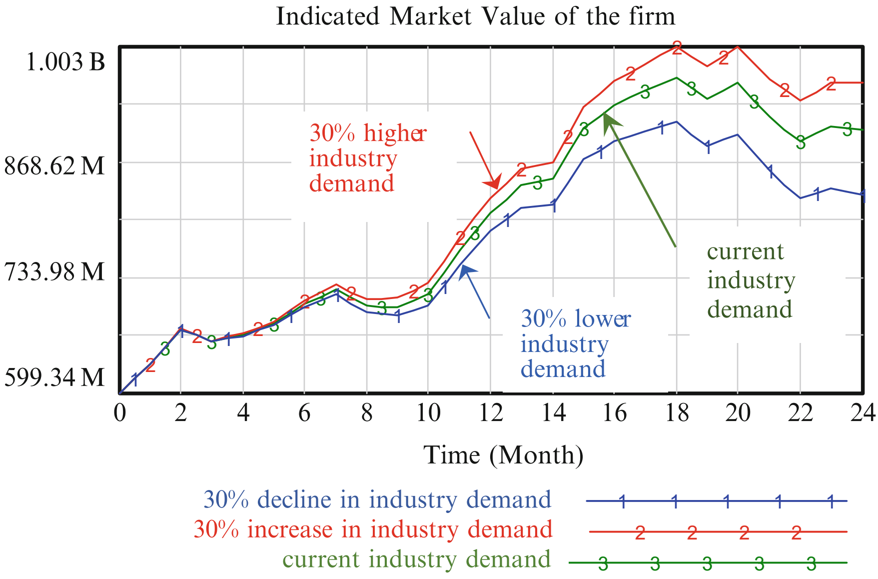


Fig. 5.7 MVF(BAU,(2±,2,2)) in higher, current, and lower industry demand

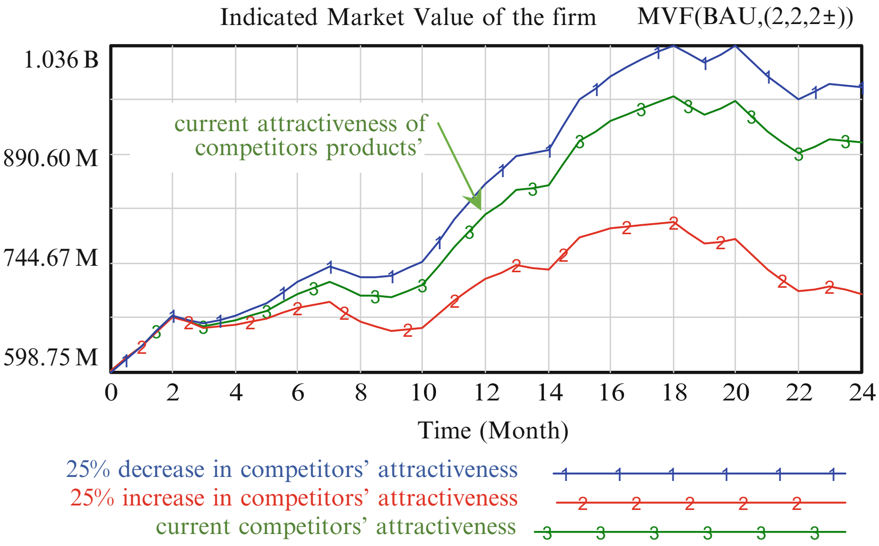


Fig. 5.8 MVF(BAU,(2,2±,2)) with higher, current, and lower competitors' products' attractiveness

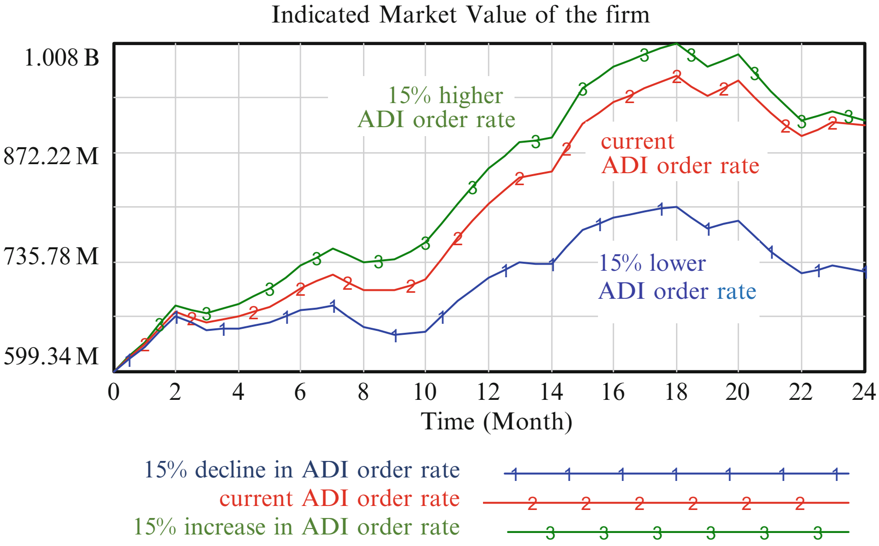


Fig. 5.9 MVF(BAU,(2,2,2±)) with higher, current, and lower order rate for ADI

Figures 5.8 and 5.9 plot MVF(BAU,(2,2±,2)) and MVF(BAU,(2,2,2±)) for the uncontrollable variables of *competitors products' attractiveness*, and *order rate* for ADI products. They show that MVF(BAU,(2,2,2+)) rises when ADI is more competitive and when *order rates* for ADI products rise MVF(BAU,(2,2+,2)). And the converse is apparent from the plots.

The stronger effects of *competitors* and customers' *order rate* for ADI products relative to *industry demand* on the MVF is evident from Figs. 5.7, 5.8 and 5.9. The market effects of *competitors* and *customer order rate* are far more intense than the industry macro variable of *industry demand* (Figs. 5.8 and 5.9 relative to 5.7) Moreover, this strong effect is present in both the upside and the downside of the uncontrollable variables. There is a delay in the timing of the impact of the uncontrollable variables. The *industry demand* macro variable makes its presence felt later by about 2 or more months. Note that the negative effect is significantly more pronounced than the positive effect. The need for robust solutions is evident.

Finding
For MVF((BAU),(2±2±2±)), our uncontrollable variables influence the dependent variable in the direction that is consistent with our understanding of the decision situation. MVF(BAU) rises with positive *industry demand*, and *ADI volume of orders*. MVF decreases with increased *attractiveness of the products from the competition*. This is consistent with our knowledge of the decision situation. The simulations support face and construct validity of these experiments.

5.2.6.3 MFV $= f$ (ensemble of uncontrollable variables)

In this section, we must introduce the idea of *uncertainty regimes*. The uncertainty space, like the decisions' alternative space, is very large. The idea of *uncertainty regimes* is to discretize the uncertainty space into a manageable set. We have shown the behavior of MVF *vis à vis* the uncontrollable variables one at a time. We now address the question: What is the behavior of Market-Value of Firm given distinctly different configurations of the uncontrollable variables?

We have three uncontrollable variables, each with three levels. The full factorial space is comprised of $3^3 = 27$ uncontrollable conditions. Thus, the uncertainty space is represented by 27 states. In Rittell and Webber's (1973) language, we have *tamed* the uncertainty space. Henceforth, the uncertainty space need not be an amorphous and intractable abstract idea. Twenty-seven is still a large number. And the cognitive load of 27 uncertainty regimes is still challenging. We resort to Miller's 7 ± 2 (Miller 1956) to *satisfice* ourselves with nine uncertainty regimes. We are most concerned with the conditions that are *worse* or *better* than the current state of uncertainty, i.e. better or worse than BAU. So, if we can specify the worst and the most favorable uncertainty regimes for MVF, we can be confident that the current state of uncertainty (2,2,2) is bracketed in between the best and worst regimes. We can specify a range of uncertainty regimes defined by the three uncontrollable variables at the end points of the three level specification. Thus we simplify to $2^3 = 8$ eight uncertainty conditions. Where "0" is the lowest and "1"is the highest of the levels 1, 2, and 3. The uncertainty space is systematically discretized into nine *uncertainty regimes* (Table 5.6), not just qualitatively as in

Table 5.6 Uncertainty regimes

Variables	Variable level								
Industry demand	Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher
ADI orders	Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger
Competitiveness	Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger
3-tuple	Current	(0,0,0) . . .	(0,0,1) Worst	(0,1,0) . . .	(0,1,1) . . .	(1,0,0) . . .	(1,0,1) . . .	(1,1,0) Best	(1,1,1) . . .

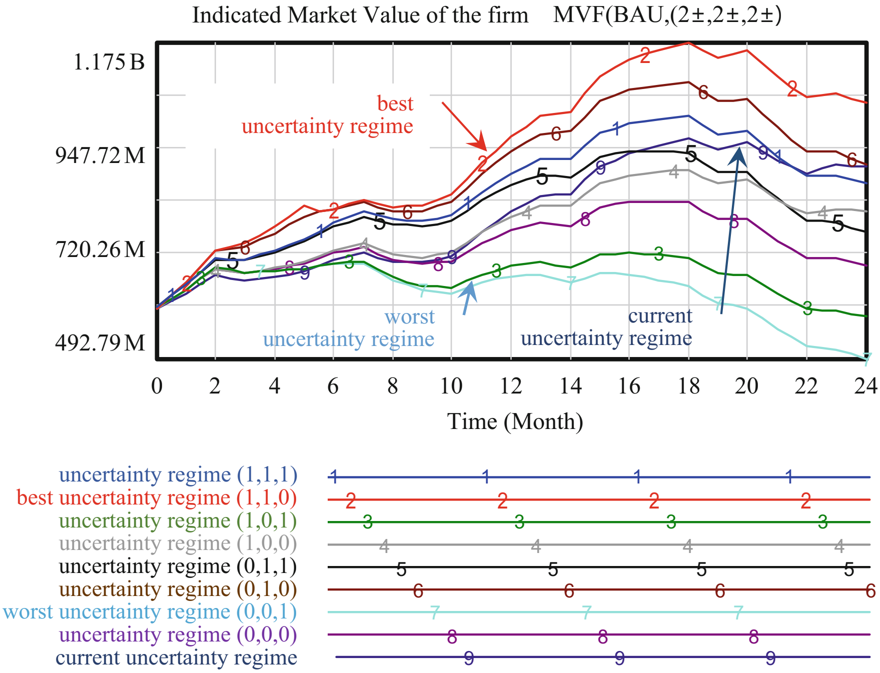


Fig. 5.10 MVF(BAU,(2±,2±,2±)) experiments under the entire *set of uncertainty regimes*

scenario analyses (e.g. van der Heijden 2011; Bradfield et al. 2005). The best uncertainty regime is (2,2,1), i.e. high *industry demand* growth, strong *ADI orders,* and weak *competitors product's*. Similarly, the worst uncertainty regime is (1,1,2) when *industry-demand growth* is weak*, ADI orders* are weak, and *competitors' products attractiveness* is strong.

Figure 5.10 shows the graphs of MVF(2,2,2,2) for all uncertainty regimes. They are bracketed between the best uncertainty regime of (1,1,0) graph #2 and the worst of (0,0,1) graph #7. The system dynamics of the interactions between the controllable and uncontrollable variables reveal that the uncontrollable regimes influence the behavior of the MVF outcomes differently throughout the decision life-cycle.

There is not a fixed order between the best and worst. For example graph #5 dominates graph #9 until t = 16. And at t = 21 graph #5 and #4 switch relative positions. The system behavior for MVF(2,2,2,2), it is not entirely linear; interaction effects reveal themselves at different times in the decision life-cycle. In Fig. 5.10, during the first 6 months, the lowest MVF is attained by graph #9 (***current*** uncertainty). Why is this so? MVF is given

$$MVF = max[(value\ of\ growth) + (PV\ of\ earnings), 0] \tag{5.1}$$

Value of growth, is a quantity that reflects Wall Street analysts' confidence (or lack of) in the potential improvement in ADI's performance. Because ADI is poorly managed, unable to produce profit (recall it fell from profit fell from \$46 M to \$6.2 M, Sect. 5.2.1). These factors are depressing MVF for the first 6 months. But Appendix 5.1 data and Fig. 5.10 data show that things could have been even worse, i.e. uncertainty regime (1,1,1). ADI is still vulnerable to uncertainty conditions by doing nothing different, i.e. sticking to BAU. It is apparent; that keeping the controllable variables, in the BAU state, demonstrates the flaw of inaction. These simulations indicate that the impact of uncertainty is forceful and convincing. It has a nontrivial impact on the performance of the dependent variable of MVF outcome.

Finding
Different configurations of the uncontrollable variables influence the MVF dependent variable in the direction that is consistent with our domain understanding of the decision situation. We showed this with one uncontrollable variable at a time in Figs. 5.7, 5.8, and 5.9. MVF under the uncertainty regimes (under ensembles of uncontrollable variables) also exhibits behavior that is consistent with our understanding of the problem (Fig. 5.10). MVF dominates performance under the best uncertainty regime (1,1,0). Conversely, MVF is consistently depressed under the worse uncertainty regime (0,0,1). Significantly, MVF is bracketed between these two regimes.

5.2.6.4 MVF = *f* (ensemble of controllable variables)

We have shown the behavior of MVF vis à vis the uncontrollable variables, one at a time. The next question is: How does MVF behave given variously different ensemble configurations of the controllable variables? We have four controllable variables each with three levels, the full factorial set has $3^4 = 81$ combinations. One of which is the BAU configuration of (2,2,2,2). The question is whether there are there other configurations of the controllable variables, experiments, that will outperform or underperform the MVF(BAU,(2,2,2))? In other words, does the configuration of controllable factor-levels matter? We need to thoughtfully answer this question before we can undertake the task of designing an experiment that can outperform BAU under unfavorable uncertainty regimes.

We surmise that an effective experiment is MVF(1,3,1,3), i.e. *r&d* is low (Fig. 5.6), *manufacturing yield* is high (Fig. 5.4), *costs of goods sold* (*cogs*) are low (Fig. 5.5), and *product price* is high (Fig. 5.3). Using similar reasoning, we reckon that MVF(3,1,3,1) is the least effective treatment. Figure 5.11 shows these three cases in the best uncertainty regime of (2,2,1). Graph #3, which is the surmised best experiment (2,2,2,2), exhibits the best performance for MVF, dominating all others. Graph #1, which is the surmised worst experiment (3,1,3,1) does indeed exhibit the worst performance. Graph #2 is the BAU experiment of (2,2,2,2) and is indeed bracketed between the best and worst experiments.

Figure 5.11 shows the behavior of MVF, for the surmised best and worst experiment, under the (2,2,1) uncertainty regime. The best experiment dominates the other experiments.

There are only three experiments shown in Fig. 5.11. But, Fig. 5.12 shows a wide variety of experiments for the output MVF. They are all bracketed by

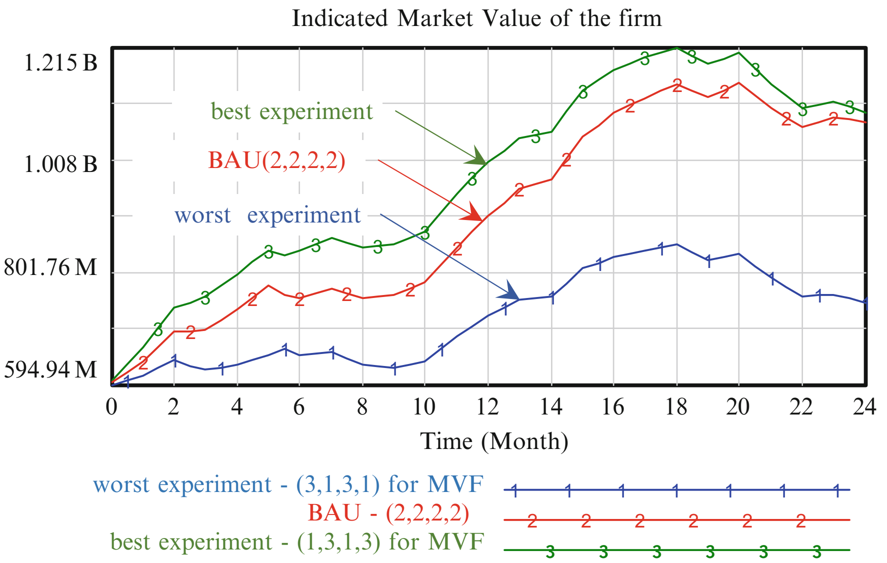


Fig. 5.11 MVF((3,1,3,1),(2,2,1)), MVF((2,2,2,2),(2,2,1)), and MVF((1,3,1,3),(2,2,1)) with surmised worst, BAU and worst experiments in the *best uncertainty regime of* (2,2,1)

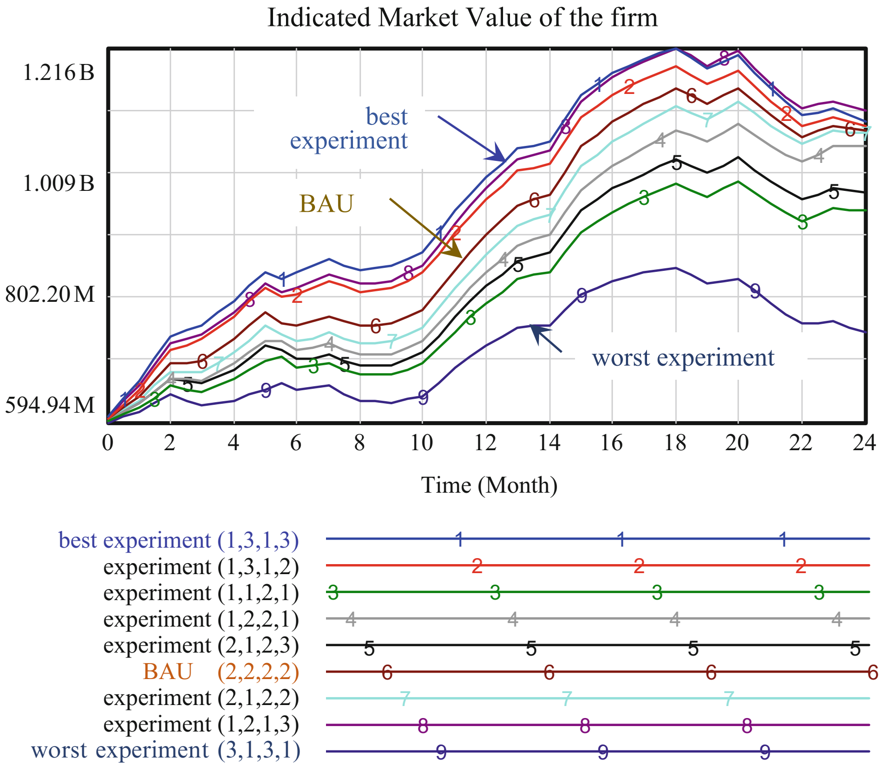


Fig. 5.12 MVF for a variety of experiments in the *best uncertainty regime* (2,2,1)

the best experiment and the worst experiment, with BAU somewhere in between.

Does this behavior (Fig. 5.12) of ADI's MVF persist in the worst uncertainty regime of (1,1,2)? The answer is in the affirmative as shown in Fig. 5.13. This figure is the analog of Fig. 5.12, but in the worst uncertainty regime for a different set of experiments and also bracketed by the best and worst experiments. And with BAU somewhere in between.

Findings

Our findings from these series of runs of the ADI surrogate support the belief that there are causal linkages among our independent variables of MVF and the

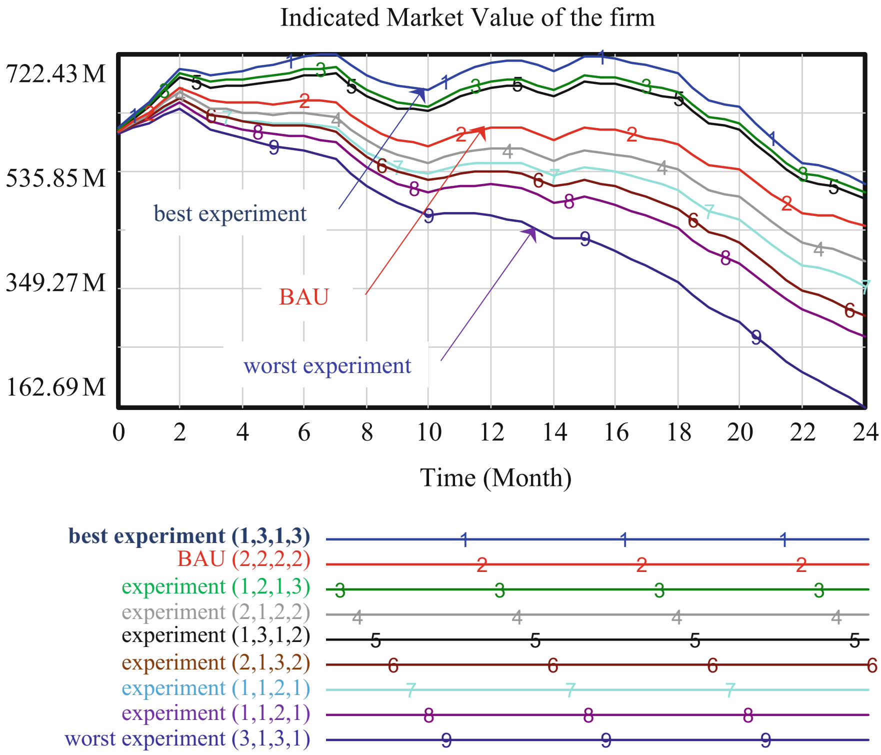


Fig. 5.13 MVF(BAU) and a variety of experiments in the *worst uncertainty regime* (1,1,2)

uncertainty regimes, i.e. the defined ensemble of dependent variables. The MVF outputs are consistent with our understanding of the corporate problem and the ADI business decision. MVF consistently rises under favorable uncertainty regimes, and the converse is also supported by the data. The simulations suggest that behavior of the ADI surrogate for MVF, given our controllable and uncontrollable variables, support face and construct validity of these experiments.

5.2.7 Summary Discussion

The goal of this section has been to test the adequacy of the ADI systems dynamics model as a surrogate company for our DOE-based decision analysis method. We framed a corporate decision, *maximizing the market value of the firm* (MVF). For this objective, we identified four controllable variables, which could be specified at three levels of performance. This gave us a space of $3^4 = 81$ possible configurations of factor-levels, they span the entire discretized Solution Space. We also simplified the uncertainty space from $3^3 = 27$ sunspaces into $2^3+1 = 9$ subspaces. We called these subspaces the *uncertainty regimes*. They span the entire uncertainty space. The size of the outcome space is then $81*9 = 729$ outcomes. It is significant and useful that the entire solutions space and uncertainty space have been discretized into more manageable sets. But for senior-executive decision-making this remains a very large space of outcomes to consider. In the remainder of this chapter, we will show how to systematically cope with this situation.

Recall, our first task was to test the behavior of the ADI surrogate using our controllable and uncontrollable variables. We tested the sensitivity of the dependent variable MVF against each of the controllable and uncontrollable variables one at a time. We followed this with a systematic set of tests to evaluate the sensitivity of the dependent variable MVF. We used ensemble configurations of structured controllable and uncontrollable variables at different levels. Significantly, the direction of the MVF movements are consistent with domain knowledge and our understanding of the decision situation. Equally important, the outcomes of the dependent variable MVF are also consistent with our understanding of the problem under different uncertainty conditions. Putting all this together, *these tests demonstrate the existence of a meaningful causal linkage between the independent and dependent variables*. We find that the ADI surrogate has face, construct, and internal validity. Table 5.7 summarizes the support for X-RL1.

Next we set out to test support of the predictive power of the controllable variables and to find support for our DOE-based decision analysis method.

Table 5.7 X-RL1 readiness level specifications for executive-management decisions

Readiness level	Our systematic process for the Problem Space	Functionality
X-RL1 Characterize Problem Space	Sense making—uncomplicate the cognitive load	☑
	Framing problem/opportunity–clarify boundary conditions	☑
	Specify goals and objectives	☑
	Specify essential variables Managerially controllable variables Managerially uncontrollable variables	☑

☑ indicates support is demonstrated

5.3 Engineering the Solution Space

> We do not have to know, or guess at, all the internal structure of the system but only that part of it that is crucial to the abstraction. (H.A. Simon)

5.3.1 Introduction

In this section, we will show how to engineer the solution space to maximize the Market Value of the Firm, MVF. In the Sect. 5.2, Characterizing the Problem Space, we framed the problem, specified the goals and objectives, and identified the controllable and uncontrollable variables. We also systematically verified that the controllable and uncontrollable variables pass our tests of face and construct validity. Behavior of the controllable and uncontrollable variables determine the outcome of MVF. We showed the direction of the MVF as a function of controllable and uncontrollable variables. However, *we do not yet have any data to support the predictive power of specific configurations of the controllable variables under uncertainty regimes*. This is our next step—to engineer the solution space and the uncertainty regimes by using specifically designed *gedanken* experiments. From these experiments, we will be able to design decision specifications to explore the solution space and analyze their outcomes to determine whether they generate our intended robust results.

5.3.2 The Subspaces of the Solution Space

In Sect. 3.3.3 of Chap. 3 (Eq. 3.3), we defined the solutions space as the Cartesian product of two spaces. This is now Eq. (5.2) in this chapter.

$$(\textit{controllable space}) \times (\textit{uncontrollable space}) = [\textit{output space}]. \tag{5.2}$$

We now proceed to construct each of these spaces. We begin with the controllable space, follow with the uncontrollable space, and finally with the output space.

5.3.2.1 Controllable Space = Alternatives Space

The controllable space is the sufficient sample set of alternatives from which we construct any new alternative and to predict its outcome and standard deviation. **This enables us to design any decision alternative anywhere in the controllable space and be able to predict its outcome** and **standard deviation. There is no alternative that cannot be analyzed.** We have four controllable variables, *r&d budget, IC yield,*[1] *cogs,* and *product price*. We array them in Table 5.8 (same as Table 5.3). For example, *r&d budget* is specified as *more-is-better*. ADI is a high technology company for which r&d is their lifeblood to maintain any technology advantages or to develop new competitive advantages.

With Table 5.8, we are able to construct Table 5.9, which is a schematic of the *entire* and *complete* set of actionable decision alternatives without uncertainty. It is the full factorial set of all combinations of the 4 variables at 3 levels, of which there are $3^4 = 81$ alternatives. Each row in Table 5.9 represents a specific decision alternative, as a 4-tuple representing a configuration of the controllable variables. For example, alternative 3 is represented as $(1,1,1,3)$ for *r&d budget* at −10%, *manufacturing yield* at −15%, *cogs* at −10%, and *product price* at −10%. Table 5.8 **shows how the complexity of the entire variety of actionable alternatives has been discretized into a finite set.** The first two columns of the arrays in Appendix 5.1 shows the entire list of all 81 4-tuples that specify the complete set of alternatives, alternatives. The set is still large and complicated, but we will show how it can reduced.

The purpose of having decision alternatives is to predict how they will perform. From that data and information, the objective is to ***engineer*** a decision a specification that will satisfice the stated goals and objectives. The outputs of each alternative are shown by the column identified as **output,** $\boldsymbol{y_\alpha} = f\,(alternative\ \alpha)$. But these outcomes are under ideal conditions **without** any uncertainty. Of course, this is not realistic. The question is, therefore, how construct the uncontrollable space. How to address this question of decisions' uncertainties is the topic of the next Sect. 5.3.2.2.

5.3.2.2 Uncontrollable Space: Uncertainty Space

Every alternative will operate under some form of uncertainty, determined by uncontrollable variables. As in the case of controllable variables, we need to ***discretize*** the uncertainty space to make it manageable. We use the uncontrollable

Table 5.8 Controllable variables and levels

Controllable factors	Level 1 (%)	Level 2	Level 3 (%)	Characteristic
r&d budget	−10	Current level	+10	More is better
IC yield	−15	Current level	+15	More is better
cogs	−10	Current level	+10	Less is better
Product price	−10	Current level	+10	More is better

---

[1] IC yield and manufacturing yield are used interchangeably.

Table 5.9 Entire set of alternatives and outputs under NO uncertainty

	(r&d budget, IC yield, *cogs*, Product price)	$\boldsymbol{y}_{\boldsymbol{\alpha}} = f$ (alternative $\boldsymbol{\alpha}$) $1 \leq \boldsymbol{\alpha} \leq 81$
alternative 1	(1,1,1,1)	$\boldsymbol{y_1}$
alternative 2	(1,1,1,2)	$\boldsymbol{y_2}$
alternative 3	(1,1,1,3)	$\boldsymbol{y_3}$
alternative 4	(1,1,2,2)	$\boldsymbol{y_4}$
...	...	...
alternative 66	(3,2,1,1)	$\boldsymbol{y_{66}}$
alternative 67	(3,2,2,1)	$\boldsymbol{y_{67}}$
...	...	...
alternative 78	(3,3,2,3)	$\boldsymbol{y_{78}}$
alternative 79	(3,3,3,1)	$\boldsymbol{y_{79}}$
alternative 80	(3,3,3,2)	$\boldsymbol{y_{80}}$
alternative 81	(3,3,3,3)	$\boldsymbol{y_{81}}$

variables to represent the space of uncertainty. Our three uncontrollable variables are: *growth rate in industry demand*, *ADI orders*, and *competitors products' attractiveness*. We array these uncontrollable variables in Table 5.8.

Using Table 5.10 (same as Table 5.4), we derive the full factorial set of uncertainty conditions. The complexity of the requisite variety of uncertainties has been discretized into a finite set of $3^3 = 27$ uncertainty conditions (Table 5.11). For example, the current state of uncertainty is (2,2,2), uncertainty 14.

5.3.2.3 Solution Space = {Alternatives space} × {Uncertainties}

Recall that the *output space* of the solution space is the Cartesian product of two mutually exclusive sets, Eq. (5.2). Schematically, the output matrix looks like Table 5.12.

The universe of alternatives under certainty is the set {*alternative* α}, where $1 \leq \alpha \leq 81$ at each of 27 uncertainty conditions. Therefore, the universe of alternatives under uncertainty is the set of 81 alternatives under the 27 uncertainty conditions. Thus the number of alternatives under uncertainty is $4^3 \times 3^3 = 27 \times 81 = 2187$. This set is shown as follows in shorthand in Table 5.12. **We have discretized the complexity of the entire set of alternatives under the entire set of uncertainties by the Cartesian product of two discrete sets.**

We have the following. First, how to represent the entire set of decision alternatives without considering uncertainties (Table 5.9). Second, how to represent the *entire set of uncertainty conditions* (Table 5.11). And finally, how the Cartesian product of the set of alternatives with the set uncertainty space produce the set of alternatives under every uncertainty condition (Table 5.12). In the next section we

Table 5.10 Uncontrollable factors at three levels each

Uncontrollable factors	Level 1 (%)	Level 2	Level 3 (%)	Characteristic
Industry growth rate	−25	Current level	+10	High is better
ADI orders rate	−25	Current level	+15	Fast is better
Competitors' attractiveness	−10	Current level	+10	Less is better

Table 5.11 Entire set of uncertainties (uncontrollable space)

Uncertainties 1–9		Uncertainties 10–18		Uncertainties 19–27	
1	(1,1,1)	**10**	(2,1,1)	**19**	(3,1,1)
2	(1,1,2)	**11**	(2,1,2)	**20**	(3,1,2)
3	(1,1,3)	**12**	(2,1,3)	**21**	(3,1,3)
4	(1,2,1)	**13**	(2,2,1)	**22**	(3,2,1)
5	(1,2,2)	**14**	(2,2,2)	**23**	(3,2,2)
6	(1,2,3)	**15**	(2,2,3)	**24**	(3,2,3)
7	(1,3,1)	**16**	(2,3,1)	**25**	(3,3,1)
8	(1,3,2)	**17**	(2,3,2)	**26**	(3,3,2)
9	(1,3,3)	**18**	(2,3,3)	**27**	(3,3,3)

will show how to reduce the size of this set, how to predict the outcomes for this reduced set, and how to construct the optimally robust decision alternative.

5.3.2.4 Uncertainty Regimes

We discussed, in Sect. 5.2.6.3, how to reduce the size of the uncertainty space, by specifying ***uncertainty regimes*** using configurations of uncontrollable variables. We developed the idea of uncertainty regimes to *uncomplicate* the uncertainty space to enable us to specify a *cognitively tractable* set of uncertainties to enable us to exhaustively explore the behavior of the sociotechnical system under any uncertainty condition (Table 5.6). This facilitates our ability to systematically explore alternative decision specifications to find and design the decision of choice that can satisfice an organization's prospects.

To evaluate any improvement requires a reference point. We specify the reference point as the current state of the controllable variables (the BAU state) and the current state of uncontrollable variables as the current *uncertainty regime* (2,2,2). This is reasonable and practical. We can expect the organization to have archival records on organizational performance and historical information on the uncontrollable variables.

However going forward, we cannot assume the uncontrollable environment will remain unchanged. Therefore, in addition to the base-line's specification, we need to complete three additional tasks. They are to specify: (i) the current state of the controllable variables, (ii) one or more specifications of *favorable states* of

Table 5.12 Entire set of alternatives outputs under entire set of uncertainty conditions

$\mathbf{y}^{j}_{\alpha} = f$ (*alternative* α, *uncertainty* j) $1 \le \alpha \le 81$, $1 \le j \le 27$		Uncertainty **1**	Uncertainty **2**	Uncertainty **3**	Uncertainty **4**	…	Uncertainty **25**	Uncertainty **26**	Uncertainty **27**	$\bar{y}_{\alpha}$	σ_{α}
alternative 1	(1,1,1,1)	$\mathbf{y}^{1}_{1}$	$\mathbf{y}^{2}_{1}$	$\mathbf{y}^{3}_{1}$	$\mathbf{y}^{4}_{1}$		$\mathbf{y}^{25}_{1}$	$\mathbf{y}^{26}_{1}$	$\mathbf{y}^{27}_{1}$	$\bar{y}_{1}$	σ_{1}
alternative 2	(1,1,1,2)	$\mathbf{y}^{1}_{2}$	$\mathbf{y}^{2}_{2}$	$\mathbf{y}^{3}_{2}$	$\mathbf{y}^{4}_{2}$		$\mathbf{y}^{25}_{2}$	$\mathbf{y}^{26}_{2}$	$\mathbf{y}^{27}_{2}$	$\bar{y}_{2}$	σ_{2}
alternative 3	(1,1,1,3)	$\mathbf{y}^{1}_{3}$	$\mathbf{y}^{2}_{3}$	$\mathbf{y3}_{3}$	$\mathbf{y}^{4}_{3}$		$\mathbf{y}^{25}_{3}$	$\mathbf{y}^{26}_{3}$	$\mathbf{y}^{27}_{3}$	$\bar{y}_{3}$	σ_{3}
alternative 4	(1,1,2,1)	$\mathbf{y}^{1}_{4}$	$\mathbf{y}^{2}_{4}$	$\mathbf{y}^{3}_{4}$	$\mathbf{y}^{4}_{4}$		$\mathbf{y}^{25}_{4}$	$\mathbf{y}^{26}_{4}$	$\mathbf{y}^{27}_{4}$	$\bar{y}_{4}$	σ_{4}
…	…	…	…	…	…	…	…	…	…	…	…
alternative 41	(2,2,2,2)	$\mathbf{y}^{1}_{41}$	$\mathbf{y}^{2}_{41}$	$\mathbf{y}^{3}_{41}$	$\mathbf{y}^{4}_{41}$		$\mathbf{y}^{25}_{41}$	$\mathbf{y}^{26}_{41}$	$\mathbf{y}^{27}_{41}$	$\bar{y}_{41}$	σ_{41}
…	…	…	…	…	…	…	…	…	…	…	…
alternative 79	(3,3,3,1)	$\mathbf{y}^{1}_{79}$	$\mathbf{y}^{2}_{79}$	$\mathbf{y}^{3}_{79}$	$\mathbf{y}^{4}_{79}$		$\mathbf{y}^{25}_{79}$	$\mathbf{y}^{26}_{79}$	$\mathbf{y}^{27}_{79}$	$\bar{y}_{79}$	σ_{79}
alternative 80	(3,3,3,2)	$\mathbf{y}^{1}_{80}$	$\mathbf{y}^{2}_{80}$	$\mathbf{y}^{3}_{80}$	$\mathbf{y}^{4}_{80}$		$\mathbf{y}^{25}_{80}$	$\mathbf{y}^{26}_{80}$	$\mathbf{y}^{27}_{80}$	$\bar{y}_{80}$	σ_{80}
alternative 81	(3,3,3,3)	$\mathbf{y}^{1}_{81}$	$\mathbf{y}^{2}_{81}$	$\mathbf{y}^{3}_{81}$	$\mathbf{y}^{4}_{81}$		$\mathbf{y}^{25}_{81}$	$\mathbf{y}^{26}_{81}$	$\mathbf{y}^{27}_{81}$	$\bar{y}_{81}$	σ_{81}

$\bar{y}_{\alpha} = average(\mathbf{y}^{1}_{\alpha}, \mathbf{y}^{2}_{\alpha}, \mathbf{y}^{3}_{\alpha}, \ldots, \mathbf{y}^{26}_{\alpha}, \mathbf{y}^{27}_{\alpha})\ 1 \le \alpha \le 81$

$\sigma_{\alpha} = stdev(\mathbf{y}^{1}_{\alpha}, \mathbf{y}^{2}_{\alpha}, \mathbf{y}^{3}_{\alpha}, \ldots, \mathbf{y}^{26}_{\alpha}, \mathbf{y}^{27}_{\alpha})\ 1 \le \alpha \le 81$

Table 5.13 Values for the BAU state and the current environmental condition

Controllable factors	BAU level	Numeric value
r&d Budget	2	\$28.47 M
Manufacturing yield	2	20%
cogs	2	\$11.28 M
Product price	2	\$17.38

Current uncertainty regime	Condition level	
Growth in demand	2	2%
ADI orders	2	1.487 M
Competitors' products attractiveness	2	4.955e-005 (an index)

uncontrollable states, and (iii) specifications of *less favorable states* of uncontrollable states. *More* or *less* favorable conditions are defined relative to the actual state of uncontrollable conditions. In the paragraphs that follow, we will show how to perform these tasks.

5.3.2.5 Business As Usual (BAU) Under Uncertainty Regimes

Table 5.13 shows the specifications for the **BAU** alternative (Table 5.5 reproduced here), which is the do nothing different alternative (2,2,2,2) in the current uncertainty-regime.

The next tasks are to specify *more favorable* uncontrollable conditions and *less favorable* uncertainty regimes. *More* or *less* favorable are relative to the current state of uncontrollable variables. We will specify the BAU(2,2,2) specification in a linearly ordered range of uncertainty conditions, which includes the current uncertainty regime is called the **base-line**. The base line is useful to bracket the BAU behavior between the current uncertainty regime, more favorable and less favorable regimes.

5.3.3 Summary Discussion

The objectives of this section has been to represent the solution space and to prescribe how to specify the base line using the current, more favorable, and less favorable uncertainty regimes. This base line is a fundamental building block for us to be able to forecast results of designed alternatives. Table 5.14 summarizes the support for X-RL2. We have demonstrated that our methodology is XRL-2 (Table 6.14).

Table 5.14 Readiness level specifications for executive decisions

Readiness level	Systematic process for the solution space	Functionality
X-RL2 Engineer solution space	Specify subspaces of solution space Alternatives space and uncertainty space	☑
	Specify entire solution space	☑
	Specify base line and uncertainty regimes Do-nothing case and choice-decision Estimate base line and dispel bias	☑

The symbol ☑ indicates support is demonstrated

5.4 Exploring the Operations Space

> I have come to believe that this is a mighty continent which was hitherto unknown. (Columbus)

5.4.1 Introduction

We now take the next step and explore the operations space to ***phenomenologically*** extract its system behavior. We explore the operations space using four DOE representation schemas for the ADI sociotechnical system. These representations will be used to analyze its behavior for MVF The phenomenological data and insights obtained will give us sufficient information to predict outcomes of any designed decision alternatives under any uncertainty-regime. We will use different schemas, of different experimental resolutions, to extract phenomenological data about the sociotechnical system that implements decision specifications. The methodology for each representation schema is the same, but the size and complexity of each schema is different because they differ in resolution. The volume of extracted volume data and information follows the size and complexity of the schema. We will be discussing the implications of this fact in order to answer the following question: does more information improve our understanding of the sociotechnical system? What information is lost with simpler experiments? Does it matter? To address these questions, DOE is the exploration mechanism (Fig. 5.14) of the operations space.

We will use three representation schemas to investigate the Solution Space. First is the *full-factorial* space $L_{81}(3^4, 2^{3+1})$ of 4 controllable variables under 10 uncertainty regimes (Tables 5.9 and 5.11). The uncertainty-regimes are comprised of three uncontrollable variables at two levels. The set of 10 uncertainty regimes is denoted by 2^{3+1} (Table 5.6) with the additional current uncertainty-regime makes 10 altogether.

We start with the full-factorial experiment. This the most complete set of experiments (Appendix 5.1). This set gives us the outcomes over the entire solution space, under all the nine uncontrollable uncertainty regimes. We use these results as

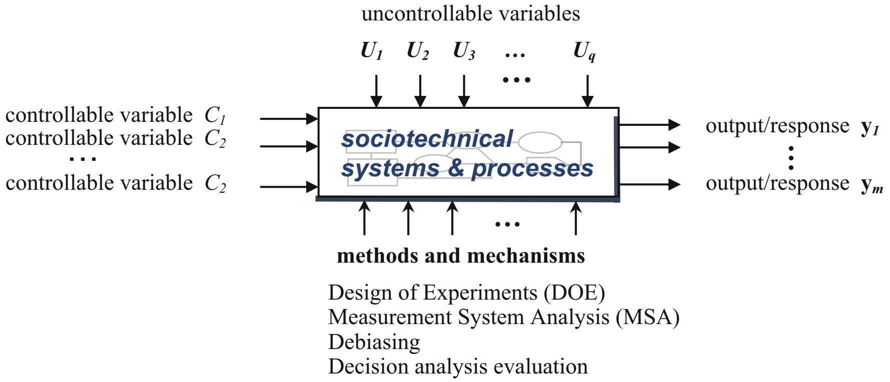


Fig. 5.14 Architecture of the operations space and role of the DOE mechanism

Table 5.15 Progression of experiments for DOE testing of MVF

Experimental design		Number of experiments	Uncertainty regimes	Complexity
$L_{81}(3^4,2^3+1)$	Full factorial	**81**	9 plus current state	Higher
$L_{27}(3^{4-1},2^3+1)$	High resolution	**27**	9 plus current state	Medium
$L_9(3^{4-2},2^3+1)$	Low resolution	**9**	9 plus current state	Low

our "gold standard" against which we will compare the results obtained from simpler experiments. And if the simpler tests yield sufficiently close results, then we can conclude that a simpler experiment may be acceptable. And if the results are sufficiently close, we want to know the conditions under which this is consistently possible. Naturally, more complex experiments produce more data. With additional data, we would like to know what additional insights we may gain from more complex experiments. And we would like to know what data and information we miss with simpler experiments. We summarize our three exploratory approaches in Table 5.15.

The second representation of the solution space is the $L_{27}(3^{4-1},2^{3+1})$ using an *orthogonal* array of 27 rows (Appendix 5.4). Orthogonal means that all three levels, for each of the three variables, are equally represented in every column. Equally represented means that the levels of the factors appear an equal number of times in the experiments. The experimental structures are designed to collect no more data for any particular variable or level. If an array's the non-orthogonal columns are few, the array is said to be *nearly orthogonal* (Wu and Hamada 2000: 311). There are situations for which constructing nearly orthogonal arrays is useful. The symbol 3^{4-1} means that a subset, of $3^{4-1} = 27$, experiments from the 3^4 full factorial are represented.

The third representation of the solution space is the $L_9(3^{4-2},2^{3+1})$ orthogonal array, which is comprised of 9 experiments and 9 uncertainty conditions. This is the simplest orthogonal array experiment we can perform (Appendix 5.8).

What is to be gained by proceeding in this way, proceeding from the most complex to successively simpler experiments? And why is it important? This systematic approach is meaningful because we want to know the simplest experiment we can perform that will give us sufficient data for a decision. And we want to go about this task systematically. A systematic approach avoids missing opportunities to explore and learn; moreover, any findings are then convincing and forceful. The simplest experiment may be meaningful and useful because any experiment is costly. The kind of experiments we will be studying—decisions for corporate problems—are generally very expensive. They require corporate staffs to collect data and perform analysis, experts to review, and management time to evaluate and discuss. Invariably new procedures and expertise are required. New equipment may need to be acquired. Specialized expertise may not exist in-house. Occasionally, high-priced consultants need to be engaged to investigate and propose solutions outside the organization's expertise. Simpler experiments mean faster results and more frugal expenditures.

5.4.2 Solution Space for MVF($L_{81}(3^4, 2^3+1)$)

5.4.2.1 Analyses of MVF($L_{81}(3^4, 2^3+1)$)

The data set for MVF($L_{81}(3^4, 2^3+1)$) is in Appendix 5.1 at the time of t = 12, i.e. 12 months out; t = 0 is the time when the experiment begins, when the decision is committed and implementation begins (Appendix 5.1.1). The data sets for t = 18 months and t = 24 months are in Appendix 5.1.2 and 5.1.3. Since this is the full factorial space, we can find, *by inspection*, the experiment for which MVF reaches its maximum. Table 5.16 shows that the best decision alternative is (1,3,1,3) by inspection of Appendix 5.1. The MVF(L_{81}(1,3,1,3), 2^3+1) experiment for the three time periods ending at t = 12, 18 and 24. The (1,3,1,3) decision-design is the one in which *r&d* is low, IC manufacturing *yield* is high, *cogs* is low, and *price* is high. In general, one would expect that high r&d would exert a positive impact on the value of a firm since it serves to strengthen product functionality and quality. But as we saw in Fig. 5.6, in ADI at this time it depresses MVF. That the best design has r&d at the lowest level may be counter intuitive, but ADI management emphasis on product quality has led to their current problems (Sect. 5.2.1). The standard deviations increase from t = 12 to t = 24. The standard deviations increase further out in time. Average standard deviations increase from 3.68, 6.29 to 14.55 for t = 12, 18, and 24 respectively and also at the maximum MVF (Table 5.16) showing that there is less precision in the predictions for outcomes. Therefore there is more risk.

Table 5.16 Maximum MVF ($L_{81}(3^4, 2^3+1)$) and standard deviation at t = 12, 18 and 24

Period	Experiment	MVF($L_{81}(3^4, 2^3+1)$)	Stdev at Max
t = 12	1,3,1,3	\$870.09 M	106.2
t = 18	1,3,1,3	\$970.82 M	177.5
t = 24	1,3,1,3	\$820.73 M	185.3

Table 5.17 $L_{81}(3^4, 2^3{+}1)$ ANOVA for MVF for $t = 12$

Source	DF	Seq SS	Adj SS	Adj MS	F	P
r&d	2	1623	1623	812	52.61	0.000
yield	2	63,350	63,350	31,675	2053.25	0.000
cogs	2	62,825	62,825	31,413	2036.26	0.000
price	2	168,603	168,603	84,301	5464.65	0.000
yield**cogs*	4	1340	1340	335	21.72	0.000
yield*price	4	901	901	225	14.61	0.000
*cogs**price	4	556	556	139	9.01	0.000
yield**cogs**price	8	263	263	33	2.13	0.049
Error	52	802	802	15		
Total	80	300,263				
$S = 3.92768$, R-Sq = 99.73%, R-Sq(adj) = 99.59%						

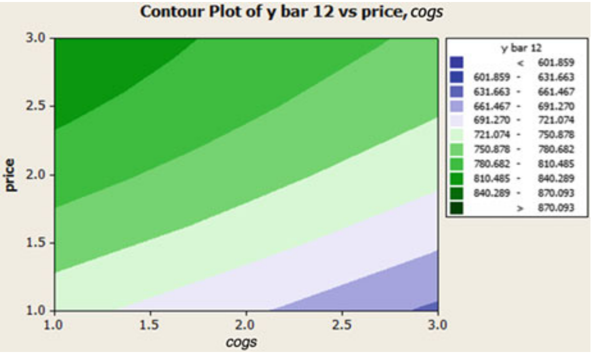


Fig. 5.15 Contour lot of price versus *cogs* for MVF at $t = 12$

For insight into this experiment, we take a detailed look at the statistics. Table 5.17 shows the ANOVA statistics for $L_{81}(3^4, 2^3{+}1)$ at $t = 12$.

All the controllable variables are statistically significant with $p = 0.000$. They are strong predictors of the outcome of MVF. There are three 2-factor interactions (2-fi) and one 3-factor interaction (3-fi). The 2-fi interactions are *yield*cogs*, *yield*price*, and *cogs*price*. The 3-fi is *yield*cogs*price*. They are also statistically significant, but their contributions are small. All interactions have $p = 0.000$ except for the 3-fi of *yield*cogs*price* with $p = 0.049$, it just makes the cut for statistical significance with $p < 0.05$. Without loss of generality, it can be considered part of the error term.

The R^2 statistics are very good. R-Sq = 99.73% and R-Sq(adj) = 99.59% for the MVF($L_{81}(3^4, 2^3{+}1)$) data. The 2-fi *cogs*price* is depicted graphically in Fig. 5.15 as a 2-dimensional response plot. The colors represent areas of iso-influence on MVF. For example, the dark-green triangle in the North-West corner shows that a high *price* obliges low *cogs* for the interaction to have an on MVF > \$810.00+. The near-decomposability as a quasilinear linear behavior is seen by the nearly parallel bands of colors.

The MVF($L_{81}(3^4, 2^3+1)$) experimental design also exhibits the three key properties—of hierarchy, sparsity, and heredity—stipulated by DOE scholars (Wu and Hamada 2000, Sect. 3.4.3.2). The hierarchy property states that single variable effects also called main effects (me), are more important than interactions' effects. The 2-fi are more important than 3-fi. And n-fi are more important than (n+1)-fi. Data from Table 5.17 show that:

$$\sum(\text{Adj SS})_{\mathbf{me}} = [1623 + 63350 + 62825 + 168603] = 296{,}401 \text{ for main effects, and}$$
$$\sum(\text{Adj SS})_{\mathbf{fi}} = [1340 + 901 + 556 + 263] = 3{,}060 \text{ for factor interactions.}$$

The total Adj SS of the single variables overwhelm the sum of interactions' SS. This is evidence of sparsity, i.e. relatively few variables dominate the overall effects. This is apparent by the SS contributions of the four controllable variables. Heredity is the property that in order for an interaction to be significant, at least one of its variables should be significant. Each of the variables in the 2-fi and 3-fi is a significant predictor of behavior of MVF($L_{81}(3^4, 2^3+1)$). These findings of the DOE properties support our choice of variables and constructs. The interactions are a very small percentage of the total Adj. MS. Although 2-fi and 3-fi are present, their contribution to the outcome are small. The behavior of the MVF($L_{81}(3^4,2^3+1)$) model is quasi-linear and near-decomposable (Simon 1997, 2001).

We now examine a histogram of the residuals. Residuals are the data that are not accounted for by the variables and interaction statistics. In a good model, the data points should be random, indicating residuals carry no useful information. In other words, the variables and their interactions amply predict the outcome. Residuals should be normally distributed N(0,σ), mean of zero, a standard deviation for some σ value and $p > 0.05$.

For $L_{81}(3^4,2^3+1)$, the residuals have zero mean. The mean is 3.22814e-14, which can be assumed to be zero, and $\sigma = 0.167$. However, $p = 0.007$, the hypothesis that the distribution is Gaussian normal is not supported. There are *outliers*. Their presence show that our DOE model is noisy; it is imperfect representation of the business process. Since no experiment is perfect, some outliers can be expected. In practice, outliers can be removed, provided they are a very small fraction of the total. We remove outliers (experiments #15, 24, 27, 42, 69, 8). The residuals now form a normal distribution (Figs. 5.16 and 5.17). We shall show, in the subsequent sections of this chapter, that the L_{27} and L_9 models behave more "regularly", their residuals are normal N(0,σ).

Our findings from the ANOVA statistics for the time periods ending at $t = 12$, $t = 18$, and $t = 24$ are in Table 5.18 (details are presented in Appendix 5.2.1 and 5.2.2). The DOE model is good and supports our choice of controllable variables. At each of these time periods, the DOE properties of *hierarchy, sparsity, and heredity* (Wu and Hamada 2000, Sect. 3.4.3.2) are prominently visible. Every controllable variable is a strong predictor, with $p = 0.000$, in the MVF($L_{81}(3^4,2^3+1)$) model.

Fig. 5.16 $L_{81}(3^4, 2^3{+}1)$ residuals of ANOVA of MVF for t = 12, excluding outliers

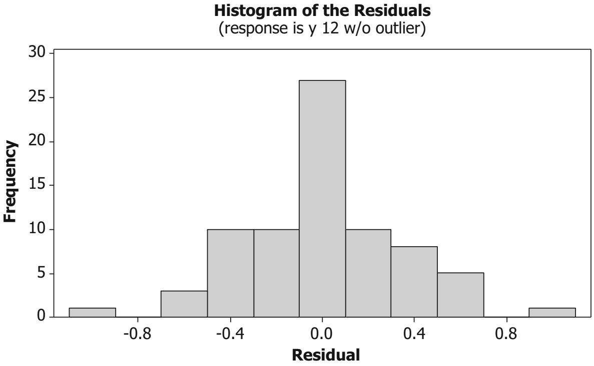


Fig. 5.17 $L_{81}(3^4, 2^3{+}1)$ residuals of ANOVA of MVF for t = 12, without outliers

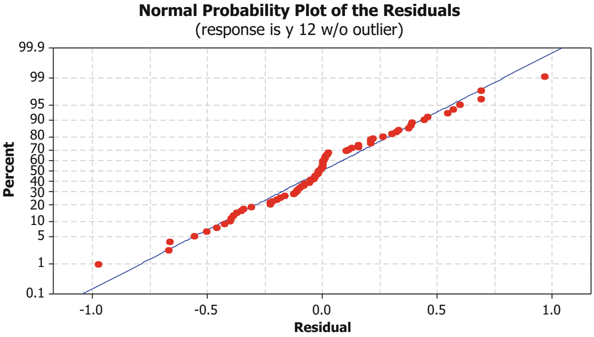


Table 5.18 $MVF(L_{81}(3^4, 2^3{+}1))$ summary for t = 12, 18 and 24

$MVF(L_{81}(3^4, 2^3{+}1))$						
	t = 12		t = 18		t = 24	
Factors	Adj. MS	p value	Adj. MS	p value	Adj. MS	p value
r&d	812	0.000	5018	0.000	10,162	0.000
yield	31,675	0.000	41,267	0.000	31,544	0.000
cogs	31,413	0.000	44,334	0.000	33,024	0.000
Product price	84,301	0.000	137,643	0.000	123,712	0.000
yield**cogs*	335	0.000	2356	0.000	6495	0.000
yield*price	225	0.000	2021	0.000	6161	0.000
*cogs**price	139	0.000	1623	0.000	5743	0.000
yield**cogs**price	33	0.049	326	0.000	1030	0.000
error	15	–	4	–	5	–
total	148,948	–	234,592	–	217,876	–
R^2 adj	99.6%		99.9%		99.9%	

Table 5.19 MVF($L_{81}(3^4, 2^3{+}1)$) MS adj ratio of interactions and no interactions for t = 12, 18 and 24

	t = 12		t = 18		**t = 24**	
	Interations	No interaction	Interations	No interaction	Interations	No interaction
∑MS-adj	732	148,201	6326	228,262	19,429	198,442
Ratio of total	732/148,201 = **0.49%**		6326/228,262 = **2.77%**		19,429/ 198,442 = **9.79%**	

As a complex sociotechnical system, interactions of the controllable variables are present (Table 5.18). There are three 2-fi of *yield*cogs*, *yield*price*, and *cogs*price*. And one 3-fi, *yield*cogs*price*. Every p value for the interactions are $p << 0.05$. They are all statistically significant predictors of the outcome. But relative to the main variables, they are very small contributors to the outcome. All the 2-fi, *yield*cogs*, *yield*price*, *cogs*price* and the 3-fi of *yield*cogs*price* all have $p = 0.000$; except for 3-fi at $t = 12$ with $p = 0.049$, indicating that it too is a statistically significant predictor of the outcome, albeit with very small impact.

A summary statistics for the interactions at the time periods of t = 12, t = 18 and t = 24 are in Table 5.19. For each period, we add MS-adj. for two groups, the controllable variables p and for the interactions. We find that the ratio of the ∑ MS-adj(nteractions) to ∑MS-adj(no interactions) is small. The influence of the interaction on the outputs is weak. The sociotechnical system is nearly-decomposable (Simon 1997, 2001).

The collective contributions of the interactions increase with time although they remain small (Table 5.19. The explanation for this lies in ADI's nature as a complex system. A defining hallmark, of a complex system, is that the aggregate of **stocks** and **flows** determine the behavior of the system (e.g. Sterman 2000). A stock is a system element that can accumulate the content of flows. For example, a bathtub accumulates water, a spring stores energy, a capacitor stores charge, a company accrues profit; they are all stocks. Stocks delay many of the system responses. It takes time to fully charge a capacitor. There is a lag between the time one turns on the hot water faucet and the time one is able to sense the rise in temperature. The cold water in the pipes delays the arrival of warm water.

Empirical data of the interactions from our experiment point to the phenomenon of the increasing contribution of the interactions at t = 12, 18, and 24. For example, between *manufacturing yield* and *product price* there are a set of complex causal relations involving stocks and flows. There are many more paths (than the one described below) that include many mediating variables. We limit ourselves to a single chain of events to simplify the illustration. x→y indicates $y = f(x)$ where f is an analytic construct, which can be algebraic, a derivative or an integral. An integral is a stock.

Manufacturing Yield → *Manufacturing Cost of Finished Good*
→ *Manufacturing Cost of Goods Sold* → *Cost of Goods Sold*
→ *Total per Unit Cost* → *Perceived Total Per Unit Cost*
→ *Target Price* → *Product Price*.

There are many stocks, e.g. *Manufacturing Cost of Finished Good*. Stocks cause delays of the interaction effects. They accumulate and are revealed more intensely only as time rolls forward.

Findings
All four controllable variables (*r&d, manufacturing yield, cogs, and product price*) are strong predictors of the MVF($L_{81}(3^4, 2^3+1)$) outcomes. They all have $p << 0.05$. Each is a strong predictor of the outcome of MVF. 2-fi interactions of *yield*cogs, yield*price*, *cogs*price* and the 3-fi of *yield*cogs*price* are present. Except for the 3-fi of *yield*cogs*price* with $p = 0.049$, the other interactions have $p = 0.000$. The collective contributions, of the interactions, to the outcome is small, but statistically significant. The model's variables exhibit the key properties of hierarchy, sparsity, and inheritance, typical of complex DOE experiments. The model MVF($L_{81}(3^4, 2^3+1)$ is very good. All R^2 adj. > 99% at $t = 12$, $t = 18$ and $t = 24$.

5.4.2.2 $\mathcal{R}$\{MVF($L_{81}(3^4, 2^3+1)$)\}: The Rotated MVF($L_{81}(3^4, 2^3+1)$) Space

Data for the **controllable** variables *vis à vis* MVF($L_{81}(3^4, 2^3+1)$) indicate they are strong predictors of the MVF outcome. The solutions space is the product of the controllable space and the uncontrollable space, which is used to obtain the output space.

$$\boldsymbol{y}((controllable\ space) \times (uncontrollable\ space)) = [output\ space] \qquad (5.3)$$

Suppose we "rotate" the controllable space and uncontrollable stapes. Trade places in the array, i.e.

$$\boldsymbol{y}((uncontrollable\ space) \times (controllable\ space))^T = [output\ space]^T \qquad (5.4)$$

where T indicates the transpose. We identify this **rotated** space by:

$$\mathcal{R}\left\{\mathrm{MVF}\left(\mathrm{L}_{81}\left(3^4, 2^3+1\right)\right)\right\}$$

Given the role reversal between the controllable and uncontrollable variables, we would like to know whether the ANOVA statistics of this rearranged space provide us with any information that is new and meaningful. We wish to examine the ANOVA statistics of this new construct. The summary statistics for this new construct are in Table 5.20. (The ANOVA tables for the time periods of $t = 18$ and

Table 5.20 ANOVA $\mathscr{R}\{\mathrm{MVF}(L_{81}(3^4, 2^3{+}1))\}$ at $t = 12$

Source	DF	Seq SS	Adj SS	Adj MS	F	P
LT growth	1	1463	1463	1463	17.08	0.014
ADI orders	1	65,794	65,794	65,794	768.54	0.000
Competitor	1	15,146	15,146	15,146	176.92	0.000
Error	4	342	342	86		
Total	7	82,745				
S = 9.25250, R-Sq = 99.59%, R-Sq(adj) = 99.28%						

Table 5.21 Summary $\mathscr{R}\{\mathrm{MVF}(L_{81}(3^4, 2^3{+}1))\}$—the rotated $\mathrm{MVF}(L_{81}(3^4, 2^3{+}1))$ space at $t = 12$, 18, 24

$\mathscr{R}\{\mathrm{MVF}(L_{81}(3^4, 2^3{+}1))\}$						
	t = 12		t = 18		t = 24	
Uncontrollable variables	Adj. MS	p value	Adj. MS	p value	Adj. MS	p value
Industry long term growth	1463	0.014	12,879	0.001	29,601	0.001
ADI orders	65,794	0.000	171,615	0.000	168,167	0.000
Competitors' prod. attractiveness	15,146	0.00	63,637	0.000	89,059	0.000
Error	86	–	214	–	491	–

24 are in Appendix 5.3.) Are the **uncontrollable** variables are also statistically significant predictors of MVFI? (Table 5.20)

Two uncontrollable variables have $p = 0.000$, and for long term growth of industry demand variable $p = 0.014$. We take a closer look at this situation. Consider the data in Table 5.21.

Overall, the rotated model is good. The p values for *Industry Long Term Growth* at $t = 18$ and $t = 24$ are $p = 0.000$, their statistical significance is very high. *The effect of the Long Term Growth uncontrollable variable is not instantaneous, there is a delay before the effect is visible*. Although its MS adj contribution is small at $t = 12$, it has a meaningful long term effect. At $t = 12$, $p = 0.014$ for *Industry Long Term Growth*. Delay is also apparent for *competitors' products attractiveness*. This is discernable by the relative rise of SS adj. From Figs. 5.7, 5.8 and 5.9, the individual influence of *ADI orders* and *competitors' attractiveness* dominate the uncontrollable influences on $\mathrm{MVF}(L_{81}(3^4, 2^3{+}1))$.

Consider the Eqs. (5.6) and (5.7) using data from Appendix 5.1. Equation (3) shows the *average* of $\mathrm{MVF}(L_{81}(3^4, 2^{3-1}))$ for the uncertain regimes in which *Industry Long Term Growth* is **high**. Equation (4) is the average of $\mathrm{MVF}(L_{81}(3^4, 2^{3-1}))$ outputs for which *Industry Long Term Growth* is **low.**

$$\begin{aligned}&\mathrm{MVF}\left(L_{81}\left(3^4,100\right)\right)+\mathrm{MVF}\left(L_{81}\left(3^4,101\right)\right)+\mathrm{MVF}\left(L_{81}\left(3^4,110\right)\right)\\&\quad+\mathrm{MVF}\left(L_{81}\left(3^4,111\right)\right)=\$246,667\,\mathrm{M}\end{aligned}\tag{5.5}$$

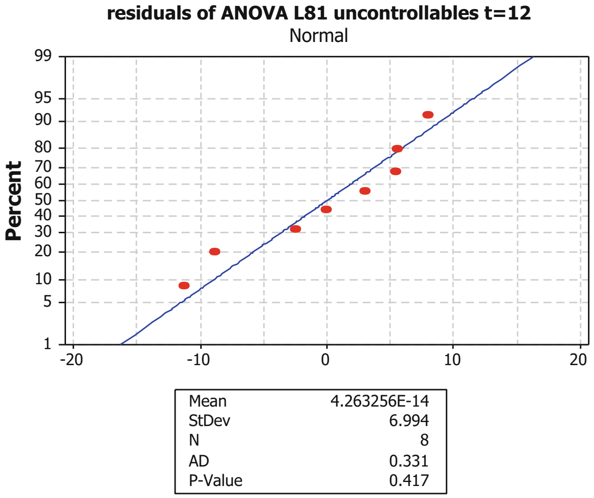


Fig. 5.18 Residuals of $\mathcal{R}$ {MVF($L_{81}(3^4, 2^3+1)$)} at t = 12

$$\mathrm{MVF}\left(L_{81}\left(3^4{,}000\right)\right)+\mathrm{MVF}\left(L_{81}\left(3^4{,}001\right)\right)+\mathrm{MVF}\left(L_{81}\left(3^4{,}010\right)\right)$$
$$+\,\mathrm{MVF}\left(L_{81}\left(3^4{,}011\right)\right)=\$237{,}905\,\mathrm{M} \tag{5.6}$$

The difference between these two equations is

$$[\$246{,}667\,\mathrm{M}-\$237{,}605\,\mathrm{M}]=\$8{,}761.7\,\mathrm{M} \tag{5.7}$$

This the difference that *Long Term Industry Growth* makes to MVF at t = 12. Even if *Industry Long Term Growth* SS-adj contribution is smaller than the other uncontrollable variables, its impact on MVF is meaningful. An executive is unlikely to ignore this difference.

For $\mathcal{R}$\{MVF($L_{81}(3^4, 2^3+1)$)\}, at t = 12, 18, and 24, all three uncontrollable variables have $p << 0.05$. They exert a meaningful influence on the MVF outcomes. The statistical distribution of the residuals (Fig. 5.18) is normal with mean $4.26{*}10^{-14}$, which can be assumed to be zero. Notably that $p = 0.417$ supports the observation that the residuals are normal.

5.4.2.3 Summary of MVF($L_{81}(3^4, 2^3+1)$) Surrogate Testing

We populated the full factorial MVF($L_{81}(3^4, 2^3+1)$) array using a spanning set of representative uncertainty regimes to be able to address the rage of uncertainty conditions of the decision situation. We are able to find, by inspection, the maximum MVF($L_{81}(3^4,2^3+1)$) for each of the time periods ending at t = 12, 18 and 24 (Table 5.16). We analyzed the L_{81} arrays at all these time periods. The ANOVA tables for the controllable variables support our belief that they are strong predictors of the output of MVF($L_{81}(3^4,2^3+1)$), e.g. Tables 5.17 and 5.18. The ANOVA statistics indicate that 2-fi and 3-fi of the controllable variables are present and statistically significant, but collectively they contribute a small percentage to MVF($L_{81}(3^4,2^3+1)$) outcomes (Tables 5.18 and 5.19). Moreover, of the **rotated** space $\mathcal{R}$\{MVF($L_{81}(3^4,2^3+1)$)\} reveals that the uncontrollable variables are statistically significant to the outcome of AOI at all three time periods of $t = 12$, 18 and 24. The ANOVA statistics indicate that the experiments using the $L_{81}(3^4,2^3+1)$ design exhibit the properties of hierarchy, sparsity, and inheritance. **With these results, we have our *gold standard* for the rest of our experiments.** The tables appear in Appendix 5.1.

5.4.3 Solution Space for MVF($L_{27}(3^{4-1}, 2^3+1)$)

5.4.3.1 Analyses of MVF($L_{27}(3^{4-1}, 2^3+1)$)

In the previous section we discussed and analyzed the explored the MVF($L_{81}(3^4, 2^3+1)$) Solution Space. We used the DOE methodology on a full factorial experimental space consisting of 81 experiments. There we could find the extremum by inspection. In this section, we will be using the reduced orthogonal Solution Space of MVF ($L_{27}(3^{4-1},2^3+1)$). The data sets for MVF($L_{27}(3^{4-1},2^3+1)$) at $t = 12$, 18, 24 are in Appendix 5.4. Using the $L_{27}(3^{4-1},2^3+1)$ instead of $L_{81}(3^{4-1},2^3+1)$ reduces the number of experiments from 81 to 27. This is an efficiency increase of $(1-27/81) = 66.67\%$ in the volume of data used. To find the extremum in this case, we will be using 27 experiments instead of 81. Unlike the previous section where we could find the extremum by inspection, we will now be constructing our extremum and other decision alternatives using DOE methods of robust design. We have traded volume of data and uncovering extremum by inspection for lower volume of data and designing decision alternatives. The key questions we will be investigating in this section are:

- Can we design decision-alternatives placed anywhere in the Solution Space?
- Can we predict their outcome under any uncertainty regimes?
- Can we design decision alternatives that are less sensitive to uncertainty?
- Will the results be consistent with our "gold standard"?

The answers to all these questions will be in the affirmative.

To answer whether the controllable variables remain as strong predictors of the MVF outcomes at $t = 12$. We turn our attention to the ANOVA table (Table 5.22). All variables are strong predictors for the MVF outcome have $p << 0.05$. Only one 2-fi appears, *yield*cogs* with $p = 0.072$. Its Adj MS contribution to the outcome MVF is nearly invisible relative to the total Adj MS. This interaction can therefore be ignored and pooled into the error term. The residuals are statistically significant, N(0,5.30) with $p >> 0.05$ (Fig. 5.19). The model is good, $R^2 = 99.35$ and the residuals are random normal with $p = 0.284$. Overall, the model is good.

Table 5.22 ANOVA statistics for MVF($L_{27}(3^{4-1}$, 2^3+1)) for t = 12

Source	DF	Seq SS	Adj SS	Adj MS	F	P
r&d	2	712	712	356	8.63	0.003
yield	2	21,686	21,686	10,843	262.82	0.000
cogs	2	20,733	20,733	10,367	251.28	0.000
price	2	58,059	58,059	29,030	703.65	0.000
yield**cogs*	2	257	257	128	3.11	0.072
Error	16	660	660	41		
Total	26	102,107				
S = 6.42305, R-Sq = 99.35%, R-Sq(adj) = 98.95%						

Fig. 5.19 MVF($L_{27}(3^{4-1}$, 2^3+1)) residuals at t = 12

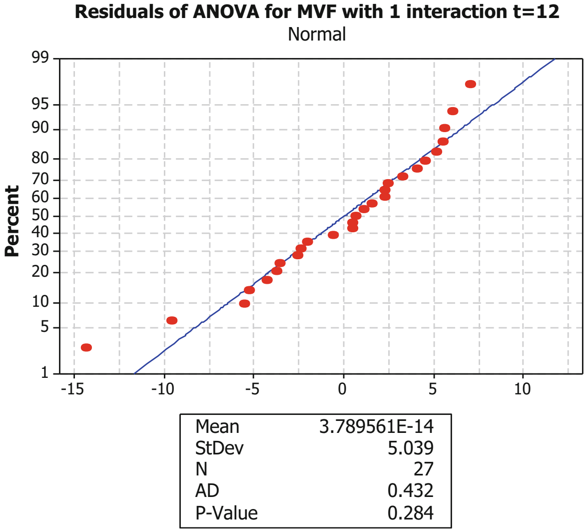


Table 5.23 shows the ANOVA statistics for the time periods ending at t = 12, 18 and 24. All controllable variables are strong predictors of the outcome of MVF with $p << 0.05$, except for r&d at t = 24. We have only one 2-fi of *yield*cogs* with $p > 0.05$ at t = 12, 18, and 24. The 2-fi *yield*cogs* is statistically insignificant and barely contributes to the overall outcome relative. It will be, therefore, be ignored.

Findings

The MVF($L_{27}(3^{4-1}$,2^3+1)) model is good. All the controllable variables (*r&d, manufacturing yield, cogs*, and *product price*) are strong predictors of the MVF ($L_{27}(3^{4-1}$,2^3+1)) outcomes, with $p << 0.05$. One exception is *r&d,* with $p = 0.65$ at t = 24. It is a moderate predictor. The one 2-fi contribution to the MVF outcome is very small. The MVF($L_{27}(3^{4-1}$,2^3+1)) model a near decomposable representation (Simon 1997, 2001). The model MVF($L_{27}(3^{4-1}$,2^3+1)) exhibits the properties of sparsity, hierarchy and inheritance. The controllable variables and the one interaction explain a very large percentage of the variations. The model fit is

Table 5.23 ANOVA MVF($L_{27}(3^{4-1}$, 2^3+1)) at t = 12, 18, 24 under (2,2,2) uncertainty regime

MVF($L_{27}(3^{4-1}$, 2^3+1))						
	t = 12		t = 18		t = 24	
Factors	Adj. MS	p value	Adj. MS	p value	Adj. MS	p value
r&d	356	0.003	2279	0.019	4599	**0.065**
yield	10,843	0.000	14,082	0.000	10,383	0.005
cogs	10,367	0.000	14,605	0.000	11,053	0.004
product price	29,030	0.000	46,417	0.000	41,335	0.000
yield**cogs*	128	**0.072**	871	**0.171**	2402	**0.213**
error	41	–	441	–	1409	–
total	50,765	–	78,695	–	71,181	–
R2 adj.	98.9%		92.9%		77.4%	

good, R^2 adj. = 98.9% at t = 12, R^2 adj· = 92.9% at t = 18 and R^2 adj. = 77.4.9% at t = 24. It is a moderate predictor.

5.4.3.2 Syntheses

The data from our MVF(($L_{27}(3^{4-1}$,2^3+1)) shows there is support our choice of controllable variables. With this support, we now take the next step to construct decision alternatives.

Using data from the MVF($L_{27}(3^{4-1}$,2^3+1)) response tables, we can design the decision for the maximum MVF, derive its value and expected standard deviation. Table 5.24 shows the response tables for t = 12. The tables for t = 18 and t = 24 are in Appendix 5.7. Table 5.24 has two parts. On the left, Response Table for Means, are the means for each level of the controllable variables. For example, *yield* level 3 has value 788.7. On the right, Response Table for Std Deviations, are the associated standard deviations for the responses on the left. For example, *yield* level 3 with value 788.7 has a standard deviation of 104.3.

Having this information is very useful to design robust decision alternatives. For example, it tells us that if we specify a design with the *yield* variable at level-3, the standard deviation for that outcome will be the highest among the levels for *yield* implying the highest risk. This makes the response tables important and very useful. This same information is shown in graphical form in Fig. 5.20. The information for t = 18 land t = 24 are shown in Appendices 7.1 and 7.2.

"Delta" in Table 5.24 denotes the difference between the highest and lowest responses for a given variable. "Rank" orders the variables by Delta. For example, Rank 3 identifies *cogs* as the third in influence on the output. Inspection of the left-hand-sides (LHS) of Table 5.24 and Fig. 5.20 reveal that *product price* is the dominant contributing factor to the outcomes of MVF(L_{27}); it has rank 1 from both a response of main effects and from the standard deviation.

Table 5.24 MVF($L_{27}(3^{4-1}, 2^3{+}1)$) response table for and stdev for t = 12

Response table for Means t = 12					Response table for Std Deviations				
Level	r&d	yield	*cogs*	price	Level	r&d	yield	*cogs*	price
1	760.4	**719.3**	787.3	693.7	1	104.2	**101.5**	104.8	100.2
2	753.3	**753.5**	754.7	761.3	2	103.1	**103.4**	103.4	103.0
3	747.8	**788.7**	719.5	806.5	3	101.8	**104.3**	101.0	105.9
Delta	12.5	69.4	67.9	112.8	Delta	2.3	2.8	3.8	5.8
Rank	4	2	3	1	Rank	4	3	2	1

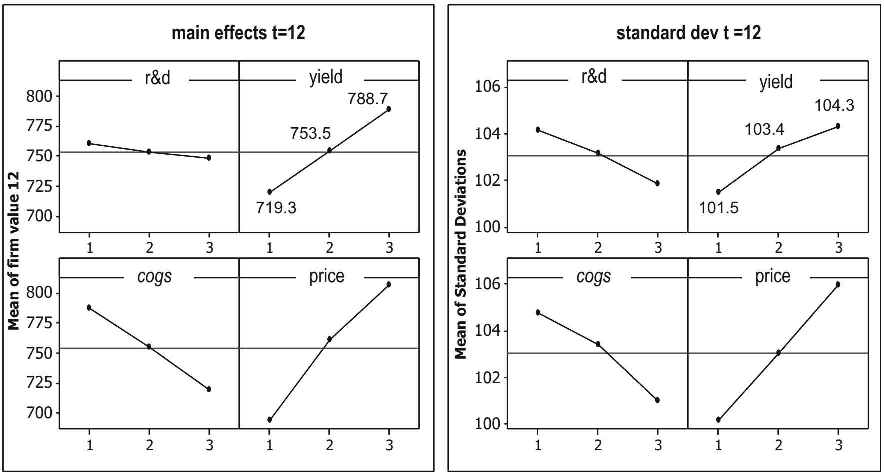


Fig. 5.20 MVF($L_{27}(3^{4-1}, 2^3{+}1)$) plots for response and stdev at t = 12 under (2,2,2)

Table 5.24, Fig. 5.20 and Appendix 5.7 **data for (MVF(L_{27}) present us with sufficient information to design any decision alternative located anywhere in the Solution Space with a standard deviation we can predict. As designer of alternatives, we can trade off outcome with risk, i.e standard deviation, if we so desire.** In the remainder of this section, we will demonstrate a systematic process to design decisions with these attributes. This the process of **synthesis**.

Appendix 5.4.1 is the MVF($L_{27}(3^{4-1},2^3{+}1)$) at t = 12 in the output Space—the Cartesian product of the controllable space with the uncontrollable space, Eq. (1). The column $\bar{y}_\alpha$, $1 \leq \alpha \leq 27$, is the average of values under the set of uncertainty regimes and σ_α is the standard deviation. From the LHS panel of Table 5.24 (and Fig. 5.20) we hypothesize that experiment (1,3,1,3) produces the highest MVF ($L_{27}(3^{4-1},2^3{+}1)$), i.e. *r&d* at level 1 (highest *r&d budget*), *manufacturing yield* at level 3 (highest), product cost *(cogs)* at level 3 (lowest), and highest *product price* at level 3 (highest). And by inspection, L_{81} Table data, in Appendix 5.1.1 tell us that MVF(L_{27}(1,3,1,3),(222)) = \$870.1 M. (1,3,1,3) is the decision specification that produces the highest MVF.

But can we predict it? We can predict the outcome using the Analysis of Means (ANOM) by means of Eq. (5.8) (e.g. Phadke 1989; Wu and Wu 2000).

$$\begin{aligned}\text{MVF}(\text{L}_{27}(1{,}3{,}1{,}3),(222)) = \text{m} + \left(\text{m} - r\&d^1\right) + \left(\text{m} - yield^3\right) \\ + \left(\text{m} - cogs^1\right) + \left(\text{m} - price^3\right)\end{aligned} \tag{5.8}$$

where the superscripts indicate the level of the variable. For example, $\text{m}^2{}_{\text{r\&d}}$ is the value of *r&d* at level 2. From the LHS of Table 5.24 $\text{m}^2{}_{r\&d} = 753.83$. And,

$$\begin{aligned}\text{m} &= average(r\&d\,\text{responses}) = 1/3(760.4 + 753.3 + 747.8) = 753.83 \text{ at t} = 12. \\ &= average(yield\,\text{responses}) = average(cogs\,\text{responses}) \\ &= average(price\,\text{responses}) = 753.83.\end{aligned} \tag{5.9}$$

Using Eq. (8), we get for

$$\begin{aligned}&\text{MVF}(L_{27}(1{,}3{,}1{,}3),(222)) = 785.3 + \left(r\&d^1 - 753.83\right) + \left(yield^3 - 753.83\right) \\ &\quad + \left(cogs^1 - 753.83\right) + \left(price^3 - 753.83\right) = 785.3 + (760.4 - 753.8) \\ &\quad + (788.7 - 753.3) + (787.3 - 753.3) + (806.5 - 7853.3) = \$881.4\,\text{M}\end{aligned}$$

This is a fundamental procedure in our methodology. We can predict the outcome of any decision alternative that has been designed.

As the MVF(L_{27}(1,3,1,3),(222)) case illustrates, the predictions are persuasive. Our Gold Standard of MVF(L_{81}(1,3,1,3),(222)) tells us the MVF outcome is \$870.1 M. Our calculations predict \$881.4 M at t = 12.

But, can we **predict the standard deviation** of the MVF(L_{27}(1,3,1,3),(222)) outcome?

The answer is in the affirmative. The procedure is not as direct as Eq. (8). We must make a simple detour. Table 5.24 shows standard deviations at t = 12. Standard deviations are not additive. However, variances are additive. Variance is defined as *variance = (stdev)*^{2}. We simply transform the stdev to variance, ***v***, and apply our analyses-of-means approach as before. We get a quantity for variance. Take the root of that quantity to get the stdev. We first calculate μ,

$$\begin{aligned}\mu &= average(r\&d\,\text{variances}) = 1/3(10850.35 + 10639.86 + 10368.18) = 10619.46 \\ &= average(yield\,\text{variances}) = average(cogs\,\text{variances}) = average(price\,\text{variances}) \\ &= 10619.46\end{aligned}$$

Then using the analyses-of-means, The *variance* (MVF(L_{27}(1,3,1,3),(222))) =

$$\begin{aligned}&= 10619.46 + (\boldsymbol{v}^1{}_{r\&d} - 10619.46) + \left(\boldsymbol{v}^3{}_{yield} - 10619.46\right) + \left(\boldsymbol{v}^1{}_{cogs} - 10619.46\right) \\ &\quad + \left(\boldsymbol{v}^3{}_{price} - 10619.46\right) \\ &= 10619.46 + (10850.35 - 10619.46) + (10877.28 - 10619.46) \\ &\quad + (10974.85 - 10619.46) + (11224.62 - 10619.46) \\ &= 12062.058\end{aligned}$$

Therefore, stdev = √12,062.058 = **109.83** at t = 12.

The standard deviation of the decision design for the (1,3,1,3) output is also higher than each of the individual standard deviations of the highest levels of the controllable variables. This is a case where the stdevs "stack up".

This is a second key procedure in our methodology. **We can predict the standard deviation of any decision alternative that has been designed.**

As the MVF(L_{27}(1,3,1,3),(222)) case illustrates, the predictions for standard deviations are also persuasive. Our Gold Standard in Appendix 5.1.1 for MVF (L_{81}(1,3,1,3),(222)) at t = 12 tells us the MVF outcome's stdev is 106.2. Our calculations predict 109.83.

The quintessential question of the prudent executive question is: Can we design a decision alternative that has a satisficing output and is also less risky? i.e. a **robust design**.

To improve robustness, make the response have less variation. We focus our attention on the variables *r&d* and *cogs* (RHS Fig. 5.20). Instead of the (1,3,1,3) design, we adopt a "greedy cheap-skate strategy" of a (2,2,3,3) design. In other words, *r&d* at the medium level 2, keep *manufacturing yield* at the current level 2 to not pressure *r&d*, drive *cogs* down to the lowest level 3 through belt tightening, but consistent with greed, raise *price*s. Predicted output is:

$$
\begin{aligned}
\mathrm{MVF}(\mathrm{L}_{27}(2{,}2{,}3{,}3),(222)) &= 785.3 + \left(r\&d^{2} - 785.3\right) + \left(yield^{2} - 785.3\right) \\
&\quad + \left(cogs^{3} - 785.3\right) + \left(price^{3} - 785.3\right) \\
&= 785.3 + (753.3 - 785.3) + (753.5 - 785.3) + (719.5 - 785.3) \\
&\quad + (806.5 - 785.3) \\
&= \$771.2\,\mathrm{M}
\end{aligned}
$$

The *variance*(MVF(L_{27}(2,2,3,3),(222)) is given by:

$$
\begin{aligned}
variance\left(\mathrm{MVF}(\mathrm{L}_{27}(2{,}2{,}3{,}3),(222)\right) &= \mu + \left(\boldsymbol{v}^{2}{}_{r\&d} - \mu\right) + \left(\boldsymbol{v}^{2}{}_{yield} - \mu\right) \\
&\quad + \left(\boldsymbol{v}^{3}{}_{cogs} - \mu\right) + \left(\boldsymbol{v}^{3}{}_{price} - \mu\right) = 10619.46 + (10639.86 - 10619.46) \\
&\quad + (10685.46 - 10619.46) + (10198.51 - 10619.46) \\
&\quad + (11224.62 - 10619.46) = 10883.40
\end{aligned}
\tag{5.10}
$$

Therefore, stdev = √10,883.404 = **104.32** at t = 12.

This is a corollary procedure. We can design decision alternatives that can satisfice and have less risk. These are the decision alternatives that are robust.

MVF(L_{27}(2,2,3,3),(222)) = \$771.2 M is less than MVF(L_{27}(1,3,1,3),(222)) = \$881.4 M. But it is also less risky. *Stdev*(MVF(L_{27}(2,2,3,3),(222))) = 104.3, which is less than the best alternative that has stdev(MVF (L_{27}(1,3,1,3),(222))) = 110.1.

Using the above procedures, we get the following for MVF(L_{27}(2,2,2,2),(222)), the BAU:

$$\begin{aligned}\mathrm{MVF}(\mathrm{L}_{27}(2{,}2{,}2{,}2),(222)) &= \$761.3\,\mathrm{M}\text{ and } stdev(\mathrm{MVF}(\mathrm{L}_{27}(2{,}2{,}2{,}2),(222)))\\ &= 103.7\end{aligned}$$

And for the worst MVF(L_{27}(3,1,3,1),(222)), we get:

$$\begin{aligned}\mathrm{MVF}(\mathrm{L}_{27}(3{,}1{,}3{,}1),(222)) &= \$618.8\text{ and } stdev(\mathrm{MVF}(\mathrm{L}_{27}(3{,}1{,}3{,}1),(222)))\\ &= 95.0.\end{aligned}$$

We take a slight pause to briefly summarize the key points of this section.

- This section is about designing decision alternatives that will produce an intended outcome.
- The decision alternative is expressed as decision specification. The specification has two parts.
- One part, is a configuration of controllable variables, each of which is specified at a level. The second part is a configuration of uncontrollable variables, each of which is also specified at a level.
- To simplify the discussion, we have considered the configuration of the uncontrollable variables to remain as-is at their current levels. In other words, we temporarily suspended considering different uncertainty regimes.
- We use the orthogonal array L_{27} array of 27 rows. Each row represents a decision alternative, which is used to experiment. Each experiment reveals the MVF, annual operating income, of the firm, MVF. In this section, these values have been obtained from simulations of the ADI surrogate.
- The structure, of this array of 27 rows of alternative decision specifications, is not an arbitrarily constructed array, but it is a statistically rigorous framework. It is grounded on rigorous and proven mathematical statistical methods. It is an orthogonal array which we use to calculate predictions over the entire solution space.
- From this set of 27 experiments, we can systematically make predictions about outcomes of any different configurations, which are **not** included in the 27. This is an extremely useful capability, for we can now predict the outcome of any decision specification.
- In addition, we can also predict the mean and the standard deviation of the data of any decision alternative. We use the response Table 5.24 and Fig. 5.20. We follow the widely accepted approach of using the standard deviation of a predicted outcome as a proxy for risk. Because the wider the spread of a possible outcome the less likely you may get what you want; i.e. the outcome is more risky.
- These statistical insights permit us to construct any decision alternative of any configuration of controllable variables. Executives can specify any hypothetical alternative, predict its outcome, under any uncertainty regime. In this way, executives can explore the entire Solution Space, without any constraints.
- These statistical insights also give us the ability to know the uncertainty of any decision specification, by predicting its standard deviation as a proxy for risk.

- We showed in detail how to construct alternatives with two key attributes. One is to obtain a desirable outcome. Two is, design alternatives with a predictable uncertainty, i.e. standard deviation. These two tasks when integrated, constitute the method of ***engineering robust decision-alternatives***. This is robust-decision synthesis.
- As concrete examples, we showed how to design and engineer decisions for the BAU, for the worse design, for the best design, and the improved-BAU design. We showed how to calculate their predicted outcomes and predicted standard deviations.
- There are two unstated and untested assumptions. One is that that there are decision alternatives, which produce more desirable results, and which are also less risky. The other is the converse, *viz.* there are worse alternatives that produce less desirable results with also more risk. We can state and show that these kinds of alternatives exist and can be designed. The following two plots, Figs. 5.21 and 5.22 are examples that demonstrate this assertion.

Now we try to put together a whole view of what we have learned. Figure 5.21 is a plot of MVF versus standard deviation for all points of the L_{27} experiments.

We added a hypothesized *best* MVF(L_{27}(1,3,1,3),(222)), and a hypothesized *worst* MVF(L_{27}(3,1,3,1),(222)), BAU experiment of MVF(L_{27}2,2,2,2),(222)), and an equidistant *midpoint* between the *bes*t and *worst* experiment. These three points

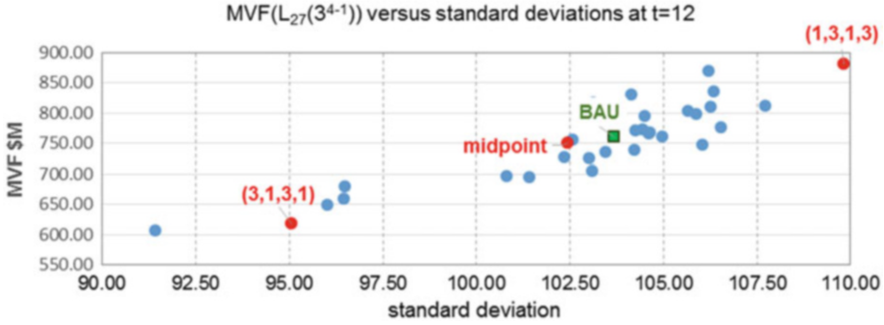


Fig. 5.21 L_{27} experiments with the *best, worst* ADI and *midpoint* experiments at t = 12

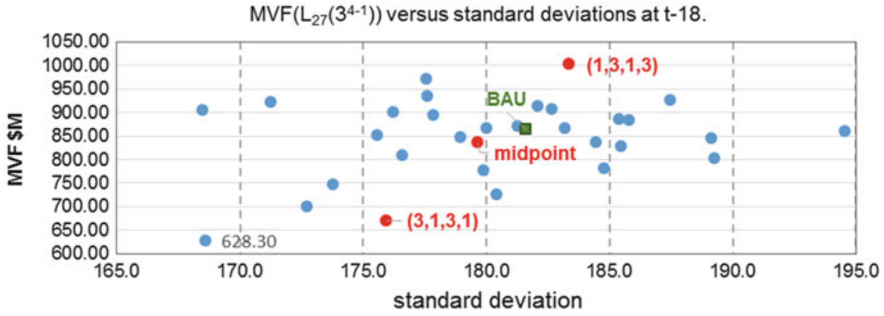


Fig. 5.22 L_{27} experiments with the *best, worst* ADI and *midpoint* experiments at t = 18

are shown in red. The BAU is shown as a square. We define a hypothesized *best* as the design that produces the highest MVF, independent of the magnitude of the standard deviation. *Worst* is analogously defined as the decision specification that produces the lowest MVF. The plot clearly demonstrates that there are many alternatives that can be designed to produce near or better results than BAU. Likewise, there are other worse alternatives. Of course, there are many more alternatives can be constructed beyond the 27 of the L_{27} array. Executives do not have to settle for the status quo. Alternatives above and to the left of the midpoint are better alternatives. The have better MVF outcomes and lower risk. Note that BAU is slightly better positioned than the *midpoint* in terms of outcome.

Figure 5.22 is similar to 5.21, but at $t = 18$. It also demonstrates the existence of additional alternative designs that are superior to the BAU alternative. Of course, there are more than 27 designs; these are only a subset of the possibilities. As in problem solving in general, domain knowledge and competence in problem solving is required for effective design of decision alternatives.

The next topic is ***uncertainty*** and its effect on MVF. Uncertainty is inexorably connected in all decisions. Particularly with executive management decisions. "Uncertainty appears as the fundamental problem for complex organizations, and coping with uncertainty, as the essence of the administrative process (Thompson 2004: 159)." We take a closer look at the set of uncertainty regimes. From Appendix 5.4 data, we add the responses of each column of outputs for each uncertainty regime, this is labeled as "∑expmt output". These are identified as a shaded row in Table 5.25. Notably, this is consistent with MVF($L_{81}(3^4, 2^3{+}1)$) in Table 5.6.

We have discretized the uncertainty spectrum into a monotonically increasing set of uncertainty regimes. This is illustrated graphically in Fig. 5.23. On the vertical axis is the average of MVF($L_{27}(3^{4-1}$, for each uncertainty regime)) including the BAU. Hence there are nine data points for each vertical column. Since we have 27 experiments in a L_{27}, there are 27 vertical columns.

The MVF($L_{27}(1,3,1,3),(222)$) output for the three time periods are shown in Table 5.26 where we also show a comparison of the **derived** values for MVF ($L_{27}(1,3,1,3),(222)$) versus the values from our "gold standard" the MVF($L_{81}(3^4, 2^3$ $+1)$). The MVF($L_{27}(3^{4-1}, 2^3{+}1)$) were calculated using the procedures discussed in this section. The $|\%\Delta|$ L_{27} vs. L_{81} are small, average of 3.8%. The predicted values compare favorably with our "gold standard". These data support our method for predicting the output of decision designs.

We can see the effect of *cogs* and *price* graphically. Using regression, we can get the phenomenological transfer function for MVF (e.g. Montgomery 2001; Otto and Wood 2001) and a contour plot (Fig. 5.24). The small triangular region on the lower right hand corner where *cogs* is low (near level 1) and *price* is high (near level 3) produces the highest MVF. The equation is quasi-linear. The transfer function satisfies our need to know the representation for the phenomenological behavior of the sociotechnical system. But the central theme of our methodology is robustness. Our paradigm concentrates on the design of robust decisions, their implementation, execution, and evaluation of results. These are the subjects for the remainder of this chapter.

Table 5.25 ∑y-bar for current state of uncertainty and each uncertainty regime at t = 12

Current	**Uncertainty regimes**								• Uncontrollable variables
Current	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	• Industry growth
Current	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	• ADI orders
Current	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	• Competitors
Current	**000**	**001**	**010**	**011**	**100**	**101**	**110**	**111**	
	. . .	Worst case	. . .	. . .	. . .	. . .	Best case		
21,520.8	**18,718.2**	**16,158.4**	**23,167.5**	**21,330.2**	**19,443.8**	**16,714.1**	**24,193.9**	**21,933.8**	**∑expmt output**
	3	**1**	7	5	4	2	**8**	6	***r***: 1 ≤ order ≤ 8

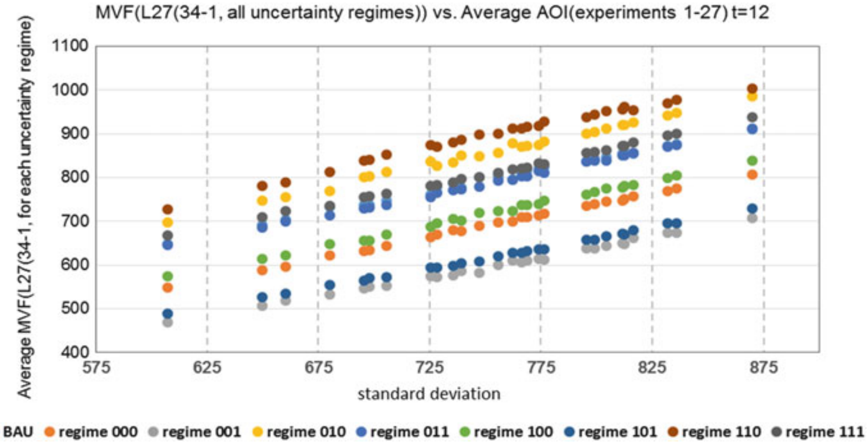


Fig. 5.23 MVF(L_{27}(3^{4-1}, all uncertainty regimes) versus Average MVF(L_{27}) for t = 12

Table 5.26 MVF for t = 12, 18, and 24, L_{27} vs L_{81}

		MVF ($L_{27}(3^{4-1}, 2^3+1)$)	**MVF ($L_{81}(3^4, 2^3+1)$)**	
	Experiment	**Derived values**	**By inspection Gold standard**	$\lvert[MVF(L_{27})-MVF(L_{81})]\rvert/MVF(L_{81})$
t = 12	1,3,1,3	$881.47 M	$870.09 M	1.3%
t = 18	1,3,1,3	$1003.3 M	$970.82 M	3.3%
t = 24	1,3,1,3	$877.00 M	$820.73 M	6.7%
				Average = 3.8%

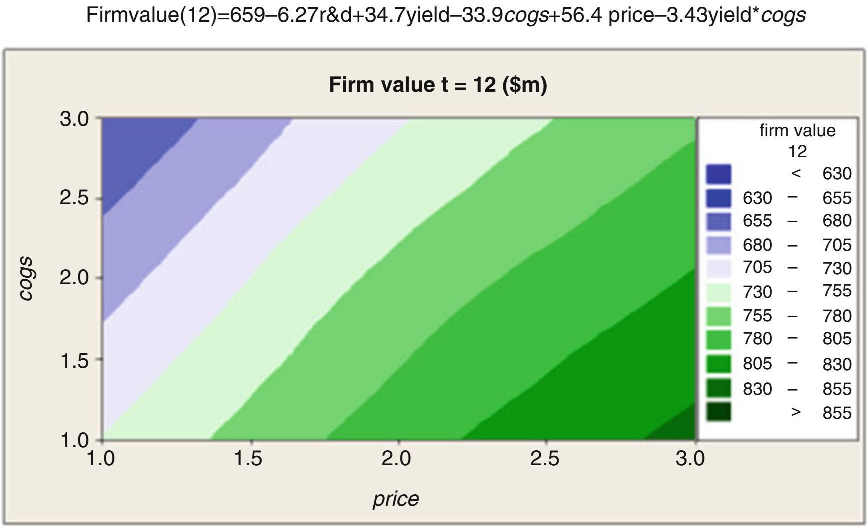


Fig. 5.24 Transfer function for MVF at t = 12 using *price* and *cogs* variables

Table 5.27 shows the contributions of the interactions. Two observations are apparent. First, the contributions of the interactions are small, but they increase over time. This may explain the increasing differences between the predicted value given by the MVF($L_{27}(3^{4-1},2^3+1)$) versus the values from our "gold standard" the MVF($L_{81}(3^4,2^3+1)$) over t = 18 and t = 24. Second, the values for "ratio of total" (Table 5.27) is approximately half as much as that shown in Table 5.19 for MVF($L_{81}(3^4,2^3+1)$). The MVF($L_{27}(3^{4-1},2^3+1)$) has less fidelity than MVF ($L_{81}(3^4,2^3+1)$). It has fewer degrees of freedom. Inspection of their respective ANOVA tables shows that two 2-fi and one 3-fi have been confounded in the rest of the data.

Table 5.27 MVF($L_{27}(3^{4-1}, 2^3+1)$) MS(adj) with and without interactions at t = 12, 18, 24

	t = 12		t = 18		t = 24	
	Interations	No interations	Interations	No interations	Interations	No interations
ΣMS-adj	128	50,596	871	77,383	2042	67,730
Ratio of total	128/50,596 = **0.25%**		871/77,383 = **1.13%**		2042/67,730 = **3.03%**	

Findings
Significantly, we have demonstrated how to design any decision alternative, how to predict its outcome and its standard deviation, which is a measure of its uncertainty. The predicted outcomes from the hypothesized best experiment of MVF (L_{27}(1,3,1,3)) experiments yield results that are close at t = 12 to the "gold standard" of MVF(L_{81}((1,3,1,3),(2,2,2))), but the predictions drift slightly apart for t = 18, and for t = 24. The interaction effects become more pronounced and there is a delay for the interaction effects to assert themselves. Because the model MVF(L_{27}(1,3,1,3)) is of lower fidelity than the equivalent L_{81} model, the interactions that were evident for the L_{81} model are not all visible with the L_{27} model. However, the predicted results for the maximum MVF are very close. We judge that the more parsimonious L_{27} model is useful albeit with some loss of information about the interactions. The contributions of the interactions, which are no longer visible, are small. We judge the functionality of the L_{27} model to be good.

5.4.3.3 $\mathcal{R}${MVF($L_{27}(3^{4-1},2^3+1)$) } = The Rotated MVF($L_{27}(3^{4-1}, 2^3+1)$) Space

The analysis proceeds as in Sect. 5.4.2.2, using the rotated space $\mathcal{R}${MVF($L_{27}(3^4,2^3+1)$) }. The ANOVA statistics of this rearranged space (Table 5.28), show that two uncontrollable variables have p = 0.000 and for *Long Term Growth* of industry demand variable has p = 0.14. At t = 18 and t = 24, *Long Term Growth* has p values of p = 0.000, indicating that, beyond t = 12, their statistical significance is high. Effects from the *Long Term Growth* uncontrollable variable is not instantaneous, there is a delay before it is visible. That at t = 12 *Long Term Growth* has p = 0.014 is reasonable as we discussed in Sect. 5.4.2.2 for $\mathcal{R}${MVF($L_{81}(3^{4-1},2^3+1)$)}.

Figure 5.7 show that the uncontrollable variable, *Long Term Growth/Demand* influence on MVF is not strong, at t < 12. In fact, *Long Term Growth/Demand* does not make its influence felt until t > 12 and in the longer term. Finally, the residuals in Fig. 5.25. They are well formed and randomly distributed.

Table 5.28 $\mathcal{R}\{\mathrm{MVF}(L_{27}(3^{4-1},2^{3}+1))\}$ at $t = 12$ for uncontrollable variables

Analysis of Variance. $\mathrm{MVF}(L_{27}(3^{4-1},2^{3}+1))$

Source	DF	Seq SS	Adj SS	Adj MS	F	P
LT growth	1	1453	1453	1453	17.32	0.014
ADI orders	1	65,810	65,810	65,810	784.12	0.000
Competitor	1	15,109	15,109	15,109	180.02	0.000
Error	4	336	336	84		
Total	7	82,708				

S = 9.16124, R-Sq = 99.59%, R-Sq(adj) = 99.29%

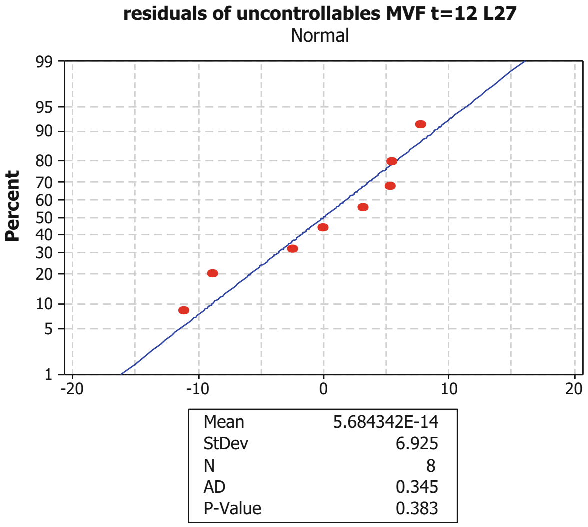


Fig. 5.25 $\mathcal{R}\{\mathrm{MVF}(L_{27}(3^{4-1}, 2^{3}+1))\}$ residuals at $t = 12$ for uncontrollable variables

We summarize our findings of uncontrollable variables' ANOVA statistics at $t = 12$, 18 and 24 (Table 5.29). The ANOVA tables for the time periods $t = 18$ and $t = 24$ are in Appendices 5.5 and 5.6. All uncontrollable variables have $p << 0.05$ are strong predictors of the outcome of MVF.

Findings

Previously, we found that data for the **controllable** variables *vis à vis* $\mathrm{MVF}(L_{27}(3^{4-1},2^{3}+1))$ support construct validity. They are strong predictors of the outcome. In this section, we explore whether the same is true for the **uncontrollable** variables. Again, we "rotate" the positions of the controllable variable and the uncontrollable variables of the $L_{27}(3^{4-1}, 2^{3}+1)$. The ANOVA table for that construct is shown in Table 5.28 and Appendices 5.5 and 5.6. All the uncontrollable variables have are statistically significant, Table 5.29.

Table 5.29 $\mathcal{R}\{\text{MVF}(L_{27}(3^{4-1}, 2^3+1))\}$at t = 12, 18, 24

Rotated $L_{27}(3^{4-1}, 2^3+1)$						
	t = 12		t = 18		t = 24	
Factors	Adj. MS	p value	Adj. MS	p value	Adj. MS	p value
Industry long term growth	1453	0.014	12,831	0.001	29,440	0.001
ADI orders	65,810	0.000	171,516	0.000	168,536	0.000
Competitors' attractiveness	15,109	0.000	63,468	0.000	89,094	0.000
Error	336	–	214	–	484	–

5.4.3.4 Summary of the MVF($L_{27}(3^{4-1},2^3+1)$)

Recall that the original questions in Sect. 5.4.3.1 were:

- Can we design decision-alternatives placed positioned anywhere in the Solution Space?
- Can we predict their outcome and their uncertainty regimes?
- Can we design decision-alternatives that are less sensitive to uncertainty?
- Will the results be consistent with our "gold standard"?

We can confidently answer all the questions in the affirmative.

We used MVF($L_{27}(3^{4-1}, 2^3+1)$) experimental model under a spanning range of well-articulated uncertainty-regimes to investigate the results. We are able to design the experiments that yield a very high MVF at each of the times of t = 12, 18, and 24 (Table 5.26). Significantly, using the $L_{27}(3^{4-1},2^3+1)$, the experiment that yields the hypothesized maximum MVF is very close to the one revealed by the L_{81} full factorial experiment. The derived values for MVF from L_{27} are very close with percentage errors that are very small, relative to values from L_{81} full factorial array, our gold standard.

The ANOVA statistics for **both** the controllable variables **and** the uncontrollable variables support our belief that they are strong predictors of MVF($L_{27}(3^{4-1},2^3+1)$) in all three time periods (e.g. Tables 5.22 and 5.23). The data show the presence of only one 2-fi of the controllable variables, *yield*cogs* but its contribution, and $p > 0.05$, not statistically significant. The MVF($L_{27}(3^{4-1}, 2^3+1)$) sociotechnical model is quasi-linear and near decomposable (Simon 1997, 2001).

5.4.4 Solution Space for MVF($L_9(3^{4-2}$,2^3+1))

5.4.4.1 Analyses of MVF($L_9(3^{4-2}$,2^3+1))

This section follows the same approach used in Sect. 5.4.3 for the $L_{27}(3^{4-1}$, 2^3+1) analysis. The $L_9(3^{4-2}$, 2^3+1) data set for t = 12, 18, and 24 are in Appendix 5.9. The $L_9(3^{4-2}$, 2^3+1) is the simplest orthogonal array we can use. Simpler experiments are noteworthy because they imply lower cost and are simpler to perform. First, we want to know whether analysis of the MVF($L_9(3^{4-2}$, 2^3+1)) will continue to support the predictive power for our MVF output using our controllable variables under a variety of uncertainty regimes. Second, we want to know whether our designed decision specifications have the predictive power that is consistent with our "gold standard" and our L_{27} experiments. This is important because it demonstrates an overall consistent functionality of our methodology.

An L_9 array does not have enough degrees of freedom (dof's) to obtain the F statistic and p values for four controllable variables. Therefore, we add two experiments to our $L_9(3^{4-2}$, 2^3+1) array as shown in Appendix 5.9.1. We denote this new array as $\boldsymbol{L'}_9(3^{4-2}$, 2^3+1). The array is *nearly orthogonal*. The ANOVA table for $\boldsymbol{L'}_9(3^{4-2}$, 2^3+1) shows that all controllable variables are strong predictors of MVF with $p < 0.05$ (Table 5.30). Because $\boldsymbol{L'}_9(3^{4-2}$, 2^3+1) is a low-resolution model, the interactions do not reveal themselves. The model statistics are good. The residuals are **not** carriers of any information, they are N(0,1.7) with $p > 0.05$ (Fig. 5.26).

Table 5.31 summarizes the ANOVA statistics for each of the time periods ending at t = 12, 18, and 24. Details are in Appendices 5.10 and 5.11.

Findings

Table 5.30, shows the MVF($\boldsymbol{L'}_9(3^{4-2}$, 2^3+1)) model the p values of the controllable variables of *r&d, manufacturing yield, cogs*, and *product price* are strong predictors of the outcomes at t = 12 and t = 18. The exceptions are at t = 24 for *r&d* and *manufacturing yield* with p = 0.075 and p = 0.146, respectively. MVF($\boldsymbol{L'}_9(3^{4-2}$, 2^3+1)) is an acceptable model for t = 12 and t = 18, but not beyond t = 18. The model is lean and parsimonious, no interactions are revealed.

Table 5.30 MVF($L'_9(3^{4-2}$,2^3+1)) ANOVA at t = 12

Analysis of Variance. MVF $L'_9(3^{4-2}$,2^3+1) t = 12

Source	DF	Seq SS	Adj SS	Adj MS	F	P
r&d	2	368.7	550.0	275.0	20.03	0.048
yield	2	4822.6	5349.4	2674.7	194.78	0.005
cogs	2	6100.8	8380.6	4190.3	305.15	0.003
price	2	21,098.0	21,098.0	10,549.0	768.21	0.001
Error	2	27.5	27.5	13.7		
Total	10	32,417.5				

S = 3.70567, R-Sq = 99.92%, R-Sq(adj) = 99.58%

Fig. 5.26 MVF($L'_9(3^{4-2}$, 2^3+1)) residuals of ANOVA at t = 12

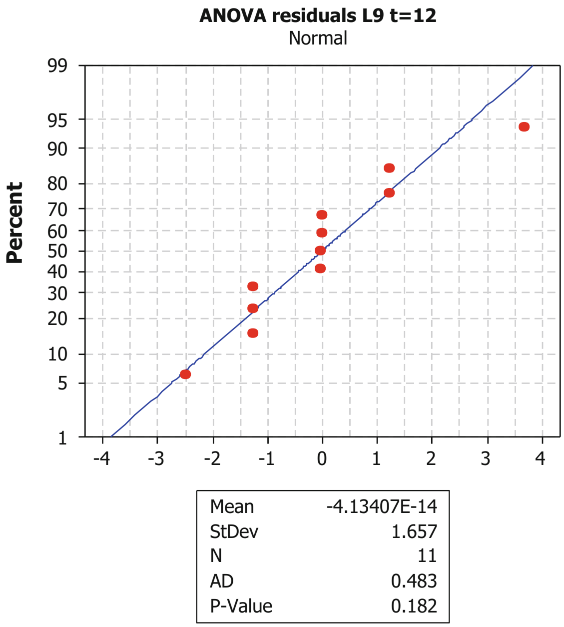


Table 5.31 MVF($L'_9(3^{4-2}$, 2^3+1)) summary at t = 12, 18, 24

MVF($L'_9(3^{4-2}$, 2^3+1))						
	t = 12		t = 18		t = 24	
Factors	Adj. MS	p value	Adj. MS	p value	Adj. MS	p value
r&d	275	0.048	1888	0.052	4591	**0.075**
Manufacturing yield	2675	0.005	3240	0.031	2185	**0.146**
cogs	4190	0.003	6547	0.016	7128	0.050
Product price	10,549	0.001	15,931	0.006	13,759	0.026
Error	13.7	–	104.1	–	374	–

5.4.4.2 Synthesis in the MVF(L_9((2,2,1,2),(222)) Space

Given that the controllable variables are good predictors for the MVF outcome, for t = 12 and t = 18, we now revert to our $L_9(3^{4-2}, 2^3+1)$. The response tables for t = 12 are shown in Table 5.32 and Fig. 5.27. The LHS shows the main effects at t = 12. The RHS shows the response table for standard deviations. These data are shown as graphs in Figure 5.27. Data for t = 18 and t = 24 are in Appendix 5.12.

From inspections of the LHS panel of Fig. 5.27, we surmise that experiment (1,3,1,3) produces the highest MVF($L_9(3^{4-2}, 2^3+1)$), i.e. *r&d* at level 1 (highest *r&d*

Table 5.32 MVF($L_9(3^{4-2}, 2^3+1)$) response table for MVF and stdev for t = 12

Response Table-Means					Response Table-St Deviations				
Level	r&d	yield	*cogs*	price	Level	r&d	yield	*cogs*	price
1	759.7	720.9	782.6	690.7	1	105.1	102.0	104.2	98.8
2	746.4	749.4	753.4	753.4	2	100.8	100.2	104.4	101.9
3	742.0	777.9	712.1	804.0	3	101.2	104.8	98.3	106.3
Delta	17.8	57.0	70.6	113.3	Delta	4.32	4.63	6.11	7.52
Rank	4	3	2	1	Rank	4	3	2	1

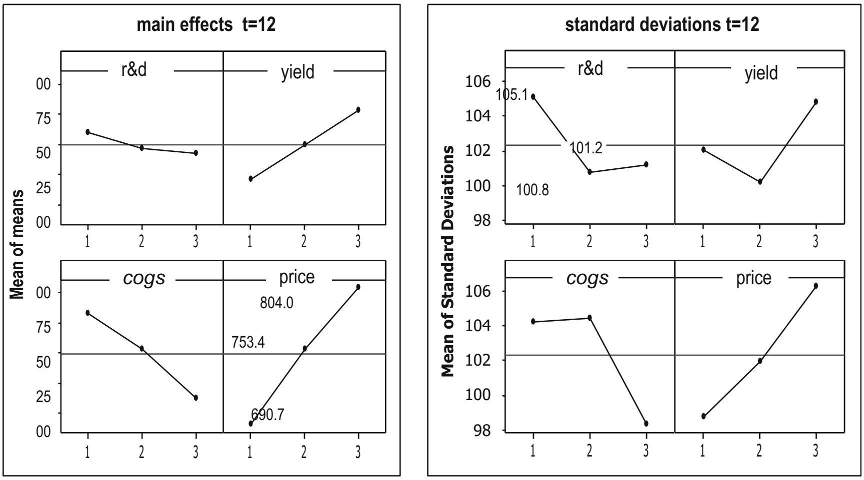


Fig. 5.27 MVF($L_9(3^{4-2}, 2^3+1)$) plots for response and stdev at t = 12

budget), *manufacturing yield* at level 3 (highest), product cost (*cogs*) at level 3 (lowest), and highest *product price* at level 3 (highest). This is the (1,3,1,3) configuration which we expect will produce the highest MVF($L_9(3^{4-2},2^3+1)$). But what is its predicted value? The predicted the value is:

$$\mathrm{MVF}(\mathrm{L}_9(1,3,1,3),(222)) = \mathrm{m} + \left(\mathrm{m} - \mathrm{m}^1{}_{r\&d}\right) + \left(\mathrm{m} - \mathrm{m}^3{}_{yield}\right) + \left(\mathrm{m} - \mathrm{m}^1{}_{cogs}\right) + \left(\mathrm{m} - \mathrm{m}^3{}_{price}\right)$$

where the superscripts denote the level of the variable, e.g. m2 r&d is the value of r&d at level 2 from the LHS of the ANOVA table, the means, thus $\mathrm{m}^1{}_{r\&d} = 759.7$.

Table 5.33 MVF at t = 12, t = 18, and t = 24 using L_9 vs. L_{27} and L_{81}

		Market Value of the Firm (MVF)				
		MVF(L_{81})	MVF(L_{27})	MVF(L_9)	|[MVF(L_{27})-MVF(L_{81})]|/MVF(L_{81})	|[MVF(L_9)-MVF(L_{81})]|/MVF(L_{81})
	Experiment	Inspection	Derived	Derived		
t = 12	1,3,1,3	$870 M	$881 M	$876 M	1.3%	0.7%
t = 18	1,3,1,3	$971 M	$1003 M	$1005 M	3.3%	3.5%
t = 24	1,3,1,3	$821 M	$877 M	$826 M	6.8%	0.6%
					Average = 3.8%	Average = 1.6%

$$\begin{aligned}\mathrm{m} &= average(r\&d\,\mathrm{responses}) = 1/3(759.7 + 746.4 + 742.0) = 749.37 \text{ at} \\ \mathrm{t} &= 12 \text{ gold standard} = average(yield\ \ responses) = average(cogs\ \ responses) \\ &= average(price\ \ responses) = 749.37\end{aligned}$$

To get for MVF(L_{27}(1,3,1,3),(222)) =

$$\begin{aligned}&= 749.37 + (\mathrm{m}^1{}_{\mathrm{r\&d}} - 749.37) + \left(\mathrm{m}^3{}_{\mathrm{yield}} - 749.37\right) + \left(\mathrm{m}^1{}_{cogs} - 749.37\right) \\ &\quad + \left(\mathrm{m}^3{}_{\mathrm{price}} - 749.37\right) = 749.37 + (759.7 - 749.37) + (777.9 - 749.37) \\ &\quad + (782.6 - 749.37) + (804.0 - 749.37) = \$876.1\,\mathrm{M}\end{aligned}$$

MVF($L_9(3^{4-2},2^3+1)$) relative to our "gold standard" MVF($L_{81}(3^4,2^3+1)$) is shown in Table 5.33.

The RHS of Fig. 5.27 show the standard deviations of MVF($L_9(3^{4-2},2^3+1)$) output responses at t = 12. Since standard deviations are ***not*** additive, but variances are additive, we calculate the variances first. Then using means analyses, we predict the variances, which we then convert to standard deviations.

Using ANOM, the variance of $\boldsymbol{v}$ (MVF(L_9(1,3,1,3),(222))) is given by:

$$\begin{aligned}&\boldsymbol{v}\left(\mathrm{MVF}(\mathrm{L}_9(1,3,1,3),(222)\right) = \mu + \left(\boldsymbol{v}^{\mathbf{1}}{}_{r\&d} - \mu\right) + \left(\boldsymbol{v}^{\mathbf{3}}{}_{yield} - \mu\right) + \left(\boldsymbol{v}^{\mathbf{1}}{}_{cogs} - \mu\right) \\ &+ \left(\boldsymbol{v}^{\mathbf{3}}{}_{price} - \mu\right) = 10481.6 + (11046 - 10481.6) + (10983 - 10481.6) \\ &\qquad\qquad\qquad + (10857.6 - 10481.6) + (11299.7 - 10481.6) \\ &\qquad\qquad\quad = 12755.8.\end{aligned}$$

Therefore, stdev = $\sqrt{}$12,755.8 = **112.94.**

MVF(L_9((1,3,1,3),(222))) is the red point, "best", on the upper RHS of Fig. 5.28. The green point is a constructed alternative using the L_9 orthogonal array. The red point at the bottom left had corner is the "worst", the exact opposite of *best*. Midpoint is the geometric center between these two, place for reference. We discuss the construction of this decision alternative (2,2,1,2).

We next want to explore construction of an alternative that is more robust than the BAU, i.e. one whose predicted MVF is better and whose standard deviation is lower. By inspection of Fig. 5.27, we design a robust alternative (2,2,1,2), i.e. we want to outperform the BAU by lowering the *cogs*. The predicted

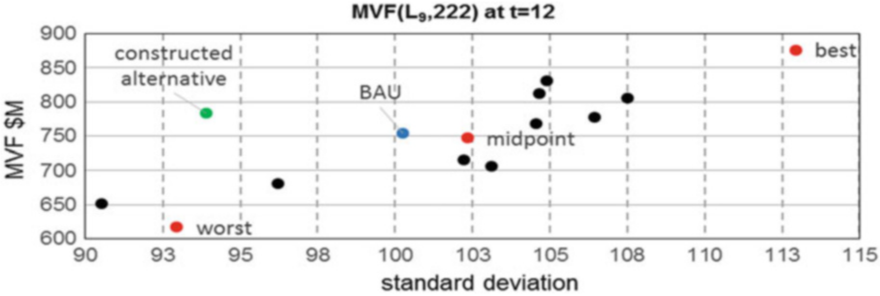


Fig. 5.28 L_9 experiments with the *best, worst* MVF and *midpoint* experiments at t = 18

$$\mathrm{MVF}(L_9(2,2,1,2),(222)) = \$783.67\,\mathrm{M} \text{ and}$$

the predicted standard deviation is stdev(MVF(L_9(2,2,1,2),(222))) = 93.9 and this alternative is shown as a green point. Relative to the BAU, the

$$[\mathrm{MVF}(L_9(2,2,1,2),(222))] - [\mathrm{MVF}(L_9(\mathrm{BAU}),(222))] = [783.67 - 754.57] \\ = \$29.20\,\mathrm{M}$$

$$\mathrm{stdev}[\mathrm{MVF}(L_9(2,2,1,2),(222))] - \mathrm{stdev}[\mathrm{MVF}(L_9(\mathrm{BAU}),(222))] \\ = [100.3 - 93.9] = 6.37$$

This construction demonstrates that we construct robust alternatives that are more robust than BAU. This is visually confirmed by the distance of the green point (constructed 2,2,1,2) from the blue point (BAU 2,2,2,2). The constructed alternative (green point) is of lower standard deviation and has a higher MVF than BAU (blue point). The green point is a robust decision alternative.

Table 5.33 shows that MVF(L_9(1,3,1,3),(222)) and MVF(L_{27}(1,3,1,3),(222)) the predicted outcomes are close. Is this still true for other decision designs? There is support for the assertion that the answer is affirmative. We picked twelve experiments from MVF(L_{27}) then we predicted their outcomes and standard deviations using the response tables data and the ANOM procedure. We then went through the exact same steps for MVF(L_9). The results are plotted in Fig. 5.29.

The MVF(L_{27}) points are in **black**, and the MVF(L_9) points are shown in red. Although visually it appears as if the points are random, but, in fact, the **correlation** between the MVF(L_{27}) and the MVF(L_9) data is **98%**. The predictive power of MVF(L_9) is good, but we are unable to detect the presence of the 2-fi of *yield*cogs*. The MVF(L_9) model is a *low-resolution* model, with corresponding *lower fidelity*.

Findings

Using the $L_9(3^{4-2},2^3+1)$ array, we are able to design the experiment that yields the maximum MVF. The experimental result is nearly identical to the one revealed by the L_{81} full factorial array and derived values (Table 5.33). We have shown that with our MVF($L_9(3^{4-2},2^3+1)$), our controllable variables are strong predictors of

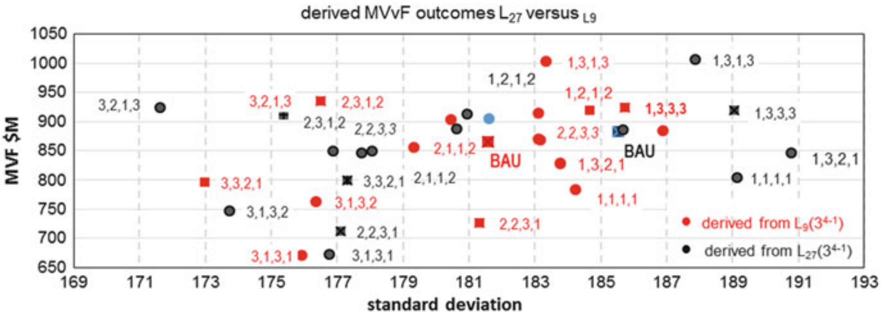


Fig. 5.29 Comparison of predicted MVF values using L_{27} and L_9 at $t = 18$

the outcomes, except for $t = 24$ for *r&d* ($p = 0.075$) and *manufacturing yield* ($p = 0.146$) (Table 5.32). Relative to our gold standard of MVF($L_9(3^{4-2},2^3+1)$), the percent errors are 3.8% and 1.6% for the derived outputs from our $L_9(3^{4-2},2^3+1)$ are respectable. Comparison of the results, for predictions using the $L_9(3^{4-2},2^3+1)$ response tables for means and standard deviations versus the predictions using the $L_{27}(3^{4-2},2^3+1)$ response tables, show a high degree of correlation. However, given that $L_9(3^{4-2},2^3+1)$ is a low resolution model, the interactions are not visible.

5.4.4.3 $\mathcal{R}$\{MVF($L_9(3^{4-2},2^3+1)$)\}: Rotated MVF($L_9(3^{4-2},2^3+1)$) Space

As before, it is appropriate to ask whether the **uncontrollable** variables in our $L_9(3^{4-2},2^3+1)$ array are also statistically significant. As before, we swap relative positions of the controllable and uncontrollable variables of $L_9(3^{4-2},2^3+1)$. The ANOVA table for that array is show in Table 5.34. With exception of *long term growth* for $t = 12$, all the uncontrollable variables have $p << 0.0.5$. This effect is consistent with the eponymous variable. The residuals are N(0,7.015) with $p >> 0.05$ (Fig. 5.26).

The ANOVA statistics for each of the time periods ending at $t = 12$, 18, and 24 (Table 5.35). The data for $t = 18$ and $t = 24$ are in Appendix 5.11.

Findings

For MVF($L_9(3^{4-2},2^3+1)$), we changed places of the controllable and uncontrollable variables to obtain $\mathcal{R}$[MVF($L_9(3^{4-2},2^3+1)$]. We found there is construct validity between the controllable and uncontrollable variables. Supported by the ANOVA statistics, we find a similar result between the uncontrollable and controllable variables. A summary of the ANOVA table for that construct is shown in Table 5.34. With exception of *long term growth* for $t = 12$, all the uncontrollable variables are statistically significant. The residuals are normal with mean zero and $p >> 0.05$ (Fig. 5.30).

Table 5.34 $\mathcal{R}$[MVF($L_9(3^{4-2},2^3+1)$)] at t = 12

Analysis of Variance						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
LT growth	1	1404	1404	1404	15.54	0.017
ADI orders	1	65,002	65,002	65,002	719.43	0.000
Competitor	1	14,657	14,657	14,657	162.22	0.000
Error	4	361	361	90		
Total	7	81,425				
S = 9.50540, R-Sq = 99.56%, R-Sq(adj) = 99.22%						

Table 5.35 $\mathcal{R}$[MVF($L_9(3^{4-2},2^3+1)$] statistical profile summary at t = 12, 18, 24

	t = 12		t = 18		t = 24	
Variables	Adj. MS	p value	Adj. MS	p value	Adj. MS	p value
Long term growth	1404	0.017	13,177	0.002	30,330	0.002
ADI orders	65,002	0.000	171,735	0.000	169,396	0.000
Competitors' attractiveness	14,657	0.000	63,271	0.000	89,062	0.000
Error	90	–	230	–	529	–

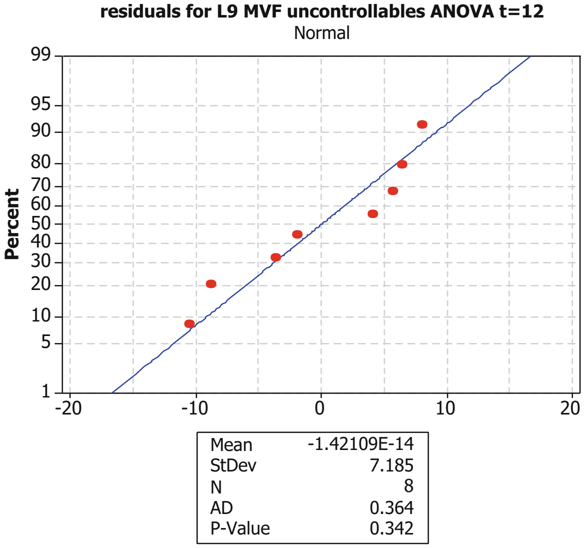


Fig. 5.30 $\mathcal{R}$[MVF($L_9(3^{4-2},2^3+1)$) residuals ANOVA at t = 12

5.4.4.4 Summary of the MVF($L_9(3^{4-2},2^{3+1})$)

We constructed the $L_9(3^{4-2},2^3+1)$ orthogonal array using a full-factorial array of uncontrollable variables to address the uncertain environments of designed decisions. We analyzed these $L_9(3^{4-2},2^3+1)$ arrays for the time periods ending at

$t = 12$, 18, and 24. The ANOVA tables for **both** the controllable variables **and** uncontrollable variables support our belief that they are predictors of the output of MVF in all three time periods (Appendices 5.9, 5.10, and 5.11). Since we do not have enough dof's in our orthogonal array, we are unable to determine the interactions. But the data show that the MAE is small relative to our gold standard of L_{81}. For decision-making, we are able to design the decision experiments that yield the maximum MVF for the time periods of $t = 12$, 18, and 24. Significantly, the MVF($L_9(3^{4-2},2^3+1)$) experiments yield the maximum MVF($L_9(3^{4-2},2^3+1)$), which is identical to the one revealed by the L_{81} arrays. Moreover, the derived values for maximum MVF($L_9(3^{4-2},2^3+1)$) are very close to the actual values from MVF($L_{81}(3^4,2^3+1)$ full factorial array average difference is 1.6%, as well as, from $L_{27}(3^{4-1},2^3+1)$ with a difference of 3.8% (Table 5.33). The L_9 model is fairly accurate, but reveals no factor interactions.

5.4.5 Summary of the Analyses of the Operations Space

There are two important results we developed in this sections.

First, we have shown construct validity using our *gedanken* experiments on behavior of the ADI surrogate using our controllable and uncontrollable variables. *These tests reveal the existence of demonstrable causal linkages between the independent and dependent variables*. The dependent variables are the controllable and uncontrollable variables. The independent variable was MVF **and** its associated standard deviation. We find that the experiments in this chapter support the functional validity of using the ADI surrogate to maximize the value of the firm, MVF.

Second, building on construct validity, we presented algorithms for decision syntheses. Paraphrasing Pahl and Beitz (1999) syntheses is the putting together of controllable and uncontrollable variables to produce intended results from the ensemble. **Synthesis is construction**. In contrast to analyses, it is arguably the most visible and creative parts of decision engineering. We presented three fundamental processes of our methodology: (i) we can predict the outcome of any decision alternative that has been designed, (ii) we can predict the standard deviation of any decision alternative that has been designed, and (iii) therefore, we can design decision alternatives that can satisfice and have less risk. These are decisions alternatives that are robust.

For construct validity, we used our DOE-based executive decision methodology. We proceeded through a progressive series of tests using L_{81}, L_{27}, and L_9 orthogonal arrays. We used this sequence of experiments to find the simplest experiment we can perform that will give us sufficient information for an intelligent decision. The corporate problems we intend to study are complicated, messy, and wicked. Therefore, simplicity is important because complex experiments are costly. They are costly because they require corporate staffs to collect data and perform analysis, experts to review, and management time to evaluate. The simpler the experiment, the smaller the costs incurred.

We started with the MVF($L_{81}(3^4, 2^3+1)$ full-factorial experiment. This is the most complete experiment consisting of $3^4 \times 2^3 + 1 = 2188$ experiments. We used its results for our "gold standard" against which we compared the results obtained from simpler experiments. We wanted to know what additional insights we may gain from more effort. Next, we successively used the L_{27} medium resolution and the L_9 low resolution arrays, respectively, for testing. Table 5.36 presents the results from our three experimental designs. The data demonstrate that our variables have high explanatory power (high R^2) and are also strong predictors ($p << 0.05$) with few exceptions, at $t = 24$ of the MVF outcome.

Table 5.37 summarizes data about the interactions. Collectively, they demonstrate that the interactions are very small contributors to the MVF outcome. This shows that the sociotechnical behavior exhibited by the ADI surrogate is quasi-linear.

We also tested the statistical significance of the uncontrollable variables on our outcome of $\mathcal{R}\{\text{MVF}\}$ using our $\mathcal{R}\{L_{81}\}$, $\mathcal{R}\{L_{27}\}_{,}$ $\mathcal{R}\{L_9\}$ arrays (Tables 5.21, 5.29 and 5.31). Collectively, the data indicate that the uncontrollable variables do create uncontrollable uncertainty conditions that have a strong influence on the outcome of $\mathcal{R}\{\text{MVF }\}$. To our knowledge, the literature does not report analyses of this type. This is a new kind of analysis for uncontrollable variables.

Data from these analyses suggest that the controllable and uncontrollable have strong predictive power on MVF (Table 5.38). By inspection, our L_{81} reveals the treatment for the maximum MVF at each of the time periods of $t = 12$, 18, and 24. With our L_{27} and L_9 orthogonal arrays, we design the decisions alternatives for maximum MVF and predict their outcomes. The designs are identical as the one revealed by our L_{81}. The derived values are close to the gold standard (Table 5.39) as shown by the very modest differences in predicted values.

Figure 5.31 is an example of the synthesis capability of our algorithm to predict the MVF and stdev of designed decision alternatives. We randomly specified 19 decision alternatives. Then we predicted their outcomes and standard deviations using the MVF(L_{27}) response tables data and the ANOM procedure. We followed the exact same steps using MVF(L_9) response tables. The MVF(L_{27}) points are in **black**, and the MVF(L_9) points are shown in red. The correlation between the MVF (L_{27}) and the MVF(L_9) data shows a **correlation of 99%.** The predictive power of AOI(L_9) is good, but we are unable to detect the presence of the 2-fi of *yield*cogs*. The MVF(L_9) model is a *low-resolution* model, with corresponding *lower fidelity*.

Finally, find that using the ADI surrogate for MVF($L_{81}(3^4,2^3+1)0$, MVF($L_{27}(3^{4-1},2^3+1)$) and MVF($L_9(3^{4-2},2^3+1)$, the criteria have been satisfied (Table 5.40).

Table 5.36 Controllable factors explanatory and predictive power at t = 12, 18, 24

	Controllable factors' p values for MVF								
	L_{81}			L_{27}			L_9		
	t = 12	t = 18	t = 24	t = 12	t = 18	t = 24	t = 12	t = 18	t = 24
r&d	0.000	0.000	0.000	0.003	0.019	0.065	0.048	0.052	0.075
yield	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.031	0.146
cogs	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.016	0.050
prod. price	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.006	0.026
yield**cogs*	0.000	0.000	0.000	0.072	0.171	0.213	–	–	–
yield*price	0.000	0.000	0.000	–	–	–	–	–	–
*cogs**price	0.000	0.000	0.000	–	–	–	–	–	–
yield**cogs**price	0.049	0.000	0.000	–	–	–	–	–	–
R^2 %	99	99	99	99	95	86	99	99	99

Table 5.37 % contribution of interactions to MVF

	% contribution of interactions to the outcome of MVF								
	L_{81}			L_{27}			L_9		
	t = 12	t = 18	t = 24	t = 12	t = 18	t = 24	t = 12	t = 18	t = 24
Interactions	0.5%	2.7%	8.9%	0.25%	1.1%	3.4%	–	–	–

Table 5.38 p values for uncontrollable variables to $\mathcal{R}\{\text{MVF}\}$ at t = 12, 18, 24

	Controllable factors' p values								
	L_{81}			L_{27}			L_9		
	t = 12	t = 18	t = 24	t = 12	t = 18	t = 24	t = 12	t = 18	t = 24
yield	0.000	0.001	0.001	0.014	0.001	0.001	0.017	0.002	0.002
cogs	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.016	0.050
Prod. price	0.014	0.000	0.000	0.000	0.000	0.000	0.001	0.006	0.026

Table 5.39 MVF at t = 12, t = 18, and t = 24 using L_9 vs. L_{27} and L_{81}

		Market Value of the Firm (MVF)				
		MVF(L_{81})	MVF(L_{27})	MVF(L_9)	|[MVF(L_{27})-MVF(L_{81})]|/MVF(L_{81})	|[MVF(L_9)-MVF(L_{81})]|/MVF(L_{81})
	Experiment	By inspection	Derived	Derived		
t = 12	1,3,1,3	\$870 M	\$881 M	\$876 M	1.3%	0.7%
t = 18	1,3,1,3	\$971 M	\$1003 M	\$1005 M	3.3%	3.5%
t = 24	1,3,1,3	\$821 M	\$877 M	\$826 M	6.8%	0.6%
					Average = 3.8%	Average = 1.6%

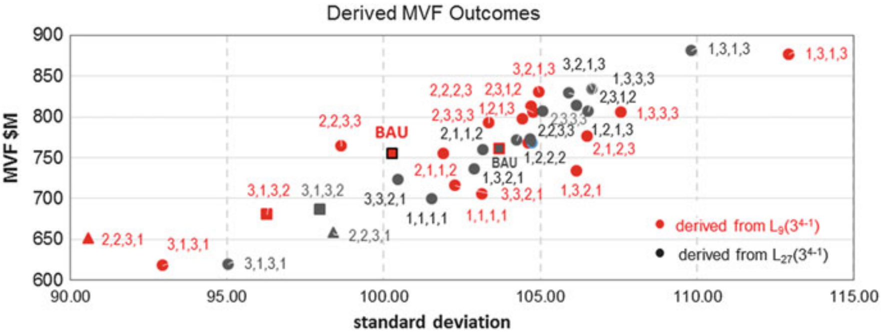


Fig. 5.31 Comparison of predicted MVF values using L_{27} and L_9 at t = 12

Table 5.40 Readiness level specifications for executive decisions

Readiness level	Systematic process for the Operations Space	Functionality
X-RL3 Explore operations space	Specify	
	Sample orthogonal array	☑
	Do-nothing case and choice decision-alternative	☑
	Predict outcomes	☑
	Design and implement robust alternative	☑
	Design and implement any what-if alternative	☑

The symbol ☑ indicates support is demonstrated

Table 5.41 Readiness level specifications for executive decisions

Readiness level	Systematic process for the performance space	Functionality
X-RL4 Evaluating performance space	Evaluate performance: analyze 4R	☐
	Robustness	☑
	Repeatability, reproducibility, reflect	☐

The symbol ☐ indicates functionality and efficacy will be shown in Part III

5.5 Evaluating the Performance Space

The discussions have concentrated on the use of DOE methods to construct decision alternatives using DOE experiments to predict performance. Experiments depend on data, but how do we know the data are "good enough"? What is good enough? How do we know the quality of those performing the experiments or of the mechanisms? These are the questions we explore and discuss by considering the sociotechnical system that implements a decision specification as a **production system**. We evaluate performance through this lens using the science and technology of a measurement system and use Gage R&R (AIAG 2002).

Because this chapter is a simulation, we cannot address the questions or repeatability and reproducibility. We will discuss them in Part III where we report the results and our findings from real enterprises from the business and national defense sectors. Full discussion of conformance to X-RL4 is deferred to Part III. Table 5.41 summarizes the X-RL4 situation at this point.

5.6 Enacting in the Commitment Space

Teddy Roosevelt famously said that at any moment of decision, the worst thing one can do is to do nothing. He also said that doing the "wrong thing" is preferable to doing nothing. Our experiences tells us the "wrong thing" means acting on a less

Table 5.42 Readiness level specifications for executive decisions

Readiness level	Systematic process for the commitment space	Functionality
X-RL5 Enacting commitment space	Decisive executive	☐
	Approval of plan	☐
	Commit funds, equipment, organizations	☐

The symbol ☐ indicates functionality and efficacy will be shown in Part III

than ideal alternative, which then provides us with information that supports or refutes the undertaken action. This is an effective learning mechanism. As a general principle, we agree that being "wrong" is better than being indecisive. Indecisiveness breeds uncertainty, doubt that propagates rapidly in an organization and erodes confidence.

Taking a decision means committing to a decision specification and gaining senior executive approval to act. Approval must include a plan with well-defined checkpoints and work products to implement the decision-specifications. A plan that is buttressed with funds, organizations and skilled experts to do the work. Because this chapter is a simulation, we cannot address this question of execution - the production of a decision specification. We will discuss these topics in Part III where we report the results and our findings from real enterprises from the business and national defense sectors. Full discussion of conformance to X-RL5 is deferred to Part III. Table 5.42 summarizes the X-RL5 situation at this point.

5.7 Discussion

> Macroscopic behavior of physical [and social systems] systems can be described or determined by only a few relevant parameters. It is not always necessary to describe the behavior is terms of the finest scale. (Bar-Yam 1997, 293)

Data from our ADI-surrogate simulations of our MVF corporate decision demonstrate support for our DOE-based methodology for decision analysis. Our method is able to parametrize the system behavior of the ADI corporation for the MVF outcome. It is also able to parametrize the entire space of uncontrollable uncertainties it faces. Using our DOE-based method, we can explore the entire solution space the dynamic behavior of the ADI over the entire space of environmental uncertainty. Simulation data show that the interactions are small and their contribution to the outcome is very small. Therefore the data show that system behavior of ADI for the MVF outcome is "nearly-decomposable" (Simon 1997) at our scale of analysis. This supports our belief that we can represent that emergent system behavior with a quasi-linear model. "Simon (1997) writes that "If we are interested only in certain aggregated aspects of behavior, it may be that we can predict those aggregates by use of an appropriately aggregated model." And that "the dynamic behavior of a nearly-decomposable system can be analyzed without examining simultaneously all the interactions of the elementary parts (Simon 1997)." Bar-Yam (1997, 2000) makes a similar argument, that by looking at complex systems at the appropriate scale, i.e. at a level where the descriptions are self-consistent, "the wealth of behavior [of lower level objects] is not relevant at the larger scale." Bar-Yam makes a very insightful observation: "The existence of multiple levels implies that simplicity can also be an emergent property. This means that the collective behavior of many elementary parts can behave simply on a much larger scale (Bar-Yam 1997)." He writes: "The central point is: When the independence of the components is reduced, scale of behavior is increased."

In the next chapter, we will use the same approach for a different outcome to determine whether the findings will continue to consistently support the findings of this chapter.

5.8 Chapter Summary

- We stipulated that our methodology ***works***, if and only if, it simultaneously satisfies two conditions, *viz*. it is ready-to-work for users in general ***and*** ready-for-work by a user for a specific set of needs. The former condition is demonstration of **functionalit**y, the latter of **efficacy**. The goal in this chapter has been to develop evidence that the methodology is ***ready-to-work*** for users; that it is functional. In other words, the methodology "works" as designed by us.
- We used the ADI surrogate as a test object to present evidence that our methodology is ready-to-work by demonstrating that it will satisfy the X-RL conditions. We played the role of a DMU. We applied our systematic decision lifecycle process. We used the ADI surrogate for the specific corporate objective of maximizing ADI's market value of the firm (MVF).
- First, we demonstrated though exhaustive analyses the construct validity of the ADI MVF($L_{81}(3^4, 2^3+1)$) model, under a wide range of uncertainty regimes. We established as the "gold standard" the results from MVF($L_{81}(3^4,2^3+1)$) under a spectrum of uncertainty regimes.
- We stepped through every step of our systematic process to demonstrate the *functionality* of our method and readiness levels, from X-RL1 to X-RL5. Our experiments with ADI demonstrate there is support for the following:

X-RL1 The *Problem Space* is very clearly characterized with controllable and uncontrollable variables, at three levels for each, to achieve the objective of Market

Value of the Firm (MVF). The controllable and uncontrollable variables were exhaustively analyzed to be construct valid.

X-RL2 The specifications for *Solution Space* is thoroughly specified using two elements. They are the controllable and uncontrollable spaces. These building blocks are used to engineer the entire space of solutions' alternatives, as well as, the uncertainty space.

X-RL3 Exploration of the *Operations Space* is exhaustively executed and analyzed. Three strategies are used to explore the operations space. First, a "gold standard" is specified for the entire solution space, uncertainty space, and outcomes space. Second, we used three experimental models of varying degrees of fidelity and complexity to test the functionality of our methodology. We find that the controllable and uncontrollable variables are all strong predictors of the outcomes under a wide range of uncertainty conditions. The predicted outcomes are quite close to the "gold standard". Two-factor and three- factors interactions are revealed more prominently in the high fidelity models. Fewer are revealed in the lesser fidelity models, but the results are very consistent with our gold standard.

X-RL4 Evaluation of the *Performance Space* of the 4-R (robustness, repeatability, reproducibility, and reflection) is only partly completed. We demonstrated robustness by using the response tables that show the standard deviations for the behavior of each controllable variable and by constructing a robust output. Reflection is demonstrated with the detailed discussions of our analyses and findings. Repeatability and reproducibility remain untested because we are acting as DMU without a quorum. This will be tested in Part III.

X-RL5 Enacting the Commitment Space remains untested because these experiments are simulations. This will be tested in Part III.

- The X-RL readiness demonstrated in this chapter is summarized in the Table 5.43.

Overall, the results reported in this chapter are evidence for the claim of functionality for our methodology. We conclude that there is strong support for the functionality of our methodology. This conclusion will be strengthened with the field experiments that will be presented in the next chapter.

Table 5.43 Readiness level specifications for executive decisions

Readiness level	Our systematic process	Functionality
X-RL1 Characterize problem space	Sense making—uncomplicate cognitive-load	☑
	Frame problem/opportunity and clarify boundary conditions	☑
	Specify goals and objectives	☑
	Specify essential variables Managerially controllable variables Managerially uncontrollable variables	☑
X-RL2 Engineer solution space	Specify subspaces of solution space Alternatives space and uncertainty space	☑
	Specify entire solution space	☑
	Specify base line and uncertainty regimes Do-nothing case and choice-decision Estimate base line and dispel bias	☑
X-RL3 Explore operations space	Specify	
	Sample orthogonal array	☑
	Do-nothing case and choice decision-alternative	☑
	Predict outcomes	☑
	Design and implement robust alternative	☑
	Design and implement any what-if alternative	☑
X-RL4 Evaluate performance space	Evaluate performance: analyze 4R	☐
	Robustness	☑
	Repeatability, reproducibility, reflect	☐
X-RL5 Enact commitment space	Decisive executive	☐
	Approval of plan	☐
	Commit funds, equipment, organizations	☐

☑ indicates support has been demonstrated
☐ indicates support will be demonstrated in Part III

Appendix 5.1 MVF(L_{81}(3^4,2^3+1)) Experiment Data Under Uncertainty Regimes

Appendix 5.1.1 MVF(L_{81}(3^4,2^3+1)) at $t = 12$

MVF(L_{81}(3^4, 2^3+1))												
		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	←Industry growth	
		Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	←ADI order rate	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	←Competitors' attractiveness	
			000	**001**	**010**	**011**	**100**	**101**	**110**	**111**		
	Experiments	**Current**	. . .	**Worst case**	. . .	. . .	. . .	. . .	**Best case**		$\bar{y}_\alpha$	σ_α
1	**1,1,1,1**	746.49	644.34	553.04	813.11	737.66	669.18	572.92	852.09	763.45	705.81	103.09
2	**1,1,1,2**	819.01	715.15	610.11	875.35	809.41	742.69	632.03	918.57	827.90	772.25	105.35
3	**1,1,1,3**	861.33	756.84	650.71	926.82	853.12	787.72	674.09	965.65	876.36	816.96	108.11
4	**1,1,2,1**	703.40	599.79	514.57	757.75	697.73	625.42	534.03	792.86	721.66	660.80	97.56
5	**1,1,2,2**	787.23	678.77	576.40	834.10	770.19	705.72	598.75	880.22	789.75	735.68	103.44
6	**1,1,2,3**	832.57	724.35	617.46	888.27	817.36	754.32	641.36	934.11	837.85	783.07	107.41
7	**1,1,3,1**	653.98	554.22	473.80	701.96	652.33	580.07	492.34	732.50	673.85	612.78	91.92
8	**1,1,3,2**	746.67	635.51	540.64	782.44	729.05	681.87	562.47	826.17	749.45	694.92	97.95
9	**1,1,3,3**	800.34	689.85	583.37	848.16	778.52	719.21	607.74	898.14	800.39	747.30	106.05
10	**1,2,1,1**	773.25	675.06	581.78	847.61	768.02	699.43	600.89	885.76	793.16	736.11	104.67
11	**1,2,1,2**	841.69	740.05	637.42	905.02	838.65	767.13	658.37	944.01	859.07	799.05	105.86
12	**1,2,1,3**	883.88	780.52	677.60	954.46	880.74	812.22	699.92	984.02	906.88	842.25	107.33
13	**1,2,2,1**	742.90	638.12	550.02	805.39	735.12	662.39	569.54	843.63	760.18	700.81	101.97
14	**1,2,2,2**	815.46	709.66	607.34	869.19	806.45	736.70	628.88	912.48	824.30	767.83	104.62
15	**1,2,2,3**	857.65	751.22	647.73	920.88	849.99	781.31	670.58	960.86	872.40	812.51	107.71

(continued)

MVF($L_{81}(3^4, 2^3+1)$)												
		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	←Industry growth	
		Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	←ADI order rate	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	←Competitors' attractiveness	
			000	**001**	**010**	**011**	**100**	**101**	**110**	**111**		
	Experiments	**Current**	...	**Worst case**	...	...	...	...	**Best case**		$\bar{y}_\alpha$	σ_α
16	**1,2,3,1**	703.10	596.90	518.38	755.23	699.17	621.98	534.37	789.60	722.60	660.15	96.46
17	**1,2,3,2**	786.26	675.64	576.53	831.67	771.06	701.79	598.37	877.29	789.90	734.28	103.04
18	**1,2,3,3**	831.26	721.29	617.34	885.87	817.73	750.56	640.65	931.31	837.60	781.51	107.03
19	**1,3,1,1**	800.68	705.78	612.96	882.76	800.57	729.19	631.17	918.09	824.60	767.31	105.57
20	**1,3,1,2**	867.16	767.17	667.78	937.55	869.69	795.12	687.68	965.83	893.80	827.98	105.32
21	**1,3,1,3**	910.30	807.26	707.45	985.33	911.16	839.38	728.67	1003.0	938.29	870.09	106.21
22	**1,3,2,1**	776.33	676.83	585.98	849.67	772.98	700.57	604.71	887.08	797.04	739.02	104.21
23	**1,3,2,2**	843.75	740.90	641.65	906.61	842.87	767.52	661.88	944.45	863.23	801.43	105.28
24	**1,3,2,3**	875.43	770.62	669.77	943.68	872.70	801.52	691.72	976.05	897.46	833.22	107.08
25	**1,3,3,1**	750.04	644.29	558.42	813.93	744.44	667.57	577.36	852.05	768.79	708.54	102.40
26	**1,3,3,2**	820.50	713.80	614.89	875.09	815.42	739.96	635.55	917.12	832.57	773.88	104.45
27	**1,3,3,3**	851.62	743.19	641.91	912.48	844.20	772.42	664.34	954.06	865.59	805.53	107.48
28	**2,1,1,1**	740.25	638.63	549.25	807.84	731.70	663.32	568.91	846.75	757.47	700.46	102.54
29	**2,1,1,2**	812.27	708.91	606.13	869.35	802.82	736.28	627.69	912.56	821.28	766.37	104.61
30	**2,1,1,3**	854.33	750.32	646.55	920.00	845.99	780.77	669.53	958.92	869.10	810.61	107.17
31	**2,1,2,1**	697.12	594.05	510.70	752.49	691.73	619.52	529.91	787.53	715.67	655.41	97.03
32	**2,1,2,2**	780.30	672.43	572.26	828.14	763.54	699.25	594.32	874.20	783.08	729.72	102.74
33	**2,1,2,3**	825.21	717.55	613.14	881.48	810.10	747.30	636.66	927.38	830.55	776.60	106.52
34	**2,1,3,1**	647.67	548.50	469.88	696.79	646.34	574.11	488.17	727.22	667.87	607.39	91.41
35	**2,1,3,2**	739.67	629.14	536.39	776.49	722.38	655.33	557.94	820.15	742.75	686.69	97.83
36	**2,1,3,3**	792.77	682.91	579.10	841.45	771.19	712.12	602.94	891.40	793.05	740.77	105.17
37	**2,2,1,1**	767.13	669.38	578.11	842.36	762.09	693.62	596.95	880.45	787.21	730.81	104.11

38	**2,2,1,2**	835.09	734.00	633.36	898.98	832.15	760.77	654.14	938.01	852.48	793.22	105.11
39	**2,2,1,3**	876.76	774.25	673.55	947.68	873.74	805.37	695.50	977.28	899.68	835.98	106.33
40	**2,2,2,1**	736.65	632.39	546.23	800.12	729.15	656.51	565.50	838.29	754.20	695.45	101.42
41	**2,2,2,2**	808.70	703.40	603.33	863.19	799.86	730.28	624.54	906.46	817.68	761.94	103.88
42	**2,2,2,3**	823.90	714.48	613.03	879.08	810.48	743.54	635.96	924.57	830.30	775.04	106.14
43	**2,2,3,1**	696.82	591.15	511.51	749.97	693.18	616.06	530.26	784.26	716.60	654.42	96.48
44	**2,2,3,2**	779.34	669.30	572.40	825.70	764.41	695.31	593.94	871.26	783.23	728.32	102.33
45	**2,2,3,3**	823.90	714.48	613.03	879.08	810.48	743.54	635.96	924.57	830.30	775.04	106.14
46	**2,3,1,1**	794.72	700.27	609.44	877.49	794.73	723.44	627.32	912.79	818.68	762.10	104.96
47	**2,3,1,2**	860.67	761.38	664.05	931.52	863.32	788.84	683.62	959.85	887.28	822.28	104.48
48	**2,3,1,3**	903.27	801.24	703.51	978.59	904.30	832.80	724.44	996.62	931.23	864.00	105.21
49	**2,3,2,1**	770.23	671.16	582.34	844.41	767.06	694.75	600.76	881.77	791.11	733.73	103.64
50	**2,3,2,2**	837.17	734.87	637.81	900.57	836.40	761.16	657.68	938.45	856.64	795.64	104.49
51	**2,3,2,3**	878.58	774.68	677.38	949.00	877.60	805.29	698.49	977.03	903.28	837.93	105.75
52	**2,3,3,1**	743.82	638.57	554.68	808.66	738.48	661.70	573.34	846.70	762.82	703.20	101.85
53	**2,3,3,2**	813.79	707.57	610.92	869.08	808.86	733.55	631.24	911.10	825.95	768.01	103.70
54	**2,3,3,3**	854.97	748.10	650.77	919.46	850.56	777.33	672.27	956.66	873.08	811.47	106.27
55	**3,1,1,1**	733.95	633.25	546.12	801.76	725.40	657.33	565.45	840.71	751.02	695.00	101.48
56	**3,1,1,2**	805.41	703.31	602.81	862.57	796.02	729.85	624.07	905.69	814.18	760.43	103.29
57	**3,1,1,3**	846.95	744.59	643.05	912.66	838.73	774.32	665.77	951.31	861.53	804.32	105.65
58	**3,1,2,1**	690.72	588.48	507.50	746.46	685.32	613.48	526.34	781.56	709.18	649.89	96.01
59	**3,1,2,2**	773.36	666.50	568.84	821.26	756.57	692.60	590.52	867.32	775.90	723.65	101.47
60	**3,1,2,3**	817.72	711.56	609.55	874.01	802.70	740.35	632.75	919.70	822.77	770.12	105.02
61	**3,1,3,1**	641.17	542.84	466.62	690.90	639.87	568.08	484.53	721.33	661.39	601.86	90.43
62	**3,1,3,2**	732.60	622.97	532.88	769.66	712.55	648.62	554.00	813.33	735.52	680.24	96.49
63	**3,1,3,3**	785.19	676.56	575.43	833.84	763.61	704.86	598.86	888.71	785.13	734.69	104.62
64	**3,2,1,1**	760.91	664.20	575.06	836.29	755.92	687.71	593.62	874.38	780.82	725.43	103.01
65	**3,2,1,2**	828.31	728.62	630.31	892.30	825.47	754.68	650.64	931.12	845.53	787.44	103.72
66	**3,2,1,3**	869.54	768.69	670.11	940.40	866.62	799.27	691.85	969.85	892.29	829.85	104.81
67	**3,2,2,1**	730.35	626.96	543.10	794.04	722.85	650.50	562.03	832.25	747.75	689.98	100.37

(continued)

MVF($L_{81}(3^4, 2^3+1)$)

		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	←Industry growth	
		Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	←ADI order rate	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	←Competitors' attractiveness	
			000	**001**	**010**	**011**	**100**	**101**	**110**	**111**		
	Experiments	**Current**	. . .	**Worst case**	. . .	. . .	. . .	. . .	**Best case**		$\bar{y}_\alpha$	σ_α
68	**3,2,2,2**	801.84	697.76	600.00	856.40	793.06	723.79	620.91	899.58	810.57	755.99	102.57
69	**3,2,2,3**	843.05	738.89	640.06	906.70	835.59	767.83	662.24	946.28	857.55	799.80	105.20
70	**3,2,3,1**	690.42	585.57	508.32	743.94	686.77	610.02	526.69	778.28	710.11	648.90	95.46
71	**3,2,3,2**	772.39	663.35	568.99	818.82	757.46	688.67	590.15	864.37	776.05	722.25	101.06
72	**3,2,3,3**	816.41	708.48	609.45	871.60	803.09	736.57	632.07	916.89	822.53	768.57	104.64
73	**3,3,1,1**	788.59	695.31	606.46	871.50	788.69	717.85	624.14	906.70	812.42	756.85	103.83
74	**3,3,1,2**	854.05	756.21	660.88	924.92	856.81	783.15	680.23	953.10	880.52	816.65	103.13
75	**3,3,1,3**	896.35	795.88	700.16	971.37	897.36	826.98	720.88	989.33	924.04	858.04	103.69
76	**3,3,2,1**	764.03	666.00	579.30	838.35	769.92	688.87	597.44	875.69	784.73	729.37	102.94
77	**3,3,2,2**	830.41	729.51	634.57	893.89	829.75	755.10	654.20	931.56	849.73	789.86	103.13
78	**3,3,2,3**	871.40	769.14	673.96	941.72	870.51	799.22	694.86	969.10	895.93	831.76	104.14
79	**3,3,3,1**	737.54	633.18	551.57	802.57	732.22	655.71	569.90	840.65	756.38	697.75	100.79
80	**3,3,3,2**	806.95	701.99	607.62	862.30	802.10	727.13	627.66	904.21	818.89	762.09	102.38
81	**3,3,3,3**	847.60	742.38	647.29	912.12	843.34	770.90	668.55	949.05	865.56	805.20	104.73
∑column		64,515.	56,102.4	48,413.9	69,441.7	63,947.3	58,298.3	50,088.7	72,541.3	65,738.7	61,009.7	

Appendix 5.1.2 MVF(L_{81}(3^4,2^3+1)) at $t = 18$

MVF(L_{81}(3^4, 2^3+1))											
		Uncertainty regimes									
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	←Industry growth	
		Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	←ADI order rate	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	←Competitors' attractiveness	
			000	**001**	**010**	**011**	**100**	**101**	**110**	**111**		
	Experiments	**Current**	. . .	**Worst case**	. . .	. . .	. . .	. . .	**Best case**		$\bar{y}_\alpha$	σ_α
1	**1,1,1,1**	908.42	687.57	513.01	980.32	813.37	768.62	571.13	1091.0	895.46	803.21	189.25
2	**1,1,1,2**	990.45	789.56	590.85	1048.0	900.13	871.30	654.53	1171.0	969.21	887.23	185.64
3	**1,1,1,3**	1029.0	831.94	632.65	1101.0	941.83	912.19	699.28	1215.0	1020.0	931.43	187.11
4	**1,1,2,1**	841.99	618.96	445.61	883.25	753.34	693.19	503.22	990.09	829.39	728.78	180.30
5	**1,1,2,2**	964.55	744.32	545.51	1008.0	854.32	830.72	612.06	1135.0	927.94	846.94	189.14
6	**1,1,2,3**	1011.0	802.26	594.97	1063.0	903.96	889.89	665.80	1195.0	980.76	900.74	190.39
7	**1,1,3,1**	755.38	530.74	371.88	787.06	671.46	611.10	426.94	883.41	742.83	642.31	171.67
8	**1,1,3,2**	903.34	670.90	484.20	923.66	795.24	760.10	548.84	1046.0	870.13	778.05	183.08
9	**1,1,3,3**	982.67	761.72	550.33	1026.0	859.09	848.16	623.34	1163.0	941.38	861.74	194.52
10	**1,2,1,1**	921.04	731.54	553.03	1014.0	843.26	807.36	608.72	1124.0	924.63	836.40	184.81
11	**1,2,1,2**	1000.0	810.35	619.64	1075.0	928.31	884.04	678.98	1184.0	998.43	908.75	182.63
12	**1,2,1,3**	1040.0	850.22	660.55	1128.0	966.45	926.16	722.49	1216.0	1048.0	950.87	182.51
13	**1,2,2,1**	905.51	676.47	506.75	967.69	809.78	757.73	564.42	1078.0	890.61	795.22	188.14
14	**1,2,2,2**	986.66	783.70	585.70	1041.0	895.56	866.05	649.22	1165.0	964.13	881.89	185.46
15	**1,2,2,3**	1026.0	825.75	627.27	1094.0	937.27	906.05	693.46	1211.0	1014.0	926.09	187.44
16	**1,2,3,1**	841.11	604.89	445.48	878.89	755.62	686.99	502.33	984.89	830.77	725.66	180.42
17	**1,2,3,2**	962.59	738.30	543.69	1005.0	854.48	823.43	609.29	1132. 0	927.01	843.98	189.34
18	**1,2,3,3**	1008. 0	797.57	562.45	1061. 0	903.29	884.37	662.37	1193. 0	979.15	894.58	197.04
19	**1,3,1,1**	932.68	757.97	585.65	1047. 0	872.23	823.36	637.05	1145. 0	949.21	861.13	182.45
20	**1,3,1,2**	1012.0	831.35	650.08	1107.0	955.22	899.24	704.76	1186. 0	1031. 0	930.74	178.25

(continued)

MVF($L_{81}(3^4, 2^3+1)$)

		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	←Industry growth	
		Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	←ADI order rate	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	←Competitors' attractiveness	
			000	**001**	**010**	**011**	**100**	**101**	**110**	**111**		
	Experiments	**Current**	. . .	**Worst case**	. . .	. . .	. . .	. . .	**Best case**		$\bar{y}_\alpha$	σ_α
21	**1,3,1,3**	1053.0	869.34	689.59	1155.0	992.88	940.88	746.67	1215.0	1075.0	970.82	177.54
22	**1,3,2,1**	921.26	732.57	555.72	1015.0	846.69	806.35	610.35	1125.0	926.00	837.66	184.42
23	**1,3,2,2**	899.59	810.15	622.04	1076.0	930.59	882.18	679.86	1183.0	1001.0	898.27	178.99
24	**1,3,2,3**	1034.0	841.31	650.36	1117.0	957.80	917.47	712.61	1214.0	1038.0	942.51	184.03
25	**1,3,3,1**	908.63	685.87	518.20	980.42	818.42	765.31	574.61	1091.0	898.41	804.54	188.19
26	**1,3,3,2**	988.90	785.38	591.54	1046.0	904.44	864.89	652.87	1168.0	970.64	885.85	185.35
27	**1,3,3,3**	1022.0	817.00	618.76	1086.0	930.59	898.14	684.86	1209.0	1006.0	919.15	189.11
28	**2,1,1,1**	889.64	674.02	506.64	964.92	797.02	752.06	563.88	1076.0	877.99	789.13	185.88
29	**2,1,1,2**	970.81	775.57	584.47	1030.0	883.25	854.28	646.94	1153.0	950.06	872.04	181.26
30	**2,1,1,3**	1009.0	818.86	626.25	1082.0	924.89	895.63	691.56	1195.0	1000.0	915.91	182.13
31	**2,1,2,1**	823.09	597.03	439.00	867.99	736.44	676.38	495.78	974.97	812.50	713.69	177.58
32	**2,1,2,2**	943.70	729.03	538.56	991.13	836.37	812.40	604.15	1118.0	908.48	831.31	185.23
33	**2,1,2,3**	989.80	787.53	588.07	1044.0	885.83	871.53	657.62	1176.0	959.71	884.45	185.77
34	**2,1,3,1**	736.45	516.68	365.19	773.93	654.57	593.95	419.41	868.64	725.89	628.30	168.59
35	**2,1,3,2**	882.23	655.24	476.93	906.43	776.45	741.34	540.70	1029.0	850.83	762.13	179.15
36	**2,1,3,3**	959.97	745.48	542.94	1006.0	839.65	828.29	614.85	1143.0	919.92	844.46	189.73
37	**2,2,1,1**	903.08	718.73	547.05	999.55	827.92	791.39	601.73	1109.0	907.35	822.87	181.49
38	**2,2,1,2**	982.06	797.88	613.65	1058.0	912.53	868.75	671.74	1167.0	980.44	894.67	178.49
39	**2,2,1,3**	1022.0	838.16	654.41	1108.0	950.52	911.09	715.32	1197.0	1030.0	936.28	177.60
40	**2,2,2,1**	886.65	662.80	500.35	952.26	793.40	741.02	557.13	1063.0	873.13	781.08	184.77
41	**2,2,2,2**	966.89	769.64	579.25	1023.0	878.70	848.72	641.59	1147.0	944.94	866.64	181.09
42	**2,2,2,3**	1006.0	812.49	620.86	1075.0	920.26	889.22	685.70	1192.0	994.42	910.66	182.70

43	**2,2,3,1**	822.22	590.94	438.87	863.62	738.72	670.06	494.89	969.75	813.65	711.41	177.05
44	**2,2,3,2**	941.73	723.06	536.77	988.57	836.57	805.08	601.38	1115.0	907.53	828.41	185.47
45	**2,2,3,3**	987.47	782.78	585.59	1041.0	885.20	865.90	654.21	1174.0	958.11	881.58	186.19
46	**2,3,1,1**	915.94	746.46	580.15	1032.0	857.98	808.91	630.43	1130.0	932.57	848.27	178.94
47	**2,3,1,2**	995.65	820.06	644.42	1089.0	940.56	885.21	698.16	1168.0	1014.0	917.23	173.69
48	**2,3,1,3**	1036.0	858.20	683.66	1136.0	977.89	927.58	740.09	1196.0	1058.0	957.05	172.64
49	**2,3,2,1**	903.43	719.77	549.84	1000.0	831.58	790.47	603.38	1109.0	908.76	824.03	180.82
50	**2,3,2,2**	981.38	797.80	616.11	1058. 0	915.01	866.56	672.71	1166	982.93	895.17	177.85
51	**2,3,2,3**	1021.0	837.11	656.17	1108.0	952.44	908.46	715.32	1195.0	1032.0	936.17	177.10
52	**2,3,3,1**	889.94	672.26	511.13	964.96	802.36	748.64	567.39	1076. 0	880.94	790.40	184.97
53	**2,3,3,2**	969.46	771.66	585.23	1029.0	887.91	847.84	645.34	1151.0	951.56	871.00	181.25
54	**2,3,3,3**	1006.0	813.61	626.18	1080.0	926.37	887.98	688.72	1192.0	1000.0	913.43	182.07
55	**3,1,1,1**	872.15	663.58	501.86	947.14	782.23	738.22	558.09	1058.0	860.00	775.70	180.92
56	**3,1,1,2**	953.54	765.03	579.50	1011.0	868.47	840.43	641.17	1133.0	932.17	858.26	175.82
57	**3,1,1,3**	993.17	808.52	621.05	1061.0	910.15	883.13	685.86	1173.0	982.75	902.07	176.20
58	**3,1,2,1**	804.82	586.04	434.09	850.42	720.74	662.14	489.72	957.53	794.47	700.00	172.71
59	**3,1,2,2**	924.61	717.38	533.37	971.00	820.36	797.11	597.82	1098.0	888.67	816.48	179.66
60	**3,1,2,3**	971.22	776.34	582.70	1022.0	870.05	856.82	651.44	1153.0	940.44	869.33	179.46
61	**3,1,3,1**	717.78	505.49	360.17	758.34	638.39	579.38	413.24	851.89	707.54	614.69	164.03
62	**3,1,3,2**	862.02	642.88	471.56	886.46	759.12	725.46	534.04	1010.0	830.76	746.92	173.76
63	**3,1,3,3**	939.62	733.27	537.39	984.15	822.60	811.87	608.16	1121.0	898.61	828.52	183.62
64	**3,2,1,1**	886.97	708.93	542.41	981.92	814.17	778.09	596.35	1091.0	890.78	810.07	176.59
65	**3,2,1,2**	966.28	788.04	608.80	1039.0	898.68	856.21	666.41	1147.0	964.22	881.63	173.07
66	**3,2,1,3**	1007.0	828.48	649.38	1088.0	936.78	899.75	709.82	1175.0	1014.0	923.13	171.77
67	**3,2,2,1**	868.99	652.23	495.57	934.45	778.57	727.05	551.30	1045.0	855.03	767.58	179.78
68	**3,2,2,2**	949.43	758.88	574.25	1003.0	863.89	834.54	635.78	1127.0	926.90	852.63	175.55
69	**3,2,2,3**	989.51	802.06	615.66	1053.0	905.48	876.42	679.98	1169.0	976.81	896.44	176.42
70	**3,2,3,1**	804.00	579.93	433.98	846.03	723.05	655.73	488.83	952.29	795.65	697.72	172.18

(continued)

MVF($L_{81}(3^4, 2^3+1)$)

		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	←Industry growth	
		Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	←ADI order rate	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	←Competitors' attractiveness	
			000	**001**	**010**	**011**	**100**	**101**	**110**	**111**		
	Experiments	**Current**	. . .	**Worst case**	. . .	. . .	. . .	. . .	**Best case**		$\bar{y}_\alpha$	σ_α
71	**3,2,3,2**	922.65	711.37	531.60	968.40	820.64	789.76	595.09	1095.0	887.76	813.59	179.89
72	**3,2,3,3**	968.89	771.61	580.23	1020.0	869.47	851.05	648.06	1151.0	938.91	866.58	179.98
73	**3,3,1,1**	901.45	737.42	575.70	1015.0	845.32	797.54	625.56	1112.0	917.77	836.42	174.11
74	**3,3,1,2**	981.54	811.02	639.77	1071.0	927.89	874.51	693.06	1148.0	999.82	905.18	168.45
75	**3,3,1,3**	1022.0	849.34	678.86	1117.0	965.21	917.11	734.78	1174.0	1044.0	944.70	167.00
76	**3,3,2,1**	887.49	709.99	545.26	982.94	818.05	777.33	598.06	1091.0	892.47	811.40	176.00
77	**3,3,2,2**	965.80	788.05	611.29	1039.0	901.34	854.53	667.41	1146.0	966.96	882.26	172.44
78	**3,3,2,3**	1006.0	827.50	651.17	1088.0	938.89	897.19	709.84	1173.0	1016.0	923.07	171.26
79	**3,3,3,1**	872.65	661.81	507.19	947.12	787.89	734.73	561.66	1058.0	863.19	777.14	179.87
80	**3,3,3,2**	952.39	761.15	580.26	1009.0	873.42	833.99	639.68	1130.0	934.07	857.11	175.52
81	**3,3,3,3**	990.20	803.33	621.02	1059.0	911.91	875.51	683.08	1170.0	983.79	899.76	176.18
∑column		76,274.	60,170.	45,577.	81,740.	69,539.	66,340.	50,484.	90,673.	75,528.		

Appendix 5.1.3 MVF(L_{81}(3^4,2^3+1)) at $t = 24$

MVF(L_{81}(3^4, 2^3+1))												
		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	←Industry growth	
		Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	←ADI order rate	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	←Competitors' attractiveness	
			000	**001**	**010**	**011**	**100**	**101**	**110**	**111**		
	Experiments	**Current**	. . .	**Worst case**	. . .	. . .	. . .	. . .	**Best case**		$\bar{y}_{\alpha}$	σ_{α}
1	**1,1,1,1**	873.24	572.20	363.26	894.02	697.36	702.91	451.41	1057.0	816.07	714.163	223.13
2	**1,1,1,2**	935.76	689.41	462.10	932.80	762.85	828.07	557.34	1107.0	865.85	793.464	200.54
3	**1,1,1,3**	958.19	714.38	489.83	960.02	783.42	849.46	587.85	1125.0	893.42	817.952	197.91
4	**1,1,2,1**	800.18	472.37	272.02	775.35	616.05	600.57	359.04	945.22	732.33	619.237	219.76
5	**1,1,2,2**	930.57	638.57	400.15	918.79	732.67	780.24	502.21	1105.0	843.83	761.337	221.41
6	**1,1,2,3**	961.66	705.48	465.61	945.23	761.05	851.44	572.08	1136.0	874.30	808.094	206.73
7	**1,1,3,1**	686.46	367.86	174.44	657.04	503.62	493.67	256.52	803.10	620.56	507.030	208.62
8	**1,1,3,2**	864.52	542.24	313.31	815.47	655.65	682.45	411.39	1008.0	773.47	674.056	222.09
9	**1,1,3,3**	951.81	659.75	404.78	932.30	731.42	802.25	517.56	1135.0	854.18	776.561	226.69
10	**1,2,1,1**	859.71	627.69	418.87	910.71	710.84	755.27	504.23	1069.0	827.78	742.678	203.64
11	**1,2,1,2**	926.56	692.88	477.92	943.72	776.75	818.76	566.05	1101.0	878.46	798.011	195.01
12	**1,2,1,3**	948.59	716.42	503.68	967.85	793.20	838.02	594.53	1112.0	907.04	820.148	191.67
13	**1,2,2,1**	873.59	557.86	354.45	885.43	694.31	689.21	442.49	1051.0	813.46	706.867	225.34
14	**1,2,2,2**	934.47	686.73	455.84	931.25	758.68	825.19	552.57	1110.0	862.86	790.843	202.93
15	**1,2,2,3**	958.29	711.10	484.42	958.35	779.21	848.74	582.54	1129.0	889.76	815.712	200.56
16	**1,2,3,1**	799.02	464.54	270.36	771.69	619.03	593.45	356.56	941.34	734.46	616.717	220.18
17	**1,2,3,2**	928.85	630.24	396.65	920.03	731.53	770.29	497.49	1107.0	843.15	758.359	223.64
18	**1,2,3,3**	960.30	701.62	461.09	946.88	759.43	846.92	597.14	1140.0	872.98	809.596	205.21
19	**1,3,1,1**	847.89	633.77	438.90	924.14	721.25	747.26	516.10	1066.0	829.99	747.256	197.46
20	**1,3,1,2**	915.22	694.70	492.10	954.61	786.97	804.93	572.61	1085.0	893.40	799.949	188.72

(continued)

MVF(L_{81}(3^4, 2^3+1))												
		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	←Industry growth	
		Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	←ADI order rate	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	←Competitors’ attractiveness	
			000	**001**	**010**	**011**	**100**	**101**	**110**	**111**		
	Experiments	**Current**	. . .	**Worst case**	. . .	. . .	. . .	. . .	**Best case**		$\bar{y}_{\alpha}$	σ_{α}
21	**1,3,1,3**	937.70	717.85	515.91	976.07	803.33	826.37	598.65	1094.0	916.72	820.733	185.36
22	**1,3,2,1**	858.11	627.65	421.49	913.27	710.75	754.15	504.68	1072.0	827.01	743.234	203.77
23	**1,3,2,2**	924.65	691.73	477.09	945.60	776.05	815.86	563.66	1103.0	878.99	797.403	196.02
24	**1,3,2,3**	950.33	713.82	496.05	965.83	787.83	839.19	588.37	1119.0	901.12	817.949	195.41
25	**1,3,3,1**	871.01	569.82	369.81	899.43	697.14	700.22	456.53	1066.0	816.85	716.312	223.46
26	**1,3,3,2**	933.80	684.44	458.28	935.67	763.47	821.85	550.74	1113.0	865.17	791.824	203.71
27	**1,3,3,3**	959.24	706.47	476.99	957.43	774.79	848.24	575.80	1136.0	885.63	813.399	204.65
28	**2,1,1,1**	842.56	556.33	356.33	865.11	676.21	680.14	443.54	1029.0	787.75	692.997	214.64
29	**2,1,1,2**	907.65	673.22	455.53	900.84	744.48	805.91	549.15	1075.0	838.85	772.292	191.30
30	**2,1,1,3**	932.83	700.01	483.45	926.88	765.62	829.71	579.73	1089.0	868.45	797.298	187.97
31	**2,1,2,1**	767.94	455.87	265.26	747.78	593.04	577.51	351.10	917.38	706.99	598.097	211.40
32	**2,1,2,2**	896.70	620.36	393.01	886.27	710.93	755.39	493.70	1073.0	812.93	738.032	211.71
33	**2,1,2,3**	931.49	688.98	458.64	909.38	741.10	827.64	563.33	1100.0	845.34	785.100	196.34
34	**2,1,3,1**	654.20	351.31	167.66	636.86	480.46	469.88	248.49	776.08	592.99	486.437	200.88
35	**2,1,3,2**	828.38	523.64	305.82	784.01	630.35	656.66	402.73	977.15	742.22	650.107	212.52
36	**2,1,3,3**	916.22	640.94	397.19	895.86	707.97	775.58	508.55	1100.0	821.23	751.504	216.09
37	**2,2,1,1**	833.16	612.97	412.75	882.13	692.66	733.99	496.90	1040.0	802.45	723.001	195.19
38	**2,2,1,2**	902.42	678.96	471.93	913.37	759.84	799.66	558.33	1069.0	854.62	778.681	186.04

39	**2,2,1,3**	926.57	703.49	497.62	937.48	776.85	821.07	587.26	1076.0	885.17	801.279	182.11
40	**2,2,2,1**	842.23	541.79	347.87	856.47	673.22	666.27	434.62	1023.0	784.75	685.580	216.70
41	**2,2,2,2**	905.81	670.53	449.23	898.96	740.04	802.32	544.38	1078.0	835.48	769.417	193.60
42	**2,2,2,3**	932.45	696.62	478.04	924.54	761.17	828.36	574.36	1093.0	864.36	794.767	190.52
43	**2,2,3,1**	766.76	447.84	263.59	743.87	596.05	570.15	348.59	913.51	707.31	595.297	211.70
44	**2,2,3,2**	895.12	612.27	389.52	887.45	710.22	745.36	489.03	1075.0	812.27	735.138	213.92
45	**2,2,3,3**	930.07	685.12	454.14	910.84	739.57	822.85	558.45	1104.0	843.99	783.226	198.86
46	**2,3,1,1**	825.72	621.08	433.40	897.07	705.38	729.50	508.99	1038.0	808.34	729.720	189.53
47	**2,3,1,2**	894.89	682.66	486.49	927.04	771.70	789.05	565.90	1053.0	873.25	782.664	180.14
48	**2,3,1,3**	918.78	706.39	510.18	948.92	788.43	812.10	1062.00	1062.0	897.88	804.088	176.99
49	**2,3,2,1**	832.05	613.02	415.43	884.63	693.15	733.09	1043.00	1043.0	802.12	723.738	195.37
50	**2,3,2,2**	900.96	678.08	471.17	915.24	759.26	796.86	1071.00	1071.0	855.67	778.261	187.05
51	**2,3,2,3**	924.43	701.78	495.75	938.82	775.69	817.68	1077.00	1077.0	885.58	800.032	183.29
52	**2,3,3,1**	840.70	553.77	363.31	870.41	677.20	677.36	1037.00	1037.0	788.96	695.273	214.77
53	**2,3,3,2**	906.27	668.93	451.89	903.48	745.10	799.10	1080.00	1080.0	838.68	770.681	194.21
54	**2,3,3,3**	929.70	694.48	477.87	929.37	762.57	823.48	1094.00	1094.0	867.70	794.542	191.47
55	**3,1,1,1**	819.65	544.95	351.95	833.63	659.35	663.54	996.08	996.08	765.06	674.623	204.75
56	**3,1,1,2**	886.86	661.42	450.51	869.77	729.54	790.05	1037.00	1037.0	818.22	754.050	181.08
57	**3,1,1,3**	913.98	688.99	478.36	897.54	751.19	816.11	1050.00	1050.0	849.86	780.001	177.97
58	**3,1,2,1**	743.14	443.89	260.37	717.80	574.77	560.61	884.53	884.53	687.23	579.682	201.94
59	**3,1,2,2**	871.61	607.55	387.82	850.88	693.27	737.26	1036.00	1036.0	788.45	717.760	200.90
60	**3,1,2,3**	909.25	676.84	453.30	875.59	724.97	810.78	1058.00	1058.0	823.58	765.466	185.15
61	**3,1,3,1**	628.78	339.40	162.69	612.08	461.48	452.39	744.85	744.85	568.93	468.083	191.86
62	**3,1,3,2**	800.91	510.88	300.44	749.12	610.39	637.83	940.07	940.07	719.89	629.480	201.78
63	**3,1,3,3**	890.15	627.76	391.67	857.41	689.35	756.23	1057.00	1057.0	795.65	729.634	203.90
64	**3,2,1,1**	813.37	602.32	408.10	853.20	677.77	718.13	1007.00	1007.0	782.77	705.979	185.84
65	**3,2,1,2**	884.40	668.44	467.15	885.46	746.36	786.36	1033.00	1033.0	836.70	762.309	176.60
66	**3,2,1,3**	910.09	693.64	492.79	911.28	763.62	808.88	1042.00	1042.0	868.39	785.829	173.44
67	**3,2,2,1**	818.78	530.29	343.09	824.57	656.33	649.57	990.00	990.00	761.51	666.949	206.79
68	**3,2,2,2**	884.59	658.63	444.21	867.06	725.82	785.82	1040.00	1040.0	814.41	750.976	183.24

(continued)

MVF(L_{81}(3^4, 2^3+1))

		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	←Industry growth	
		Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	←ADI order rate	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	←Competitors' attractiveness	
			000	**001**	**010**	**011**	**100**	**101**	**110**	**111**		
	Experiments	**Current**	. . .	**Worst case**	. . .	. . .	. . .	. . .	**Best case**		$\bar{y}_\alpha$	σ_α
69	**3,2,2,3**	913.29	685.53	472.93	849.43	746.73	814.37	1053.00	1053.0	845.46	772.151	177.14
70	**3,2,3,1**	742.02	435.77	258.69	713.40	577.85	553.07	880.65	880.65	687.37	576.787	202.23
71	**3,2,3,2**	870.01	599.47	384.35	851.77	692.82	727.21	1037.00	1037.0	787.59	714.727	202.84
72	**3,2,3,3**	907.74	673.13	448.81	876.65	723.55	805.71	1062.00	1062.0	822.16	763.532	187.56
73	**3,3,1,1**	809.08	611.50	428.99	871.37	692.32	716.93	1006.00	1006.0	791.94	714.679	180.78
74	**3,3,1,2**	879.55	673.45	482.02	902.62	759.45	777.54	1022.00	1022.0	857.52	768.327	172.09
75	**3,3,1,3**	904.57	697.56	505.72	925.99	776.32	801.38	1033.00	1033.0	882.90	790.487	169.63
76	**3,3,2,1**	812.61	602.42	410.80	855.71	678.69	717.60	1010.00	1010.0	782.88	706.917	186.03
77	**3,3,2,2**	883.26	667.70	466.43	887.35	745.89	783.66	1035.00	1035.0	838.05	762.010	177.60
78	**3,3,2,3**	908.28	691.99	490.98	912.62	762.62	805.57	1043.00	1043.0	869.05	784.692	174.62
79	**3,3,3,1**	818.04	542.38	358.57	838.61	661.04	660.72	1004.00	1004.0	766.48	676.940	204.91
80	**3,3,3,2**	885.87	657.47	446.95	872.15	730.67	783.55	1043.00	1043.0	818.47	752.766	184.13
81	**3,3,3,3**	911.19	683.69	472.83	899.70	748.47	809.86	1055.00	1055.0	849.37	777.351	181.38
∑column		70,957.	50,449.	33,489.	71,125.	57,628.	60,612.	40,873.	84,389.	66,224.06		

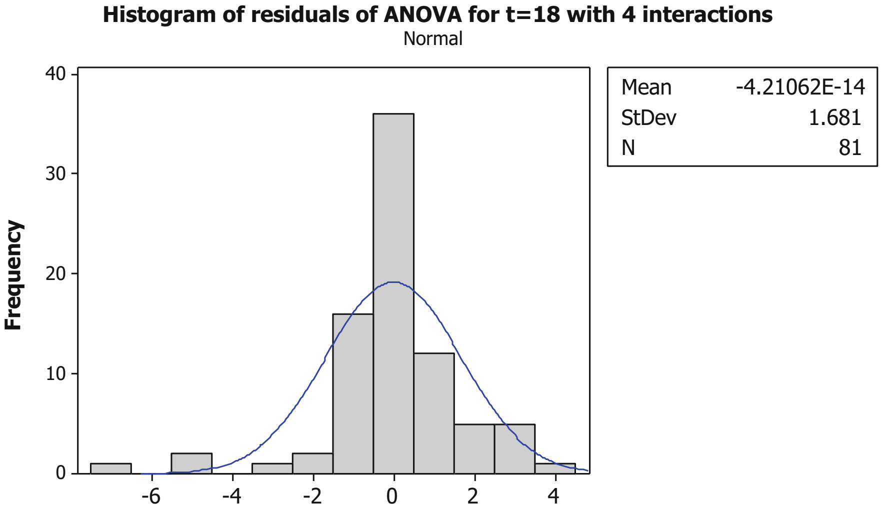
Appendix 5.2 MVF(L_{81}(3^4,2^3+1)) Controllable Variables Statistics

Appendix 5.2.1 MVF(L_{81}(3^4,2^3+1)) Controllable Variables ANOVA and Residuals at t = 18

Analysis of Variance **L_{81}(3^4,2^3+1) MVF t = 18**

Source	DF	Seq SS	Adj SS	Adj MS	F	P
r&d	2	10,036	10,036	5018	1154.58	0.000
yield	2	82,533	82,533	41,267	9494.95	0.000
cogs	2	88,669	88,669	44,334	10,200.80	0.000
price	2	275,285	275,285	137,643	31,669.83	0.000
yield**cogs*	4	9422	9422	2356	541.99	0.000
yield*price	4	8085	8085	2021	465.04	0.000
*cogs**price	4	6492	6492	1623	373.42	0.000
yield**cogs**price	8	2609	2609	326	75.04	0.000
Error	52	226	226	4		
Total	80	483,357				

S = 2.08475, R-Sq = 99.95%, R-Sq(adj) = 99.93%

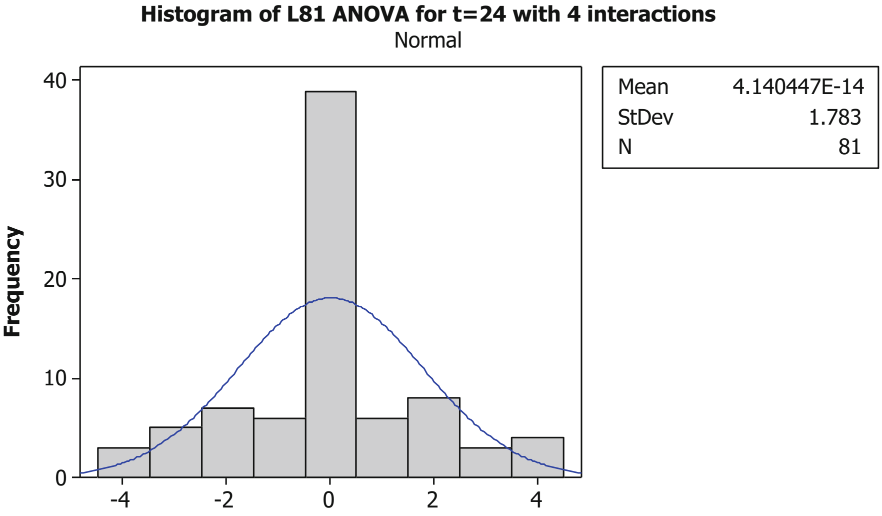


Appendix 5.2.2 MVF($L_{81}(3^4,2^3+1)$) Controllable Variables ANOVA and Residuals at t = 24

Analysis of Variance **$L_{81}(3^4,2^3+1)$ MVF t = 24**

Source	DF	Seq SS	Adj SS	Adj MS	F	P
r&d	2	20,325	20,325	10,162	2078.86	0.000
yield	2	63,088	63,088	31,544	6452.87	0.000
cogs	2	66,048	66,048	33,024	6755.64	0.000
price	2	247,424	247,424	123,712	25,307.32	0.000
yield**cogs*	4	25,979	25,979	6495	1328.58	0.000
yield*price	4	24,642	24,642	6161	1260.24	0.000
*cogs**price	4	22,971	22,971	5743	1174.75	0.000
yield**cogs**price	8	8240	8240	1030	210.72	0.000
Error	52	254	254	5		
Total	80	478,972				

S = 2.21097, R-Sq = 99.95%, R-Sq(adj) = 99.92%



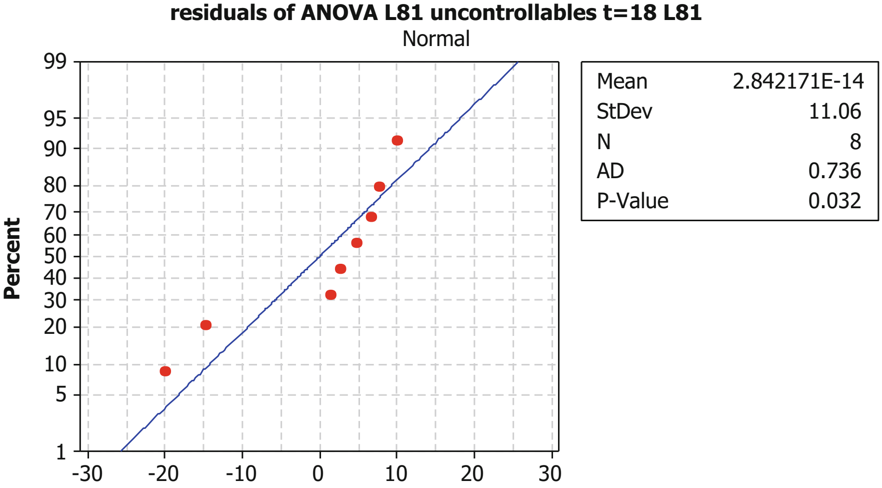
Appendix 5.3 MVF($L_{81}(3^4,2^3+1)$) Uncontrollable Variables Statistics

Appendix 5.3.1 Uncontrollable Variables ANOVA Table and Residuals at t = 18

Analysis of Variance for MVF t = 18

Source	DF	Seq SS	Adj SS	Adj MS	F	P
LT growth	1	12,879	12,879	12,879	60.17	0.001
ADI orders	1	171,615	171,615	171,615	801.84	0.000
Competitor	1	63,637	63,637	63,637	297.33	0.000
Error	4	856	856	214		
Total	7	248,987				

S = 14.6296, R-Sq = 99.66%, R-Sq(adj) = 99.40%



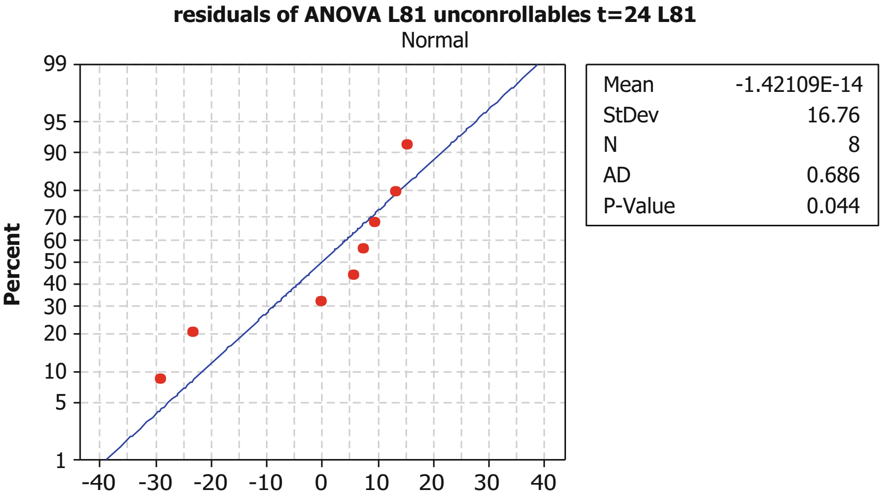
Appendix 5.3.2 Uncontrollable Variables ANOVA Table and Residuals at t = 24

Analysis of Variance

MVF $L_{81}(3^4,2^3+1)$ t = 24 uncontrollable variables

Source	DF	Seq SS	Adj SS	Adj MS	F	P
LT growth	1	29,601	29,601	29,601	60.25	0.001
ADI orders	1	168,167	168,167	168,167	342.28	0.000
Competitor	1	89,059	89,059	89,059	181.27	0.000
Error	4	1965	1965	491		
Total	7	288,792				

S = 22.1655, R-Sq = 99.32%, R-Sq(adj) = 98.81%



Appendix 5.4 MVF($L_{27}(3^{4-1},2^3+1)$) Experiment Data Under Uncertainty Regimes

Appendix 5.4.1 MVF($L_{27}(3^{4-1},2^3+1)$) at $t = 12$

MVF($L_{27}(3^{4-1}, 2^3+1)$)												
		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	←Industry demand	
		Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	←ADI orders	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	←Competitiveness	
			000	**001**	**010**	**011**	**100**	**101**	**110**	**111**		
	Experiments	**Current**	. . .	**Worst regime**	. . .	. . .	. . .	. . .	**Best regime**		$\bar{y}_{\alpha}$	σ_{α}
1	**1,1,1,1**	746.49	644.34	553.04	813.11	737.66	669.18	572.92	852.09	763.45	705.8	103.09
2	**1,1,2,2**	787.23	678.77	576.40	834.10	770.19	705.72	598.75	880.22	789.75	735.7	103.45
3	**1,1,3,3**	800.34	689.85	583.37	848.16	778.52	719.21	607.74	898.14	800.39	747.3	106.05
4	**1,2,1,2**	841.69	740.05	637.42	905.02	838.65	767.13	658.37	944.01	859.07	799.0	105.86
5	**1,2,2,3**	857.65	751.22	647.73	920.88	849.99	781.31	670.58	960.86	872.40	812.5	107.71
6	**1,2,3,1**	703.10	596.90	518.38	755.23	699.17	621.98	534.37	789.60	722.60	660.1	96.463
7	**1,3,1,3**	910.30	807.26	707.45	985.33	911.16	839.38	728.67	1003.0	938.29	870.1	106.21
8	**1,3,2,1**	776.33	676.83	585.98	849.67	772.98	700.57	604.71	887.08	797.04	739.0	104.21
9	**1,3,3,2**	820.50	713.80	614.89	875.09	815.42	739.96	635.55	917.12	832.57	773.9	104.45
10	**2,1,1,2**	812.27	708.91	606.13	869.35	802.82	736.28	627.69	912.56	821.28	766.4	104.61
11	**2,1,2,3**	825.21	717.55	613.14	881.48	810.10	747.30	636.66	927.38	830.55	776.6	106.52
12	**2,1,3,1**	647.67	548.50	469.88	696.79	646.34	574.11	488.17	727.22	667.87	607.4	91,410
13	**2,2,1,3**	876.76	774.25	673.55	947.68	873.74	805.37	695.50	977.28	899.68	836.0	106.33
14	**2,2,2,1**	736.65	632.39	546.23	800.12	729.15	656.51	565.50	838.29	754.20	695.4	101.42
15	**2,2,3,2**	779.34	669.30	572.40	825.70	764.41	695.31	593.94	871.26	783.23	728.3	102.33
16	**2,3,1,1**	794.72	700.27	609.44	877.49	794.73	723.44	627.32	912.79	818.68	762.1	104.97
17	**2,3,2,2**	837.17	734.87	637.81	900.57	836.40	761.16	657.68	938.45	856.64	795.6	104.49
18	**2,3,3,3**	854.97	748.10	650.77	919.46	850.56	777.33	672.27	956.66	873.08	811.5	106.27

(continued)

MVF($L_{27}(3^{4-1}, 2^3+1)$)

		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	←Industry demand	
		Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	←ADI orders	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	←Competitiveness	
			000	**001**	**010**	**011**	**100**	**101**	**110**	**111**		
	Experiments	**Current**	. . .	**Worst regime**	. . .	. . .	. . .	. . .	**Best regime**		$\bar{y}_\alpha$	σ_α
19	**3,1,1,3**	846.95	744.59	643.05	912.66	838.73	774.32	665.77	951.31	861.53	804.3	105.65
20	**3,1,2,1**	690.72	588.48	507.50	746.46	685.32	613.48	526.34	781.56	709.18	649.9	96.006
21	**3,1,3,2**	732.60	622.97	532.88	769.66	712.55	648.62	554.00	813.33	735.52	680.2	96.489
22	**3,2,1,1**	760.91	664.20	575.06	836.29	755.92	687.71	593.62	874.38	780.82	725.4	103.02
23	**3,2,2,2**	801.84	697.76	600.00	856.40	793.06	723.79	620.91	899.58	810.57	756.0	102.57
24	**3,2,3,3**	816.41	708.48	609.45	871.60	803.09	736.57	632.07	916.89	822.53	768.6	104.64
25	**3,3,1,2**	854.05	756.21	660.88	924.92	856.81	783.15	680.23	953.10	880.52	816.7	103.13
26	**3,3,2,3**	871.40	769.14	673.96	941.72	870.51	799.22	694.86	969.10	895.93	831.8	104.14
27	**3,3,3,1**	737.54	633.18	551.57	802.57	732.22	655.71	569.90	840.65	756.38	697.7	100.79
∑column		21,520.8	18,718.2	16,158.4	23,167.5	21,330.2	19,443.8	16,714.1	24,193.9	21,933.8		

Appendix 5.4.2 MVF($L_{27}(3^{4-1},2^3+1)$) at $t = 18$

MVF($L_{27}(3^{4-1}, 2^3+1)$)												
		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	←Industry demand and	
		Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	←ADI orders	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	←Competitiveness	
			000	**001**	**010**	**011**	**100**	**101**	**110**	**111**		
	Experiments	**Current**	. . .	**Worst regime**	. . .	. . .	. . .	. . .	**Best regime**		$\bar{y}_\alpha$	σ_α
1	**1,1,1,1**	908.42	687.57	513.01	980.32	813.37	768.62	571.13	1091.0	895.46	803.21	189.25
2	**1,1,2,2**	964.55	744.32	545.51	1008.0	854.32	830.72	612.06	1135.0	927.94	846.94	189.14
3	**1,1,3,3**	982.67	761.72	550.33	1026.0	859.09	848.16	623.34	1163.0	941.38	861.7	194.52
4	**1,2,1,2**	1000.0	810.35	619.64	1075.0	928.31	884.04	678.98	1184.0	998.43	908.75	182.63
5	**1,2,2,3**	1026.0	825.75	627.27	1094.0	937.27	906.05	693.46	1211.0	1014.0	926.09	187.44
6	**1,2,3,1**	841.11	604.89	445.48	878.89	755.62	686.99	502.33	984.89	830.77	725.66	180.42
7	**1,3,1,3**	1053.0	869.34	689.59	1155.0	992.88	940.88	746.67	1215.0	1075.0	970.82	177.54
8	**1,3,2,1**	921.26	732.57	555.72	1015.0	846.69	806.35	610.35	1125.0	926.00	837.66	184.42
9	**1,3,3,2**	988.90	785.38	591.54	1046.0	904.44	864.89	652.87	1168.0	970.64	885.85	185.35
10	**2,1,1,2**	970.81	775.57	584.47	1030.0	883.25	854.28	646.94	1153.0	950.06	872.04	181.26
11	**2,1,2,3**	989.80	787.53	588.07	1044.0	885.83	871.53	657.62	1176.0	959.71	884.45	185.77
12	**2,1,3,1**	736.45	516.68	365.19	773.93	654.57	593.95	419.41	868.64	725.89	628.30	168.59
13	**2,2,1,3**	1022.0	838.16	654.41	1108.0	950.52	911.09	715.32	1197.0	1030.0	936.28	177.60
14	**2,2,2,1**	886.65	662.80	500.35	952.26	793.40	741.02	557.13	1063.0	873.13	781.08	184.77
15	**2,2,3,2**	941.73	723.06	536.77	988.57	836.57	805.08	601.38	1115.0	907.53	828.41	185.47
16	**2,3,1,1**	915.94	746.46	580.15	1032.0	857.98	808.91	630.43	1130.0	932.57	848.27	178.94
17	**2,3,2,2**	981.38	797.80	616.11	1058.0	915.01	866.56	672.71	116.0	982.93	895.17	177.85
18	**2,3,3,3**	1006.0	813.61	626.18	1080.0	926.37	887.98	688.72	1192.0	1000.0	913.43	182.07
19	**3,1,1,3**	993.17	808.52	621.05	1061.0	910.15	883.13	685.86	1173.0	982.75	902.07	176.20
20	**3,1,2,1**	804.82	586.04	434.09	850.42	720.74	662.14	489.72	957.53	794.47	700.0	172.71

(continued)

MVF($L_{27}(3^{4-1}, 2^3+1)$)

		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	←Industry demand and	
		Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	←ADI orders	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	←Competitiveness	
			000	**001**	**010**	**011**	**100**	**101**	**110**	**111**		
	Experiments	**Current**	. . .	**Worst regime**	. . .	. . .	. . .	. . .	**Best regime**		$\bar{y}_{\alpha}$	σ_{α}
21	**3,1,3,2**	862.02	642.88	471.56	886.46	759.12	725.46	534.04	1010.0	830.76	746.92	173.76
22	**3,2,1,1**	886.97	708.93	542.41	981.92	814.17	778.09	596.35	1091.0	890.78	810.07	176.59
23	**3,2,2,2**	949.43	758.88	574.25	1003.0	863.89	834.54	635.78	1127.0	926.90	852.63	175.55
24	**3,2,3,3**	968.89	771.61	580.23	1020.0	869.47	851.05	648.06	1151.0	938.91	866.58	179.98
25	**3,3,1,2**	981.54	811.02	639.77	1071.0	927.89	874.51	693.06	1148.0	999.82	905.18	168.45
26	**3,3,2,3**	1006.0	827.50	651.17	1088.0	938.89	897.19	709.84	1173.0	1016.0	923.07	171.26
27	**3,3,3,1**	872.65	661.81	507.19	947.12	787.89	734.73	561.66	1058.0	863.19	777.14	179.87
∑column		25,462	20,061	15,211.8	27,253.9	23,187.9	22,118	16,835.3	30,226	25,185		

Appendix 5.4.3 MVF($L_{27}(3^{4-1},2^3+1)$) at $t = 24$

MVF($L_{27}(3^{4-1}, 2^3+1)$)												
		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	←Industry demand	
		Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	←ADI orders	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	←Competitiveness	
			000	**001**	**010**	**011**	**100**	**101**	**110**	**111**		
	Experiments	**Current**	. . .	**Worst regime**	. . .	. . .	. . .	. . .	**Best regime**		$\bar{y}_\alpha$	σ_α
1	**1,1,1,1**	572.20	363.26	894.02	697.36	702.91	451.41	1057.0	816.07	873.24	714.16	223.13
2	**1,1,2,2**	638.57	400.15	918.79	732.67	780.24	502.21	1105.0	843.83	930.57	761.34	221.41
3	**1,1,3,3**	659.75	404.78	932.30	731.42	802.25	517.56	1135.0	854.18	951.81	776.56	226.69
4	**1,2,1,2**	692.88	477.92	943.72	776.75	818.76	566.05	1101.0	878.46	926.56	798.01	195.01
5	**1,2,2,3**	711.10	484.42	958.35	779.21	848.74	582.54	1129.0	889.76	958.29	815.71	200.56
6	**1,2,3,1**	464.54	270.36	771.69	619.03	593.45	356.56	941.34	734.46	799.02	616.72	220.18
7	**1,3,1,3**	717.85	515.91	976.07	803.33	826.37	598.65	1094.0	916.72	937.70	820.73	185.36
8	**1,3,2,1**	627.65	421.49	913.27	710.75	754.15	504.68	1072.0	827.01	858.11	743.23	203.77
9	**1,3,3,2**	684.44	458.28	935.67	763.47	821.85	550.74	1113.0	865.17	933.80	791.82	203.71
10	**2,1,1,2**	673.22	455.53	900.84	744.48	805.91	549.15	1075.0	838.85	907.65	772.29	191.30
11	**2,1,2,3**	688.98	458.64	909.38	741.10	827.64	563.33	1100.0	845.34	931.49	785.10	196.34
12	**2,1,3,1**	351.31	167.66	636.86	480.46	469.88	248.49	776.08	592.99	654.20	486.44	200.88
13	**2,2,1,3**	703.49	497.62	937.48	776.85	821.07	587.26	1076.0	885.17	926.57	801.28	182.11
14	**2,2,2,1**	541.79	347.87	856.47	673.22	666.27	434.62	1023.0	784.75	842.23	685.58	216.70
15	**2,2,3,2**	612.27	389.52	887.45	710.22	745.36	489.03	1075.0	812.27	895.12	735.14	213.92
16	**2,3,1,1**	621.08	433.40	897.07	705.38	729.50	508.99	1038.0	808.34	825.72	729.72	189.53
17	**2,3,2,2**	678.08	471.17	915.24	759.26	796.86	556.11	1071.0	855.67	900.96	778.26	187.05
18	**2,3,3,3**	694.48	477.87	929.37	762.57	823.48	571.71	1094.0	867.70	929.70	794.54	191.47
19	**3,1,1,3**	688.99	478.36	897.54	751.19	816.11	573.98	1050.0	849.86	913.98	780.00	177.97
20	**3,1,2,1**	443.89	260.37	717.80	574.77	560.61	344.80	884.53	687.23	743.14	579.68	201.94

(continued)

MVF($L_{27}(3^{4-1}, 2^3+1)$)

		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	←Industry demand	
		Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	←ADI orders	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	←Competitiveness	
			000	**001**	**010**	**011**	**100**	**101**	**110**	**111**		
	Experiments	**Current**	. . .	**Worst regime**	. . .	. . .	. . .	. . .	**Best regime**		$\bar{y}_\alpha$	σ_α
21	**3,1,3,2**	510.88	300.44	749.12	610.39	637.83	395.79	940.07	719.89	800.91	629.48	201.78
22	**3,2,1,1**	602.32	408.10	853.20	677.77	718.13	491.15	1007.0	782.77	813.37	705.98	185.84
23	**3,2,2,2**	658.63	444.21	867.06	725.82	785.82	538.24	1040.0	814.41	884.59	750.98	183.24
24	**3,2,3,3**	673.13	448.81	876.65	723.55	805.71	552.04	1062.0	822.16	907.74	763.53	187.56
25	**3,3,1,2**	673.45	482.02	902.62	759.45	777.54	560.79	1022.0	857.52	879.55	768.33	172.09
26	**3,3,2,3**	691.99	490.98	912.62	762.62	805.57	578.12	1043.0	869.05	908.28	784.69	174.62
27	**3,3,3,1**	542.38	358.57	838.61	661.04	660.72	442.62	1004.0	766.48	818.04	676.94	204.91
∑expmt output		23,707	16,939	11,317	23,838	19,341	20,277	13,736	28,182	22,183		

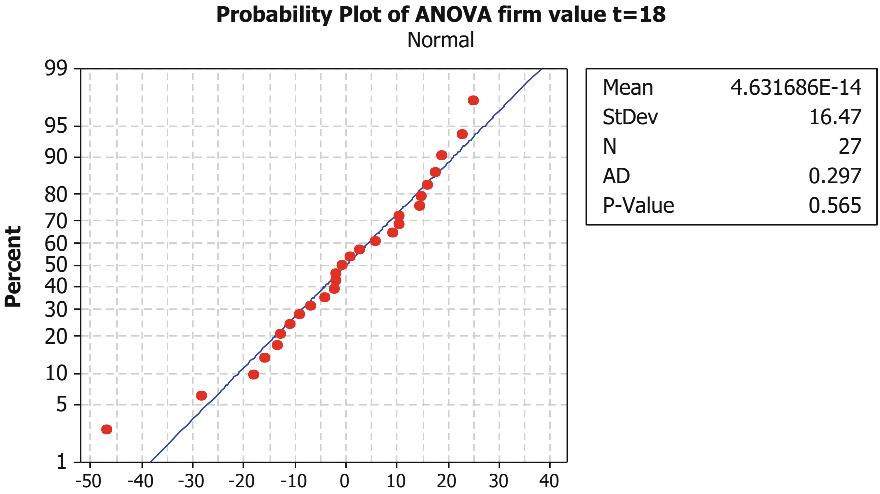
Appendix 5.5 MVF($L_{27}(3^{4-1},2^3+1)$) Controllable Variables Statistics

Appendix 5.5.1 Controllable Variables ANOVA and Residuals at t = 18

Analysis of Variance for firm value

Source	DF	Seq SS	Adj SS	Adj MS	F	P
r&d	2	4557	4557	2279	5.17	0.019
yield	2	28,165	28,165	14,082	31.95	0.000
cogs	2	29,211	29,211	14,605	33.14	0.000
price	2	92,834	92,834	46,417	105.32	0.000
yield**cogs*	2	1743	1743	871	1.98	0.171
Error	16	7051	7051	441		
Total	26	163,561				

S = 20.9931, R-Sq = 95.69%, R-Sq(adj) = 92.99%

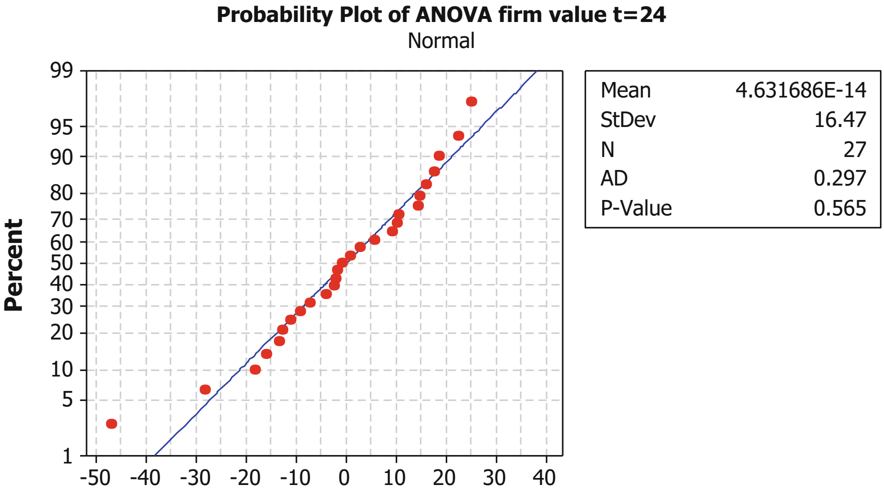


Appendix 5.5.2 Controllable Variables ANOVA and Residuals at $t = 24$

Analysis of Variance for firm value MVF(L_{27}) t = 24

Source	DF	Seq SS	Adj SS	Adj MS	F	P
r&d	2	9199	9199	4599	3.26	0.065
yield	2	20,765	20,765	10,383	7.37	0.005
cogs	2	22,106	22,106	11,053	7.85	0.004
price	2	82,669	82,669	41,335	29.34	0.000
yield**cogs*	2	4803	4803	2402	1.70	0.213
Error	16	22,542	22,542	1409		
Total	26	162,085				

S = 37.5350, R-Sq = 86.09%, R-Sq(adj) = 77.40%



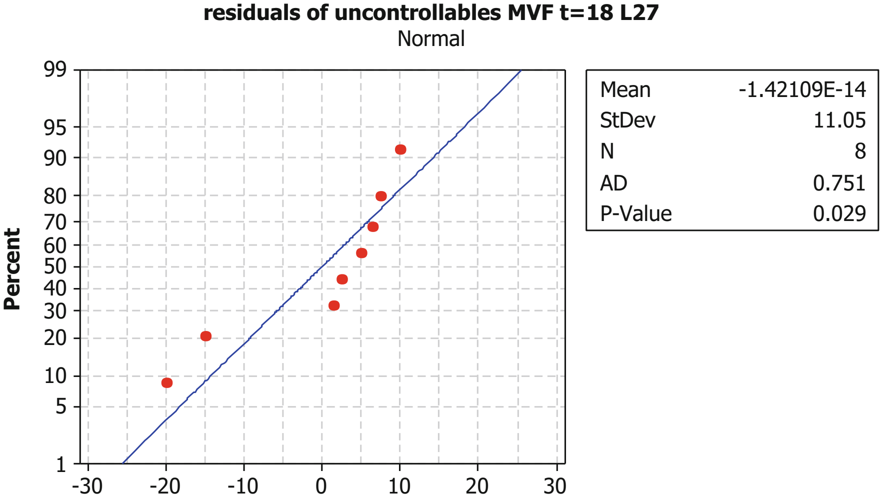
Appendix 5.6 MVF($L_{27}(3^{4-1},2^3+1)$) Uncontrollable Variables Statistics

Appendix 5.6.1 Uncontrollable Variables: Table and Residuals Graph at t = 18

Analysis of Variance for MVF(L_{27}) t = 18

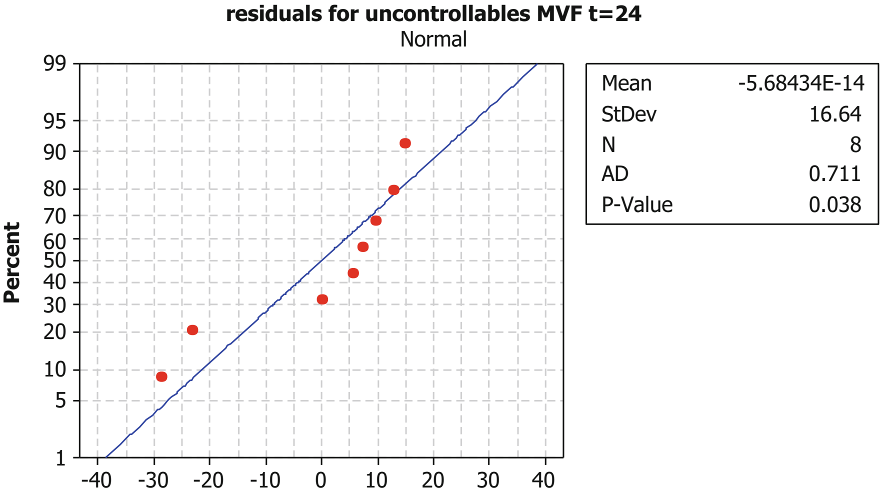
Source	DF	Seq SS	Adj SS	Adj MS	F	P
LT growth	1	12,831	12,831	12,831	60.02	0.001
ADI orders	1	171,516	171,516	171,516	802.31	0.000
Competitor	1	63,468	63,468	63,468	296.89	0.000
Error	4	855	855	214		
Total	7	248,670				

S = 14.6211, R-Sq = 99.66%, R-Sq(adj) = 99.40%



Appendix 5.6.2 Uncontrollable Variables: Table and Residuals Graph at t = 24

Analysis of Variance for MVF(L_{27}) t = 24						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
LT growth	1	29,440	29,440	29,440	60.77	0.001
ADI orders	1	168,536	168,536	168,536	347.87	0.000
Competitor	1	89,094	89,094	89,094	183.89	0.000
Error	4	1938	1938	484		
Total	7	289,008				
S = 22.0111, R-Sq = 99.33%, R-Sq(adj) = 98.83%						



Appendix 5.7 MVF(L_{27}(3^{4-1},2^3+1)) Experiment Responses: Means and Standard Deviations

Appendix 5.7.1 Response Tables MVF(L_{27}(3^{4-1},2^3+1)) at t = 18

Response Table for Means

Level	r&d	yield	*cogs*	price
1	863.0	805.1	884.1	767.9
2	843.0	848.4	849.7	860.2
3	831.5	884.1	803.8	909.4
Delta	31.5	79.0	80.3	141.5
Rank	4	3	2	1

Response Table for Standard Deviations

Level	r&d	yield	*cogs*	price
1	185.6	181.2	178.7	179.5
2	180.3	181.2	181.0	179.9
3	174.9	178.4	181.1	181.4
Delta	10.7	2.8	2.4	1.9
Rank	1	2	3	4

Appendix 5.7.2 Response Tables MVF(L_{27}(3^{4-1},2^3+1)) at t = 24

Response Table for Means

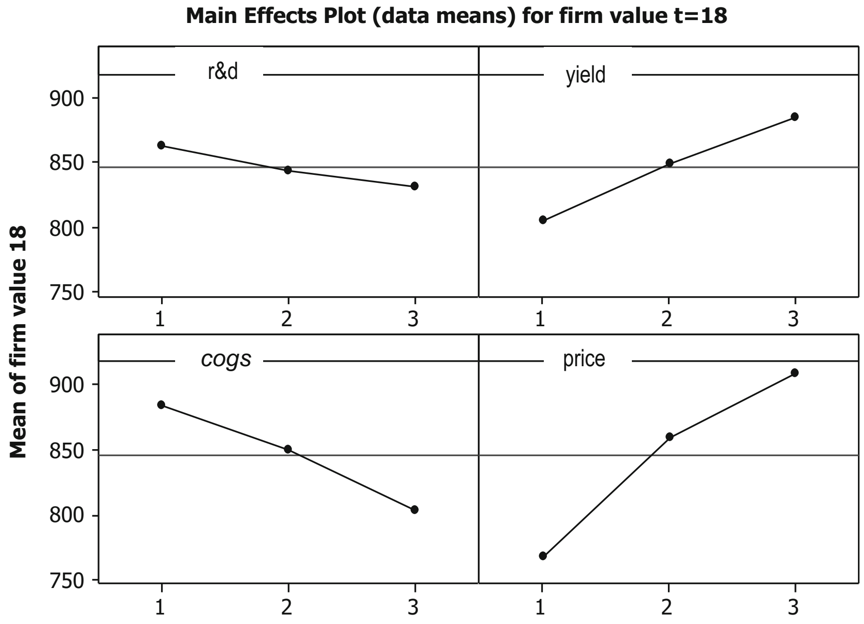
Level	r&d	yield	*cogs*	price
1	759.8	698.3	765.6	659.8
2	729.8	741.4	742.7	754.0
3	715.5	765.4	696.8	791.3
Delta	44.3	67.0	68.8	131.5
Rank	4	3	2	1

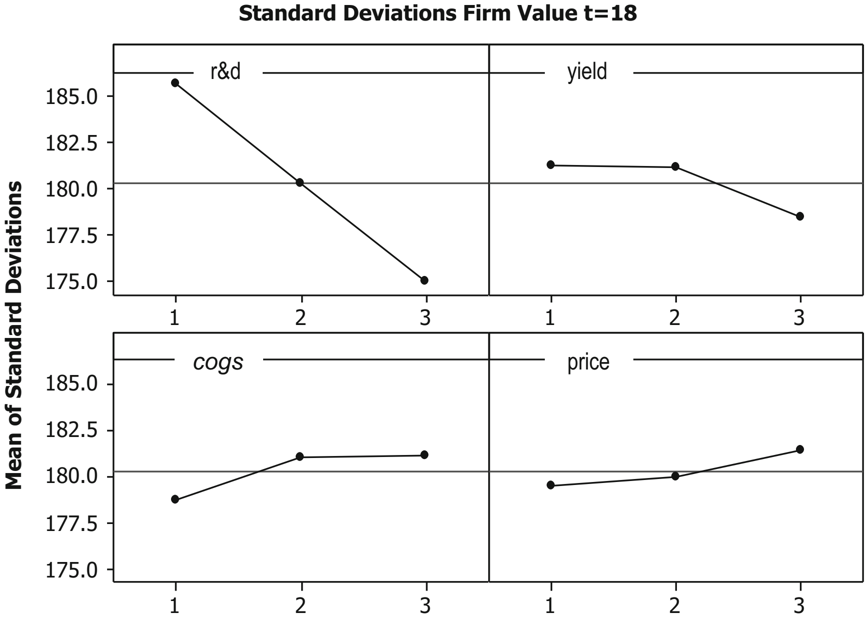
Response Table for Standard Deviations

Level	r&d	yield	*cogs*	price
1	208.9	204.6	189.1	205.2
2	196.6	198.3	198.4	196.6
3	187.8	190.3	205.7	191.4
Delta	21.1	14.3	16.5	13.8
Rank	1	3	2	4

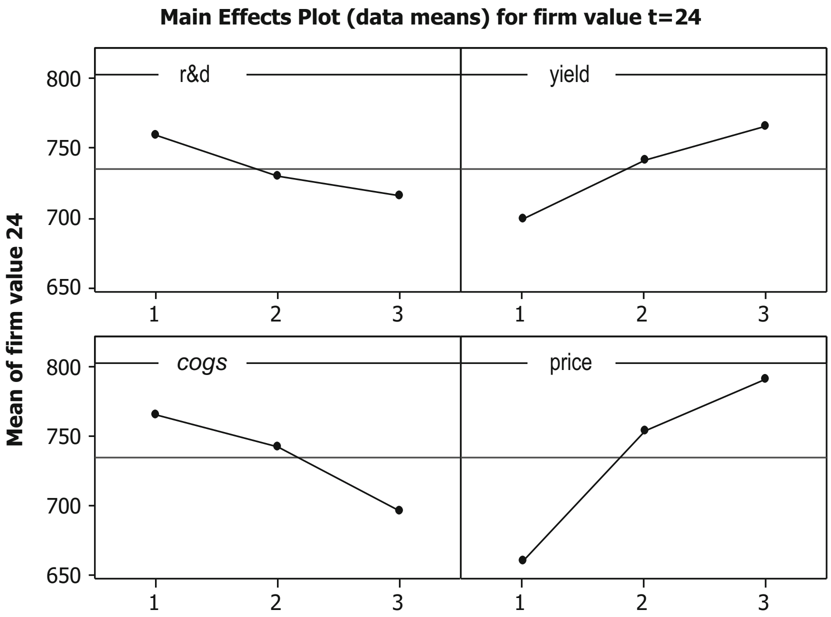
Appendix 5.8 MVF($L_{27}(3^{4-1},2^3+1)$) Plots: Means and Std. Dev.

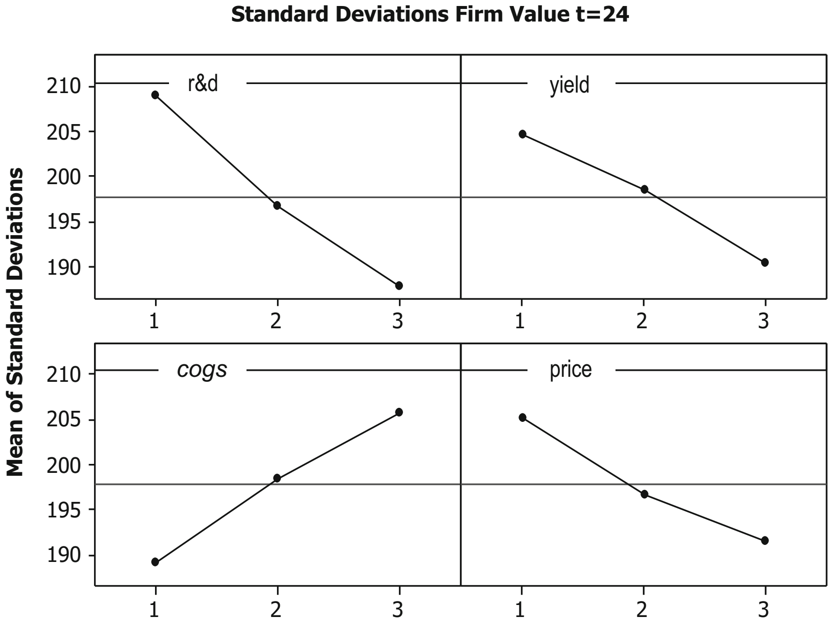
Appendix 5.8.1 Plots: Means and Standard Deviations at t = 18





Appendix 5.8.2 Plots: Means and Standard Deviations at $t = 24$


Main Effects Plot (data means) for firm value t=24


Standard Deviations Firm Value t=24

Appendix 5.9 MVF($L_9(3^{4-1},2^3+1)$) Experiment Data Under Uncertainty Regimes

Appendix 5.9.1 MVF($L_9(3^{4-1},2^3+1)$) at $t = 12$

MVF($L_9(3^{4-2}, 2^3+1)$)															
					Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	←Industry demand	
					Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	←ADI orders	
					Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	←Competitiveness	
						000	**001**	**010**	**011**	**100**	**101**	**110**	**111**		
	Experiments				**Current**		**Worst case**					**Best case**		$\bar{y}_\alpha$	σ_α
1	**1**	**1**	**1**	**1**	746.49	644.34	553.04	*813.11*	737.66	669.18	572.92	852.09	763.45	705.81	103.1
2	**1**	**2**	**2**	**2**	815.49	709.66	607.34	*869.19*	806.45	736.70	628.88	912.48	824.30	767.83	104.6
3	**1**	**3**	**3**	**3**	851.62	743.19	641.91	912.48	844.20	772.42	664.34	954.06	865.59	805.53	107.5
4	**2**	**1**	**2**	**3**	825.21	717.55	613.14	881.48	810.10	747.30	636.66	927.38	830.55	776.60	106.5
5	**2**	**2**	**3**	**1**	696.82	591.15	511.51	749.97	693.18	616.06	530.26	748.26	716.60	650.42	91.02
6	**2**	**3**	**1**	**2**	851.44	751.90	653.53	920.13	852.57	779.16	673.42	952.71	875.27	812.24	104.7
7	**3**	**1**	**3**	**2**	732.60	622.97	532.88	769.66	712.25	648.62	554.00	813.33	735.52	680.20	96.48
8	**3**	**2**	**1**	**3**	869.54	768.69	670.11	*940.40*	866.62	799.27	691.85	969.85	892.29	829.85	104.8
9	**3**	**3**	**2**	**1**	752.91	653.49	566.91	*823.96*	747.99	676.43	585.40	862.55	772.69	715.81	102.4
10*	**1**	**2**	**2**	**2**	815.49	709.7	607.34	869.19	806.5	736.70	628.88	912.48	824.30	761.9	
11*	**1**	**3**	**3**	**3**	851.62	743.2	641.91	912.48	844.2	772.42	664.34	954.06	865.59	747.3	

rows 10 and 11* only used for $L'_9(3^{4-2}+2, 3^2+1)$, one time use array to obtain F and p values for controllable variables

Appendix 5.9.2 MVF($L_9(3^{4-1},2^3+1)$) at $t = 18$

MVF($L_9(3^{4-2}, 2^3+1)$)															
					Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	←Industry demand	
					Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	←ADI orders	
					Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	←Competitiveness	
						000	**001**	**010**	**011**	**100**	**101**	**110**	**111**		
	Experiments				**Current**		**Worst case**					**Best case**		$\bar{y}_{\alpha}$	σ_{α}
1	**1**	**1**	**1**	**1**	908.42	687.57	513.01	980.32	813.37	768.62	571.13	1091.0	895.46	803.21	189.5
2	**1**	**2**	**2**	**2**	986.66	783.70	585.70	1041.0	895.56	866.05	649.22	1165.0	964.13	881.89	185.4
3	**1**	**3**	**3**	**3**	1022.0	817.00	618.76	1086.0	930.59	898.14	684.86	1209.0	1006.0	919.15	189.1
4	**2**	**1**	**2**	**3**	989.80	787.80	588.07	1044.0	885.83	871.53	657.62	1176.0	959.71	884.48	185.8
5	**2**	**2**	**3**	**1**	822.22	590.94	438.87	863.62	738.72	670.06	494.89	969.75	813.65	711.41	177.1
6	**2**	**3**	**1**	**2**	990.78	812.55	634.12	1079.0	930.95	879.31	689.20	1169.0	1002.0	909.66	175.5
7	**3**	**1**	**3**	**2**	862.02	642.88	471.56	886.46	759.12	725.46	534.04	1010.0	830.76	746.92	173.8
8	**3**	**2**	**1**	**3**	1007.0	828.48	649.38	1088.0	936.78	899.75	709.82	1175.0	1014.0	923.13	171.8
9	**3**	**3**	**2**	**1**	882.12	695.90	530.66	969.05	805.30	765.29	585.18	1080.0	882.11	799.51	177.2
10*	**2**	**2**	**2**	**2**	966.9	769.7	579.25	1023.0	878.70	848.72	641.59	1147.0	944.94	866.64	966.9
11*	**1**	**1**	**3**	**3**	982.7	761.7	550.33	1026.0	859.09	848.16	623.34	1163.0	941.38	861.74	982.7

rows 10 and 11* only used for $L'_9(3^{4-2}+2, 3^2+1)$, one time use array to obtain F and p values for controllable variables

Appendix 5.9.3 MVF($L_9(3^{4-1},2^3+1)$) at $t = 24$

MVF($L_9(3^{4-2}, 2^3+1)$)

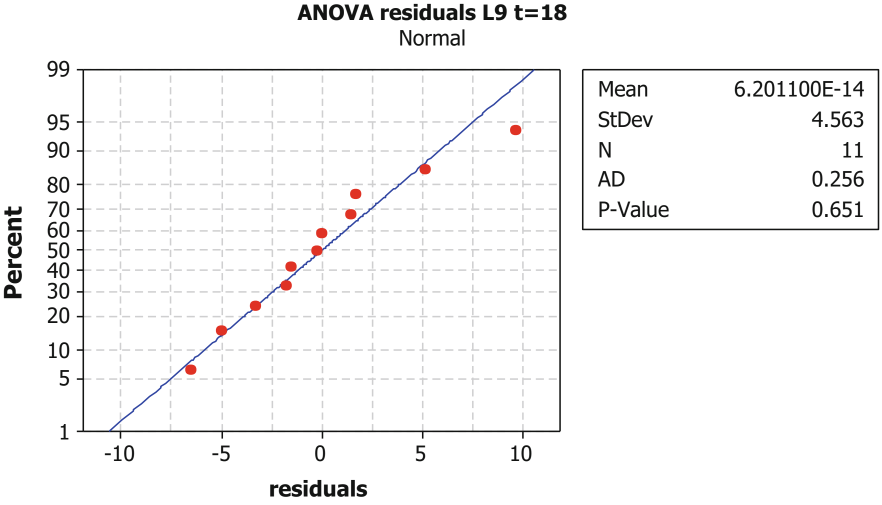
					Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	←Industry demand	
					Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	←ADI orders	
					Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	←Competitiveness	
						000	**001**	**010**	**011**	**100**	**101**	**110**	**111**		
	Experiments				**Current**		**Worst case**					**Best case**		$\bar{y}_\alpha$	σ_α
1	**1**	**1**	**1**	**1**	873.24	572.20	363.26	894.02	697.36	702.91	451.41	1057.0	816.07	714.16	223.1
2	**1**	**2**	**2**	**2**	934.47	686.73	455.84	931.25	758.68	825.19	552.57	1110.0	862.86	790.84	202.9
3	**1**	**3**	**3**	**3**	959.24	706.47	476.99	957.43	774.79	848.24	575.80	1136.0	885.63	813.40	204.7
4	**2**	**1**	**2**	**3**	931.49	688.98	458.64	909.38	741.10	827.64	563.33	1100.0	845.34	785.10	196.3
5	**2**	**2**	**3**	**1**	766.76	447.84	263.59	743.87	596.05	570.15	348.59	913.51	707.31	595.30	211.7
6	**2**	**3**	**1**	**2**	897.58	681.39	481.94	922.29	767.65	792.67	563.73	1059.0	866.77	781.45	182.0
7	**3**	**1**	**3**	**2**	800.91	510.88	300.44	749.12	610.39	637.83	395.79	940.07	719.89	629.48	201.8
8	**3**	**2**	**1**	**3**	910.09	693.64	492.79	911.28	763.62	808.88	581.77	1042.0	868.39	785.83	173.4
9	**3**	**3**	**2**	**1**	815.25	588.04	392.65	848.31	672.09	702.85	477.44	1009.0	778.63	698.25	191.8
10*	**2**	**2**	**2**	**2**	905.81	670.53	449.23	898.96	740.04	802.32	544.38	1078.0	835.48	769.42	
11*	**1**	**1**	**3**	**3**	951.81	659.75	404.78	932.30	731.42	802.25	517.56	1135.0	854.18	776.56	

rows 10 and 11* only used for $L'_9(3^{4-2}+2, 3^2+1)$, one time use array to obtain F and p values for controllable variables

Appendix 5.10 MVF($L_9(3^4,2^3+1)$) Controllable Variables Statistics

Appendix 5.10.1 Controllable Variables ANOVA Table and Residuals at t = 18

Source	DF	Seq SS	Adj SS	Adj MS	F	P
r&d	2	3276.7	3775.4	1887.7	18.13	0.052
yield	2	5835.3	6479.2	3239.6	31.12	0.031
cogs	2	9537.0	13,094.5	6547.2	62.89	0.016
price	2	31,861.2	31,861.2	15,930.6	153.02	0.006
Error	2	208.2	208.2	104.1		
Total	10	50,718.4				
S = 10.2033, R-Sq = 99.59%, R-Sq(adj) = 97.95%						

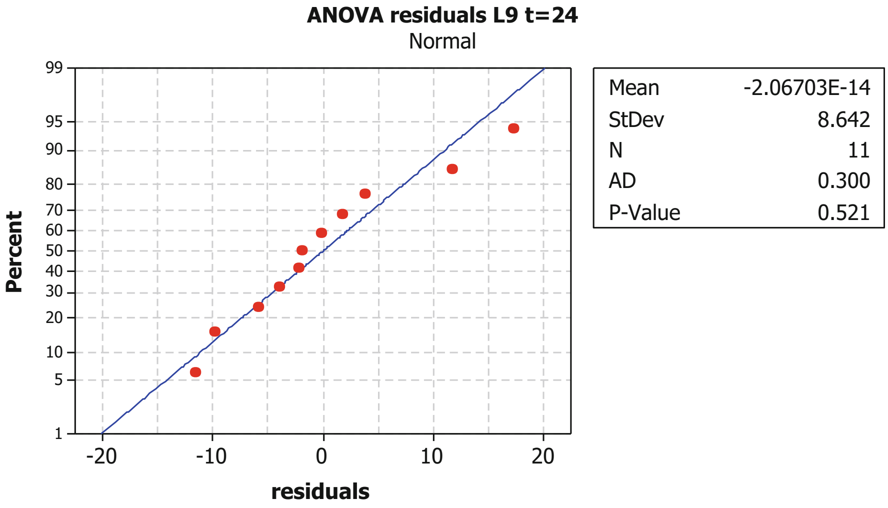


Appendix 5.10.2 Controllable Variables ANOVA Table and Residuals at t = 24

Analysis of Variance for firm value 24

Source	DF	Seq SS	Adj SS	Adj MS	F	P
r&d	2	8536.5	9182.5	4591.2	12.29	0.075
yield	2	3895.9	4370.6	2185.3	5.85	0.146
cogs	2	10,892.8	14,255.3	7127.6	19.09	0.050
price	2	27,518.3	27,518.3	13,759.1	36.84	0.026
Error	2	746.9	746.9	373.5		
Total	10	51,590.4				

S = 19.3251, R-Sq = 98.55%, R-Sq(adj) = 92.76%



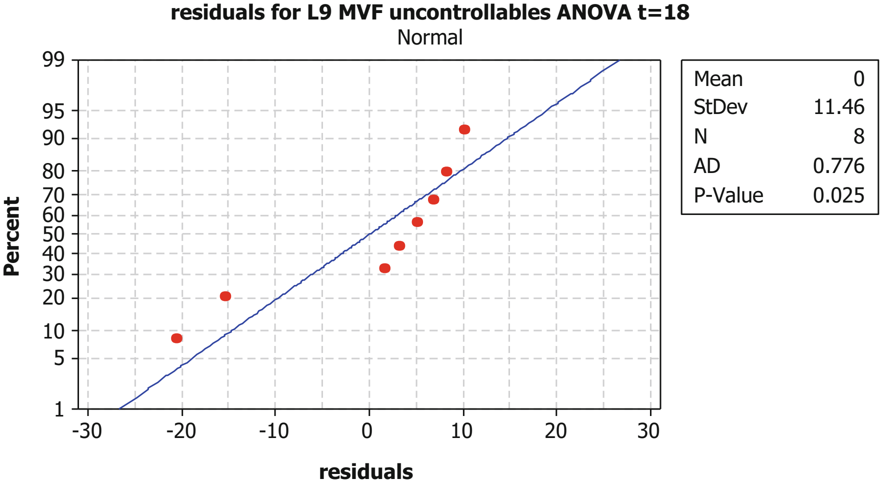
Appendix 5.11 ANOVA $L_9(3^{4-2},2^3+1)$ Uncontrollable Variables Statistics

Appendix 5.11.1 Uncontrollable Variables ANOVA and Residuals at t = 18

Analysis of Variance for MVF t = 18, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
LT growth	1	13,177	13,177	13,177	57.34	0.002
ADI orders	1	171,735	171,735	171,735	747.27	0.000
Competitor	1	63,271	63,271	63,271	275.31	0.000
Error	4	919	919	230		
Total	7	249,102				

S = 15.1597, R-Sq = 99.63%, R-Sq(adj) = 99.35%

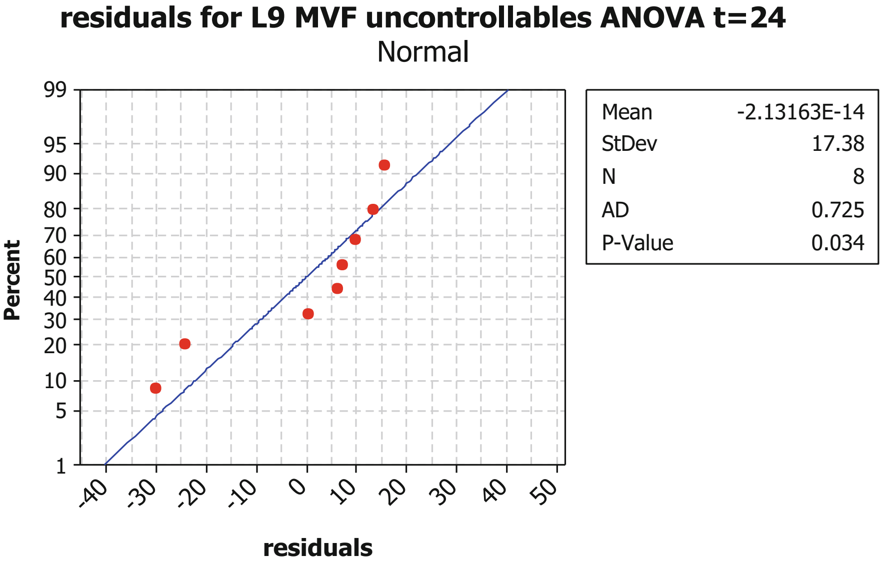


Appendix 5.11.2 Uncontrollable Variables ANOVA and Residuals at t = 24

Analysis of Variance for MVF

Source	DF	Seq SS	Adj SS	Adj MS	F	P
LT growth	1	30,330	30,330	30,330	57.35	0.002
ADI orders	1	169,396	169,396	169,396	320.31	0.000
Competitor	1	89,062	89,062	89,062	168.41	0.000
Error	4	2115	2115	529		
Total	7	290,904				

S = 22.9966, R-Sq = 99.27%, R-Sq(adj) = 98.73%



Appendix 5.12 MVF($L_9(3^{4-1},2^3+1)$) Response Means and Standard Deviations

Appendix 5.12.1 Tables: Means and Standard Deviations at $t = 18$

Response Table for Means				
Level	r&d	yield	*cogs*	price
1	868.1	811.5	878.7	771.4
2	835.2	838.8	855.3	846.2
3	823.2	876.1	792.5	908.9
Delta	44.9	64.6	86.2	137.5
Rank	4	3	2	1

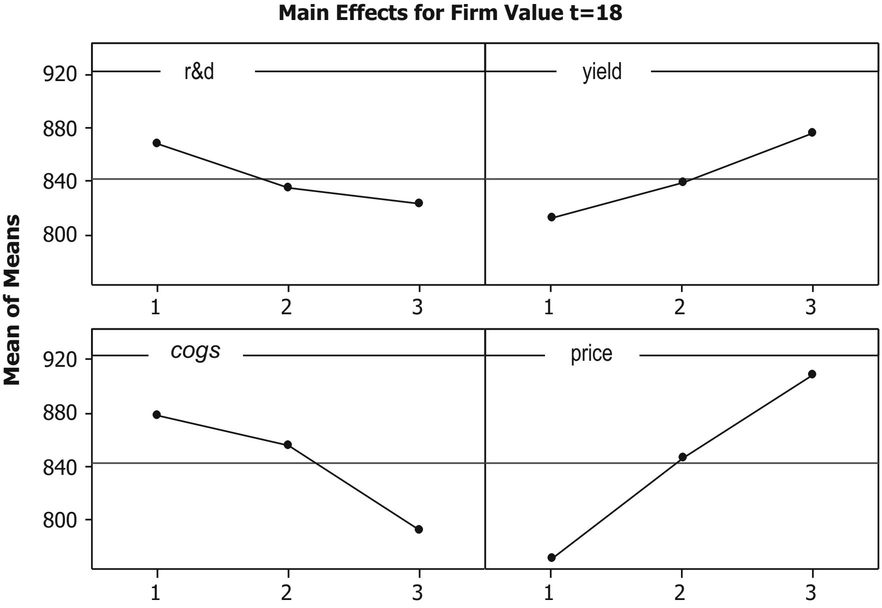
Response Table for Standard Deviations				
Level	r&d	yield	*cogs*	price
1	187.9	182.9	178.8	181.2
2	179.4	178.1	182.8	178.2
3	174.2	180.6	180.0	182.2
Delta	13.7	4.8	4.0	4.0
Rank	1	2	4	3

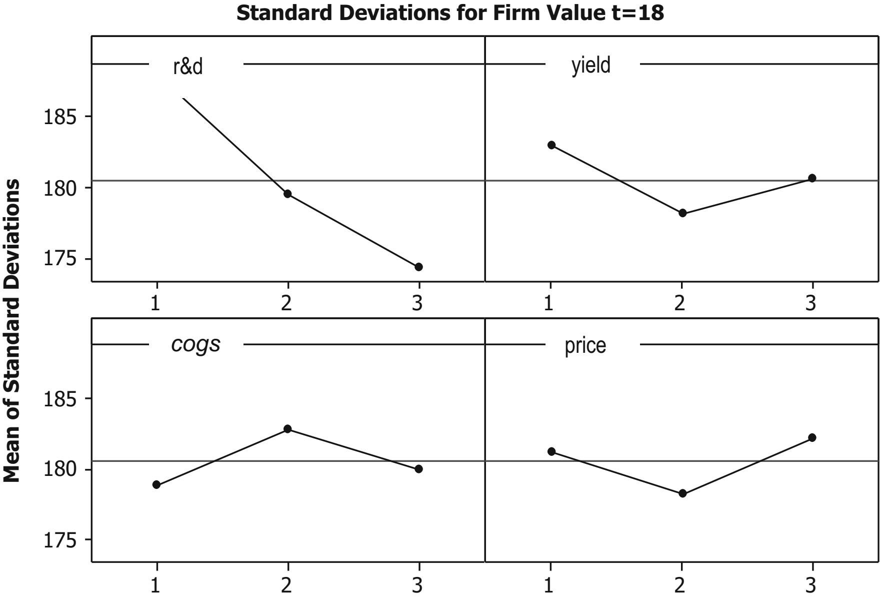
Appendix 5.12.2 Tables: Means and Standard Deviations at $t = 24$

Response Table for Means				
Level	r&d	yield	*cogs*	price
1	772.8	709.6	760.5	669.2
2	720.6	724.0	758.1	733.9
3	704.5	764.4	679.4	794.8
Delta	68.3	54.8	81.1	125.5
Rank	3	4	2	1

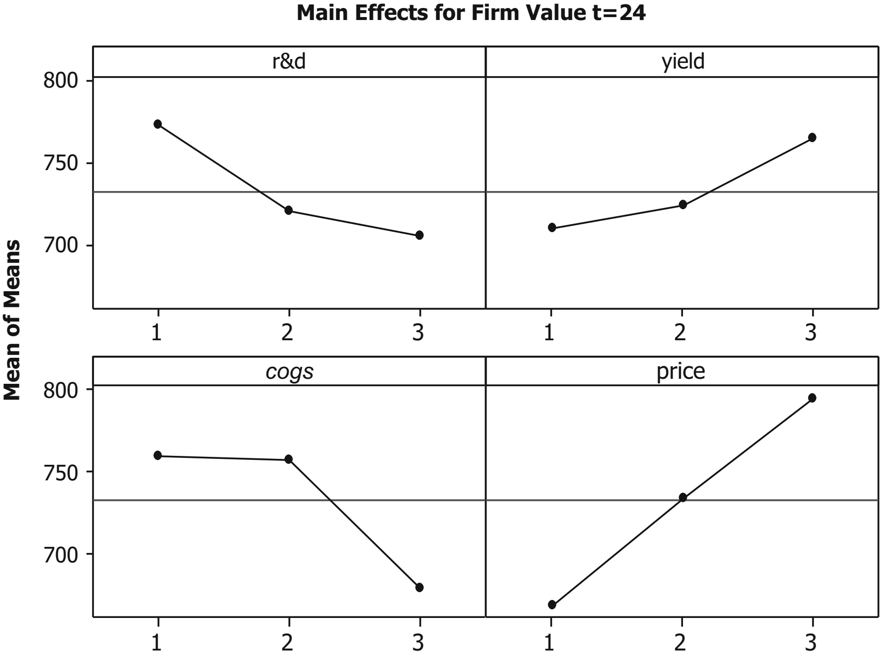
Response Table for Standard Deviations				
Level	r&d	yield	*cogs*	price
1	210.2	207.1	192.9	208.9
2	196.7	196.0	197.0	195.6
3	189.0	192.8	206.0	191.5
Delta	21.2	14.3	13.2	17.4
Rank	1	3	4	2

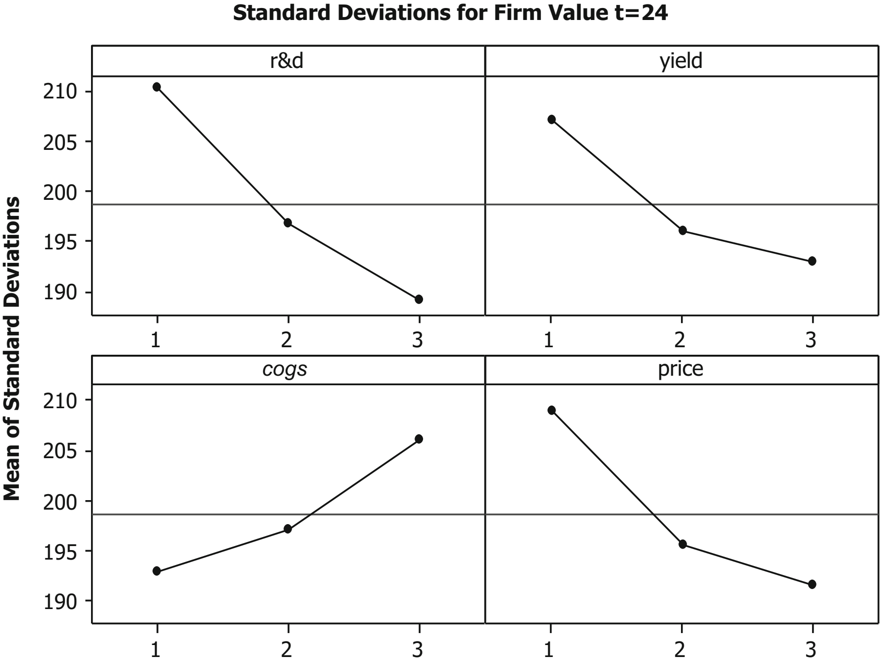
Appendix 5.12.3 Graphs: Means and Standard Deviations at t = 18





Appendix 5.12.4 Graphs: Means and Standard Deviations at t = 24





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Chapter 6
Verifying Functionality: Maximizing Annual Operating Income (AOI)

Abstract This chapter is another verification simulation using the same ADI surrogate except for a different executive decision—to maximize annual operating income (AOI). This a decision to deal with internal operations. The goal is to demonstrate to the industry and its employees that the executive managers of the firm and competent and are able to run ADI. Best effort has been made to attach the data for the simulations as appendices and all the calculations are shown and illustrated.

6.1 Introduction

In this chapter, using the ADI surrogate, we demonstrate that our methodology works for the objective of Maximizing Annual Operating Income (AOI). In Chap. 4, we argued that our methodology ***works***, if and only if, it simultaneously satisfies two necessary and sufficient conditions, *viz.* it is ready-**to**-work for users ***and*** ready-**for**-work by a user for a specific class of decision situations. Ready-to-work needs to be demonstrated by us as creators of the methodology. We have to demonstrate its *functionality*, Fig. 6.1.

We have to show that the methodology ***works*** as intended by us, as engineers of the executive-decision methodology. Separately, users need to independently satisfy themselves the methodology *works* for them. Namely, that the methodology is ready-for-work. Users require evidence of the *efficacy* of the methodology. This requirement is natural given the complex sociotechnical nature of executive decisions and the scope of their potential impact. The methodology must work for them, i.e. users must convince themselves it is ready-**for**-work.

We will use the ADI surrogate as a test object to find evidence that our methodology is *ready-**to**-work* by demonstrating that it will satisfy the X-RL conditions (Table 6.1). In this simulation, we play the role of a DMU. As a DMU, we will apply and evaluate our systematic decision life-cycle process.

In Chap. 4, we discussed why we need a company surrogate, how to select one, and the reasons the ADI system dynamics model will play this role. Using the ADI surrogate as test object, we will verify the readiness of our methodology for the design of a specific executive-decision specifications (Fig. 6.2). We will demonstrate that our methodology will meet the X-RL specifications for *functionality*.

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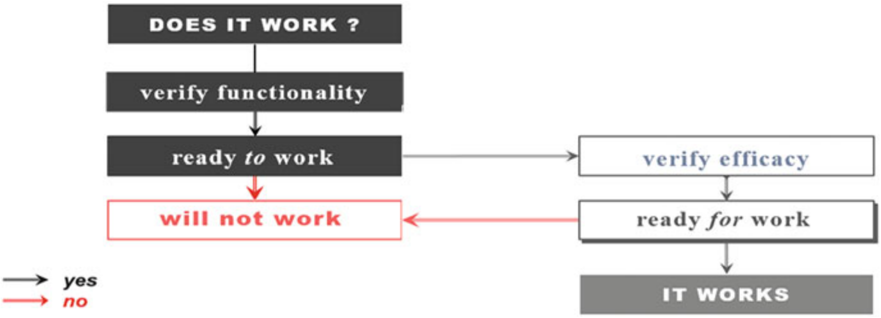

Fig. 6.1 Functionality is a necessary condition to demonstrate methodology *works*

Table 6.1 Readiness level specifications for executive decisions

Readiness level	Our systematic process		Strategy
X-RL1	Characterize	Problem space	Sense making
X-RL2	Engineer	Solution space	Engineer experiments/alternatives
X-RL3	Explore	Operations space	Explore entire solution and uncertainty spaces
X-RL4	Evaluate	Performance space	Measure robustness, repeatability, reproducibility
X-RL5	Enact	Commitment space	Commit plan with approved resources

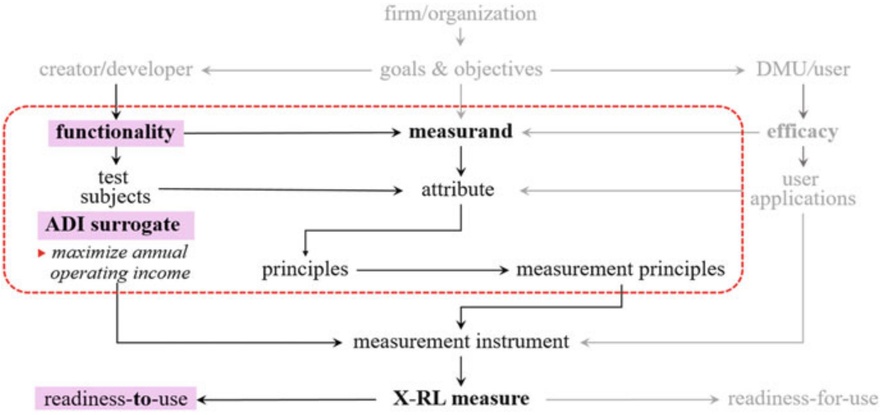

Fig. 6.2 Functionality is a necessary condition to demonstrate methodology *works*

Using the ADI surrogate to simulate the ADI system behavior, we test our methodology to meet the corporate objective of *maximizing Annual Operating Income* (AOI), at every phase of the decision life-cycle.

This chapter has eight sections. In addition to an introduction, a discussion, and summary, we devote a chapter-section to each of the five phases of the executive decision life-cycle—the Problem, Solution, Operations, Performance, and Commitment Spaces (Table 6.1). The objective is to systematically determine the extent of X-RL readiness at each phase of our methodology. The overall findings are discussed in the Chapter Summary.

Section 6.2 covers Characterizing the Problem Space. We characterize the decision situation adhering to our principles of abstraction and uncomplicatedness to develop a mental model for an executive decision. We verify the f*unctionality* of our methodology for this crucial step. Given the non-trivial nature of the decision situation and the systematic processes to verify our characterization; this section is lengthy, but necessary. We introduce a notation, a short hand intended to avoid long and unwieldly descriptive sentences. We will demystify the notation so that it is clear at a glance.

In Sect. 6.3, Engineering the Solution Space, we identify the essential variables, the problem solving constructs used for the solution space and the representations for the whole spectrum of uncertainty conditions. We discretize the uncertainty space into a discrete and spanning set of *uncertainty-regimes*. This is a fundamental process because it makes the entire uncertainty space tractable. Sections 6.2, and 6.3 establish the base-line for the work in subsequent sections.

In Sect. 6.4, Exploring the Operations Space, we use an array of experiments under our set of uncertainty regimes that span the entire uncertainty space. We use three representations, of different resolutions and fidelity, for our analyses of the Solution Space. We show a procedure for constructing and exploring any hypothetical decision alternative with the ability to determine a risk profile represented by standard deviations. In this way, we collect data for the evaluations needed in the Performance Space.

Section 6.5, We use different representations to determine the additional utility of more complex models. The Analysis of the Performance Space is highly abbreviated because we do not have a DMU quorum. Though we are playing the role of a DMU, we do not have a quorum to evaluate two of the 3R's. We address Robustness, but defer Repeatability and Reproducibility to Part III where we report on customer engagements. Section 6.6, on the Commitment Space, is similarly abbreviated for the same reasons. Section 6.7 closes this chapter with a summary of the key learning from the simulations studies.

6.2 Characterizing the Problem Space

Our goal is to make each description of our surrogate experiments self-contained; therefore, some repetition from previous chapters is unavoidable. We will keep repetition to a minimum.

> In the systems that occur in nature, or are designed by man, not all components interact strongly with other components. Most such systems are, in fact, nearly completely, decomposable. (H. A. Simon[1])

6.2.1 Sense-Making and Framing

In 1987, ADI launched a TQM initiative and concentrated its efforts on the firm's technically-intensive functions. The results were dramatic improvements in product quality and manufacturing. Yield doubled, cycle time was cut by half, product defects fell by a factor of ten, and on-time delivery improved from 70 to 90%. People worked very hard to achieve these impressive results. However, operating profit and stock price continued to plunge. Specifically, operating profit fell from $46 M to $6.2 M. The stock market had lost confidence in ADI. Price per share dropped from $24 to $6 during the period of 1987–1990. And, unprecedented in ADI's history, people were laid off and manufacturing jobs were transferred overseas, long before it became fashionable. Management had lost credibility with the ADI workforce. The firm's financial crisis threatened Ray Stata, founder and CEO of the firm, with a hostile takeover from raiders in Wall Street. An ADI senior manager observed "... with its [low] market value, ADI could have been acquired for about 3 years' cash flow from operations." Ray Stata is reported to have remarked "... there was something about the way we were managing the company that was not good enough (Sterman et al. 1997)".

6.2.2 Goals and Objectives

No entrepreneur wants to lose control of their business or not make money. For Stata, it is critical to demonstrate his ability to turn around ADI. He urgently needs to improve the performance of its key business functions and restore confidence and morale of its workforce. Whatever strategy Stata may choose, financial resources will be required. Therefore, a steady source of funds is a critical requirement. Ray Stata's decision situation is thus framed as in Table 6.2.

The goal is to mount a defense against the threat of ADI being taken over by outsiders. The objective in this chapter is to maximize Annual Operating Income (AOI). High AOI serves to increase the stockholders' confidence in the current management. So that if it comes to a proxy fight, stockholders will be more favorably inclined to retain them. The second equally objective is to restore trust and confidence in ADI's management by improving operating profit. Operating profit reflects management's ability to control cost and expense. Cost is an indicator of engineering and manufacturing effectiveness; and expense is an indicator of

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[1] Simon (1997, 107).

Table 6.2 ADI's decision situation

Problem	• Threat of hostile takeover • Loss of confidence in ADI management
Goal and opportunity	• Turn around the company • Retain control of the firm
Objectives	• Maximize market value of the firm, MVF • Maximize annual operating profit, AOI

operational efficiency and effectiveness of the other functions of the firm (e.g. Brealey and Myers 2006). Operating profit **puts these two measures together**. As such it is a good proxy that reflects the quality of the firm's management. This chapter concentrates on objective 2 of Table 6.2.

6.2.3 The Essential Variables

Essential variables are the key controllable and uncontrollable variables that satisfice to represent the ADI sociotechnical system for analyses. They are consistent and meaningful given the scale and level of abstraction of the problem (Chap. 3, Sect. 3.3.2).

6.2.3.1 Controllable and Uncontrollable Variables

For the controllable variables, we concentrate on the key business functions, which are fundamental and typical in high technology companies. They are r&d, manufacturing, engineering, and finance. We assume that a senior functional-executive is in charge of each function. This is reasonable given the specialized disciplinary knowledge and the operational experience required to manage each of these technically intensive domains. To each of them, we can pose the questions about ways to maximize the Annual Operating Income (AOI). Specifically:

- What are key variables you can control?
- What is the range of controllability for those variables?
- What are the key secular variables that you cannot control?, and
- Can you describe their plausible scope and behavioral range?

We begin with the managerially controllable variables. Consistent with the scale and level of abstraction, in which we are considering our problem, we identify the following controllable variables. For r&d, the key controllable variable is the *r&d budget*; for manufacturing it is *manufacturing yield*; for engineering it is the cost of goods sold *(cogs)*, and for finance it is *product price*. Table 4.3 in Chap. 4, shows that these variables have a very good statistical fit in the ADI surrogate model.

$R^2_{r\&d} = 0.91$ for *r&d*, $R^2_{yield} = 0.82$ for *manufacturing yield*, $R^2_{defects} = 0.91$ for defects, and for *product price* $R^2_{price} = 0.70$. These data strengthen our belief that these variables are well chosen.

We now turn our attention to the key uncontrollable variables. We concentrate on the most influential variables that management cannot control, either extremely difficult or prohibitively costly to control, and whose behaviors have a direct and strong impact on our chosen objectives. *It is the behavior of these variables that generate the uncertainty conditions under which the controllable variables will operate*. These variables collectively characterize the key external uncertainty conditions facing ADI in its efforts to maximize annual operating income (AOI). In the documentation of the problem, Sterman et al. (1997) point us to three major uncontrollable variables.

- First is the *long term growth of industry-demand*, which can "raise or lower all boats" in the industry. In a free market, unless one has a monopoly or a dominant industry position, industry-wide demand is not something that is controllable. ADI's revenues and profit alone indicate ADI does not fit the profile of a monopoly or dominant player in the market.
- The second uncontrollable variable is the *rate of ADI orders*. By virtue of its product line and position in the supply chain, ADI has very limited influence on the rate or volume of customer orders. ADI is not a consumer product company. Its market is an *industrial market* (e.g. Anderson and Narus 1999). ADI is an original equipment manufacturer (OEM), a commodities supplier of electronic components that are delivered as parts to many other product manufacturers. Demand for ADI's components is derived from the sales of the final products of those manufacturers, such as computers, components for consumer products, medical equipment and the like. ADI's ability to control industry demand for final products is infinitesimally small.
- Finally, the third uncontrollable variable is the *attractiveness of competitors' products*. As a relatively small player among many in a free market, ADI has no control over competitors' products functionality, performance, price, quality, fulfillment or services capabilities. ADI cannot control *competitors' product attractiveness*. It is an uncontrollable variable.

6.2.3.2 Levels for Controllable Variables and Uncontrollable Variables

Next we set the levels that bracket the range of controllability for the controllable variables (Table 6.3). In practice, these are set by a DMU through discussions, until a general consensus is reached. Playing the role of a DMU, we specify three levels

Table 6.3 Controllable factors and levels

Controllable factors	Level 1 (%)	Level 2	Level 3 (%)	Characteristic
r&d budget	−10	Current level	+10	More is better
IC yield	−15	Current level	+15	More is better
cogs	−10	Current level	+10	Less is better
Product price	−10	Current level	+10	More is better

to demarcate the ranges of controllability. We set level 3, at which there is an improvement from the current level of operations. In all cases except for *cogs* an increase is expected to improve the output of AOI. For example, we would expect that all things being equal, an increase in the *products' prices* will increase the AOI since it can boost revenues. Whether this is a sustainable approach is influenced by uncontrollable factors, which we will be investigating. Increasing *cogs* will make the product less competitive; it will pressure profit margins and price. Higher *cogs* will not improve the outcome of AOI.

Except for *cogs*, the +xx% represents our assumption for the maximum improvement that can be achieved with a very strong effort. The best level for *cogs* is assumed to be at −10%. Again except for *cogs*, the −xx% represents our assumptions for the maximum declines that are tolerable to management. Note that ±10% is non-trivial. For example, a 10% gain of an investment portfolio is an achievement that cannot be attained automatically. In this chapter, we will test the behavior of ADI under each of these assumptions. *Current level* is the as-is operational level, with **no** changes. This level is also referred to as Business-As-Usual (BAU) throughout this chapter.

Superficially, it may appear that a useful approach is to drive all the controllable variables to their levels that maximize the objective. But this is not feasible because the *r&d Budget* variable serves as a regulating factor. The managerial cross functional interactions, in the DMU, do not make indiscriminate outcome maximization, with profligate resource expenditures, practical or feasible. For example, to lower cost of goods *(cogs)*, one has to invest in manufacturing, this raises r&d expenditures and puts pressure on expenses. These issues will naturally come to the DMU's attention. Compromises will have to be made. The principle of No Free Lunch (Sect. 3.3.2.2) will assert itself during the managerial competition for funds and people.

The levels for the uncontrollable variables are based on the maximum and minimum plausible values of the uncontrollable variables. They are our assumptions about the best and worst case that must be realistic. Domain expertise and competent judgment are required to set these upper and lower bounds. For example, for a pharmaceutical startup, demand for a new product can be extraordinary or it can be negligible. This is reasonable and logical given the high failure rates of new drugs. However, for a mature product in a mature market, these suppositions are not reasonable. For a mature product in a mature industry, incremental and momentum growth is more logical. Unlike the controllable variable levels, which specify the limits of managerial action, the levels for the uncontrollable variables represent **secular** conditions, which are plausible as most favorable or most unfavorable to the firm (Table 6.4).

With three uncertainty, uncontrollable variables, each at three levels, ADI faces $3^3 = 27$ full factorial potential distinct scenarios of uncertainty that are distinct from its current condition.

Table 6.4 Uncontrollable factors and levels

Uncontrollable factors	Level 1	Current state	Level 2	Characteristic
Industry growth rate	Current − 25%	Current	Current + 25%	Fast is better
ADI orders rate	Current − 25%	Current	Current + 25%	High is better
Competitors' attractiveness	Current − 25%	Current	Current + 25%	Lower is better

6.2.4 Notation

To simplify the way we narrate the variables and their levels, we prescribe the following notation. A specific configuration of $\boldsymbol{n}$ factors with $\boldsymbol{k}$ levels, we use *a* $\boldsymbol{n}$-tuple where each entry is an integer representing a level $\leq k$. For a specific configuration of our four controllable factor-levels, we use a 4-tuple. For example, (2,1,2,2) means factor1 at level 2, factor2 at level 1, factor3 at level 2, and factor4 at level 2. For three uncontrollable factors, a 3-tuple denotes a specific configuration. For example, the (2,1,2,2) decision alternative at the uncertainty condition of (1,2,3) is written as ((2,1,2,2),(1,2,3)). And occasionally also as ((2,1,2,2),(123)).

6.2.5 The Business-As-Usual (BAU) Situation

The BAU situation is ((2,2,2,2),(2,2,2)) in the current uncertainty-regime. This regime is the "center point" of the uncontrollable space hypercube (Table 6.5). From the definition and the level specifications for the uncontrollable variables, we surmise that for ADI the best environment is (3,3,1), i.e. *industry demand* is high, *ADI orders* are strong, and *competitors' products* are unattractive and weak. Similarly, the worst environment is (1,1,3) when *industry demand growth* is weak, *ADI orders* are weak, and c*ompetitor products' attractiveness* are strong. We will test these assumptions in this chapter.

6.2.6 Validity of the Essential Variables

Validity is defined as "how accurately the account represents participants' realities of the social phenomena and is credible to them" (Creswell and Miller 2000; Borsboom and Markus 2013; Borsboom et al. 2004). This implies the criteria of face validity, construct validity, internal validity and external validity (Yin 2013; Hoyle et al. 2002; Johnson 1997). To these ends, we will test the sensitivity of AOI with respect to our controllable and uncontrollable variables. We test for the presence of causal linkages between the AOI outcome (the dependent variable), and the independent variables (our uncontrollable variables). We examine whether these linkages behave as we expect given our domain knowledge and understanding of the decision situation. And finally, we use statistics to determine whether there is support for the constructs and the narratives of the sociotechnical system behavior, i.e. does it all make sense? This begins with Table 6.5.

Table 6.5 Values for the BAU state and the current environmental condition

Controllable factors	BAU	Numeric value
r&d budget	Level 2	\$28.47 M
Manufacturing yield	Level 2	20%
cogs	Level 2	\$11.28 M
Product price	Level 2	\$17.38

Uncontrollable factors	Condition	Numeric value
Growth in demand	Current level	2%
ADI orders	Current level	1.487 M
Competitors' products attractiveness	Current level	4.955e-005 (this is an index)

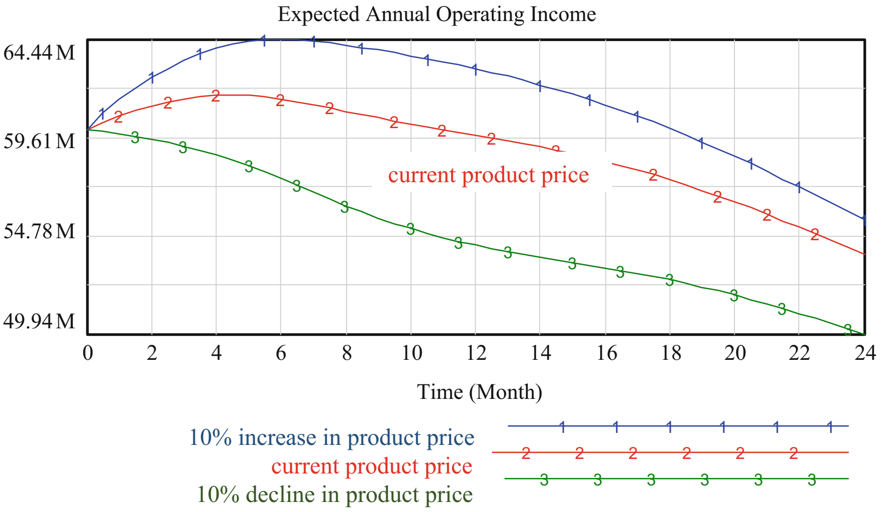


Fig. 6.3 AOI((2,2,2,2±),(2,2,2)) with higher, current, and lower price

6.2.6.1 AOI = *f*(single controllable variable)

We show the behavior of the dependent variable, AOI, **under the current BAU situational condition** as a function of the independent variables (the controllable variables). We express this condition as AOI((2,2,2,2),(2,2,2)) or AOI((2,2,2,2),(2,2,2)). The objectives, for the analyses are to determine whether there is a causal linkage between the dependent variable and the independent variables. And to assess whether the observed behavior is consistent with our understanding of the problem and domain knowledge of the situation. AOI((2+,2,2,2),(2,2,2)) is the situation in which the first controllable variable is changed to level 3, while the others remain unchanged.

Figure 6.3 plots AOI versus *product price* as a function of time. Graph #2 is AOI under the current BAU situation. A 10% increase in *product price* is shown as graph

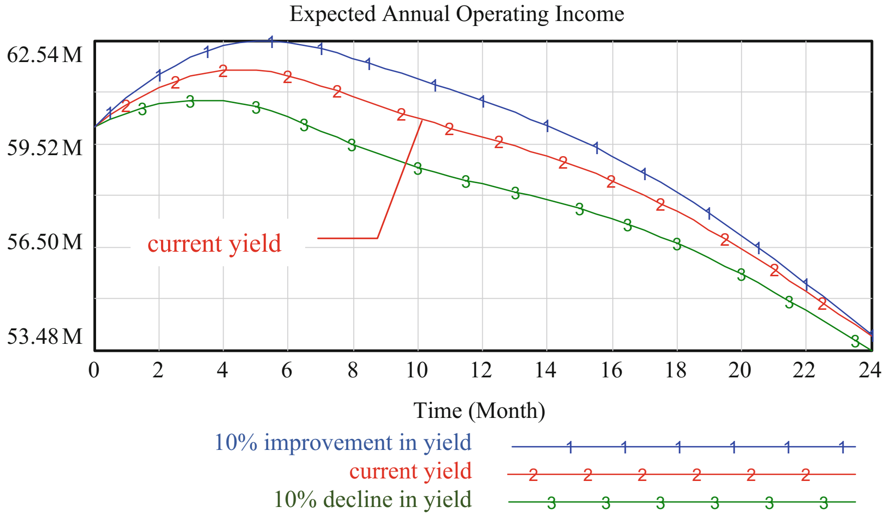


Fig. 6.4 AOI((2,2±,2,2),(2,2,2)) with higher, current, and lower manufacturing yield

#1. Graph #3 shows AOI under a 10% decline in *product price*. We find that the dependent variable, AOI, qualitatively behaves as one would expect relative to price changes. AOI rises as price increases and it declines as price decreases. But note that the negative impact on AOI by a 10% price decrease is more pronounced than a 10% increase in price. Graph #3 declines more precipitously and deeper than graph #1. Prospect Theory predicts this kind of phenomenon (Chap. 2, Sect. 2.3.2.2).

Figures 6.4, and 6.5 are similar plots of AOI for the controllable variables of *manufacturing yield*, and *cogs* respectively. AOI rises when manufacturing yield rises because as *yield* increases, all things being equal, sales increase, producing more income. As *cogs* declines, gross margin increases, boosting AOI. In Fig. 6.6, as *r&d* expense declines, AOI increases and vice versa. Note that, in contrast to Figs. 6.4 and 6.5, there is a delay of about five months before the effect of the r&d controllable variable is visible.

Finding

For **AOI(2±,2±,2±,2±),(222)**, our controllable variables (*r&d budget, IC yield, cogs, and product price*) influence the dependent variable, AOI in the directions that are consistent with our understanding of the decision situation and domain knowledge. AOI fluctuates in the opposite direction of *cogs*. Higher product costs reduces AOI. In the long run (t > 5) AOI moves in the opposite direction of *r&d*. This shows that for ADI's current strategy, all things being equal, *r&d* just depletes funds. This effect kicks in earlier than AOI. The impact occurs earlier internally in AOI before propagates externally through AOI.

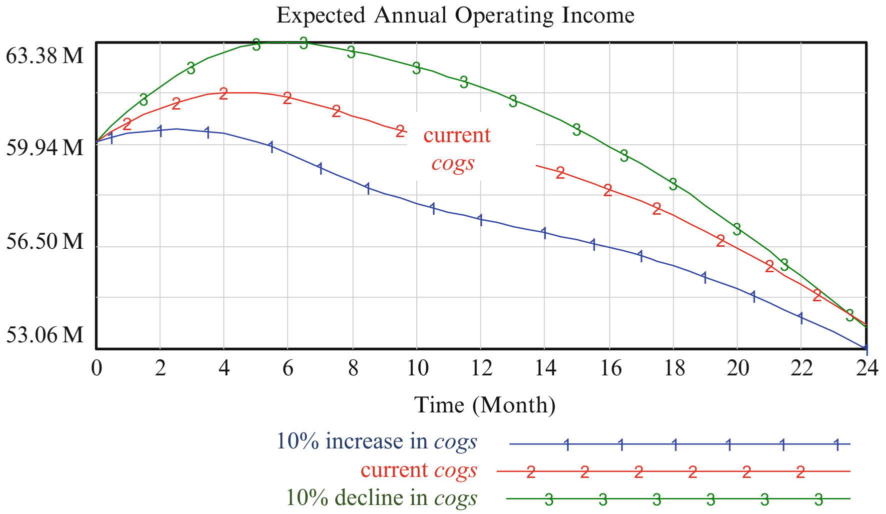


Fig. 6.5 AOI((2,2,2±,2),(2,2,2)) with higher, current, and lower *cogs*

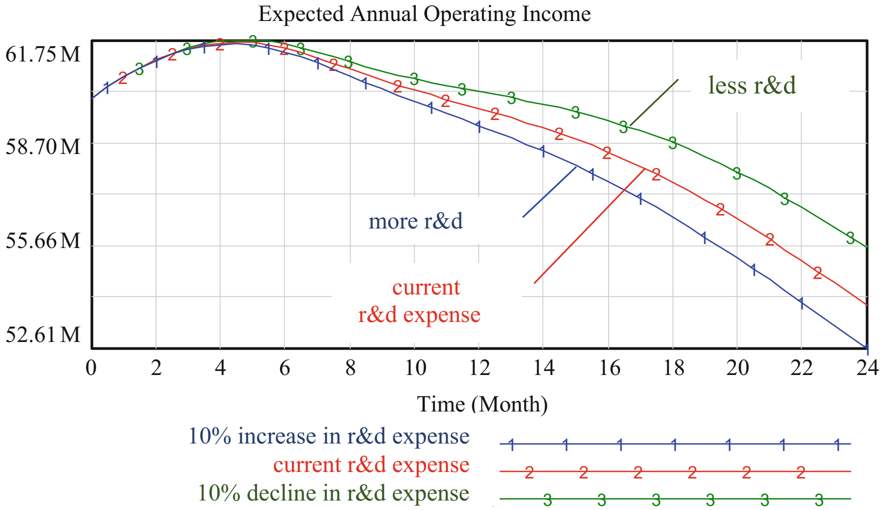


Fig. 6.6 AOI((2,2,2,2±),(2,2,2)) with higher, current, and lower r&d expense

6.2.6.2 AOI = *f*(single uncontrollable variable)

In the previous Sect. 6.2.6.1, we have shown the behavior of AOI as a function of the ***controllable*** variables. In this section, we show the behavior of AOI as a function of the ***uncontrollable*** variables. As in the previous section, the goal is to determine whether there is a causal linkage between the AOI dependent variable

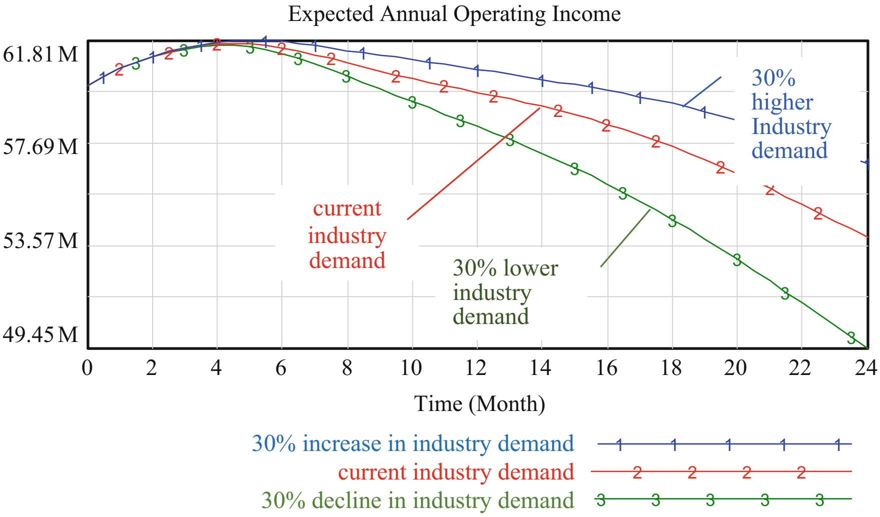


Fig. 6.7 AOI (BAU(2±,2,2)) in higher, current, and lower industry demand

and the uncontrollable variables. For BAU under different uncontrollable conditions, we write AOI (BAU,(2±,2±,2±)), as appropriate.

Figure 6.7 plots AOI as a function of time versus the uncontrollable factor, *industry demand-growth*. Graph #2 is the AOI situation with current industry demand-growth "as is". AOI rises and falls as industry-demand growth rate rises and falls, graphs #1 and #3, respectively. The AOI dependent variable behaves as one would expect. Figures 6.8 and 6.9 are the analogous plots of AOI as a function of the uncontrollable variables of *competitors' attractiveness*, and *order rate* for ADI products. AOI rises when ADI is more competitive and when orders for ADI products rise. And the converse is also apparent from the plots.

In Figs. 6.8 and 6.9, the strong effect of *competitors* and customers' *order rate* for ADI products on the AOI is discernable. The market effects of *competitors* and *customer order rate* are far more intense than the industry macro variable of *industry demand*. Moreover, this strong effect is present in the upside and the downside of the uncontrollable variables. These market driven effects are more intense than the macro-driven effect of industry demand.

Finding

For AOI((BAU),(2±2±2±)), our uncontrollable variables influence the AOI dependent variable in the direction that is consistent with our understanding of the decision situation. AOI rises with positive *industry demand*, and *ADI volume of orders*. AOI decreases with increased *attractiveness of competitors' product*. Note that the negative effect on AOI of the uncontrollable variables also exhibit a Prospect Theory behavior. This is consistent with our knowledge of the decision situation. The industry macro uncontrollable variable impact is less intense that the market-driven uncontrollable variables. There is a delay in the impact of the

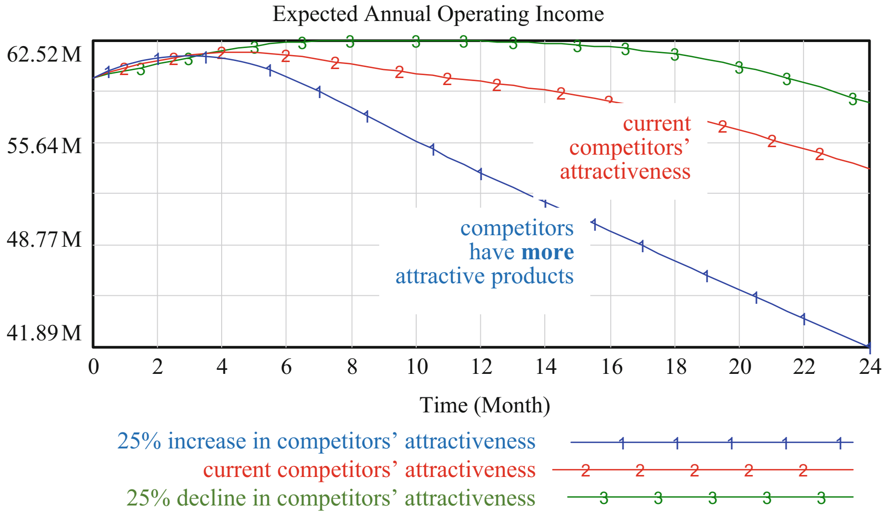


Fig. 6.8 AOI (BAU(2,2±,2)) with higher, current, and lower competitors' attractiveness

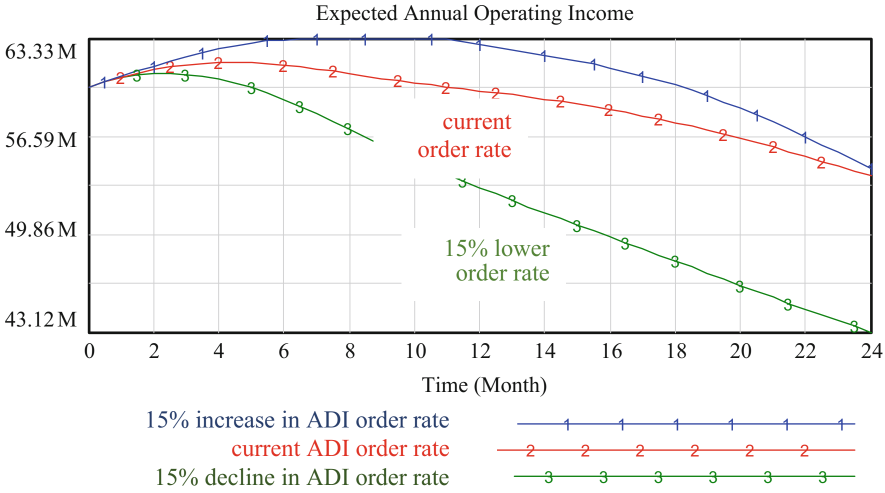


Fig. 6.9 AOI (BAU(2,2,2±)) with higher, current, and lower order rates for ADI

uncontrollable variables. The *industry demand* macro variable makes its presence felt later by more than two months. Although all three variables of *industry demand, competitors products' attractiveness*, and *order rate* are uncontrollable, the data suggests that tactical actions taken can ameliorate to some extent the impact of these uncontrollable variables.

6.2.6.3 AOI = *f*(ensemble of uncontrollable variables)

In this section, we must introduce the idea of *uncertainty regimes*. The uncertainty space, like the decisions' alternative space, is very large. The idea of *uncertainty regimes* is to discretize the uncertainty space into a manageable set. We have shown the behavior of AOI *vis à vis* the uncontrollable variables one at a time. We now address the question: What is the behavior of Market-Value of Firm given distinctly different configurations of the uncontrollable variables?

We have three uncontrollable variables, each with three levels. The full factorial space is comprised of $3^3 = 27$ uncontrollable conditions. Thus, the uncertainty space is represented by 27 states. In Rittel and Webber's (1973) language, we have *tamed* the uncertainty space. Henceforth, the uncertainty space is no longer an amorphous and intractable abstract idea. Twenty-seven is still a large number. And the cognitive load of 27 uncertainty conditions is still cognitively challenging. We resort to Miller's 7 ± 2 (Miller 1956) to *satisfice* ourselves with nine uncertainty regimes. We are most concerned with the conditions that are *worse* or *better* than the current state of uncertainty, i.e. better or worse than BAU. So, if we can specify the worst and the most favorable uncertainty regimes for AOI, we can be confident that the current state of uncertainty (2,2,2) is bracketed in between the best and worst regimes. We can specify a range of uncertainty regimes defined by the three uncontrollable variables at the end points of the three level specification. Thus we simplify to $2^3 = 8$ eight uncertainty conditions. Where "0" is the lowest and "1" is the highest of the levels 1, 2, and 3. The uncertainty space is systematically discretized into nine *uncertainty regimes* (Table 6.6), not just qualitatively as in scenario analyses (e.g. van der Heijden 2000). The best uncertainty regime is (2,2,1), i.e. high *industry demand* growth, strong *ADI orders,* and weak *competitors product's*. Similarly, the worst uncertainty regime is (1,1,2) when *industry-demand growth* is weak*,* *ADI orders* are weak, and *competitors' products attractiveness* is strong.

Figure 6.10 shows the graphs of AOI(2,2,2,2) for all uncertainty regimes. They are bracketed between the best uncertainty regime of (1,1,0) graph #2 and the worst of (0,0,1) graph #7 (note that per the previous paragraph, "0" and "1" translates (1,1,0) to (2,2,1) and analogously (0,0,1) to (1,1,2) best and worst uncertain regime, respectively). The system dynamics of the interactions among the controllable and uncontrollable variables reveal that the uncontrollable regimes influence the behavior of the AOI outcomes differently throughout the decision life-cycle.

Indeed under the best uncertainty regime (1,1,0) graph #2 AOI attains the highest values. Graph #7 is the worst uncertainty regime (0,0,1). And indeed under the worst uncertainty regime, AOI attains its lowest values, in general. BAU in the current uncertainty regime underperforms even the worst uncertainty regime. Why? Because Operating Income is given by:

$$operating\ \ Income = gross\ \ margin - operating\ \ expense \tag{6.1}$$

ADI's undertook TQM to improve technical operations, which were performing poorly from t = 0 through t = 6. This resulted in declining gross margins.

Table 6.6 Uncertainty regimes

Variables	Variable level								
Industry demand	Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher
ADI orders	Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger
Competitiveness	Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger
3-tuple	Current	(0,0,0) …	(0,0,1) Worst	(0,1,0) …	(0,1,1) …	(1,0,0) …	(1,0,1) …	(1,1,0) Best	(1,1,1) …

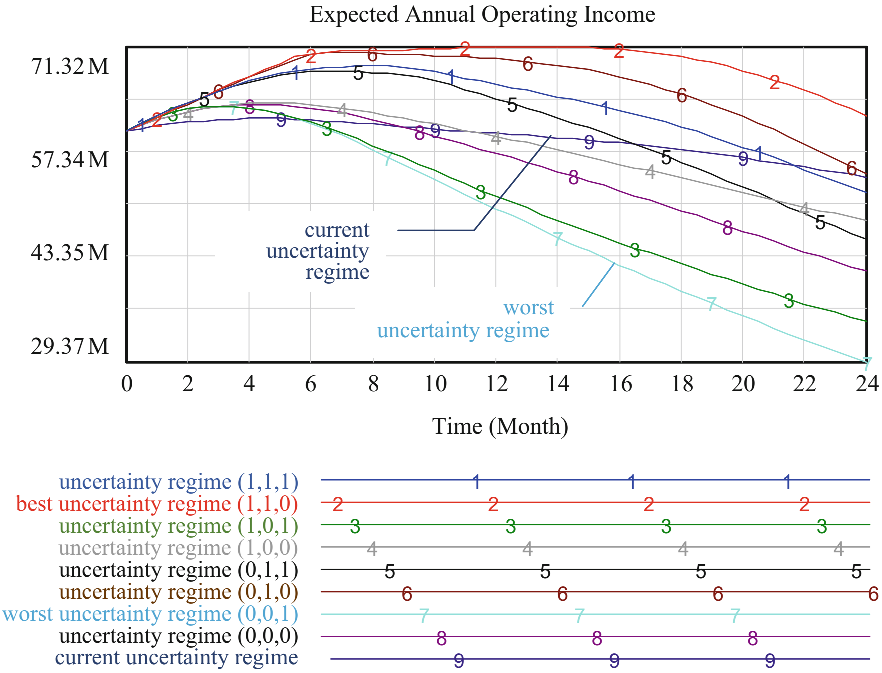


Fig. 6.10 AOI (BAU(2±,2±,2±)) under the entire spectrum of uncontrollable conditions

Simultaneously, ADI had a track record of escalating expenses that further depressed operating income during the first 6 months. The combination of declining gross margins and increasing operating expenses overwhelmed the financial results of ADI to the point that uncertainty could not influence the financials of ADI. However after five months, the surrogate simulations indicate that the impact of uncertainty is forceful and convincing. It has a nontrivial effect on the performance of the dependent variable of AOI outcome.

Finding

Different configurations of the uncontrollable variables influence the AOI dependent variable in the direction that is consistent with our domain understanding of the decision situation. We showed this with one uncontrollable variable at a time in Figs. 6.8, 6.9 and 6.10. AOI under the uncertainty regimes (under ensembles of uncontrollable variables) also exhibits behavior that is consistent with our understanding of the problem. AOI dominates performance under the best uncertainty regime (1,1,0) graph #2. Conversely, AOI is consistently depressed under the worse uncertainty regime (0,0,1) graph #7. Significantly, AOI is bracketed between these two regimes. Graphs #1, #5, #6, in Fig. 6.10.

6.2.6.4 AOI = *f* (ensemble of controllable variables)

We have shown the behavior of AOI vis à vis the uncontrollable variables. We show in this section the effect of configurations of controllable factor-levels.

We surmise that a potentially effective experiment is (1,3,1,3), *r&d* is low, *yield* is high, product costs *(cogs)* are low, and *product price* is high. Similarly, we surmise (3,1,3,1) is least effective. Figure 6.11 shows these three cases in the best uncertainty regime of (2,2,1). Graph #1, the surmised best experiment, exhibits the best performance. Graph #3, the surmised worst experiment, exhibits the worst performance. Graph #2 is BAU. It is bracketed by the best and worst experiments. There are many other possible experiments within the envelope of Fig. 6.11.

Does this AOI pattern (Fig. 6.12) in the best uncertainty regime (2,2,1) persist in the worst uncertainty regime of (1,1,2)? The answer is in the affirmative, Fig. 6.13. This is the analog of Fig. 6.12, in the worst uncertainty regime in this case.

Findings

Our findings from these series of simulation runs, of the ADI surrogate, support the belief that there are causal linkages among our independent variables of AOI and the uncertainty regimes, i.e. the defined ensemble of dependent variables. The AOI outputs are consistent with our understanding of the corporate problem and the ADI business decision. AOI consistently rises under favorable uncertainty regimes, and the converse is also supported by the data. The simulations suggest that behavior of the ADI surrogate for AOI, given our controllable and uncontrollable variables, supports face and construct validity of these experiments.

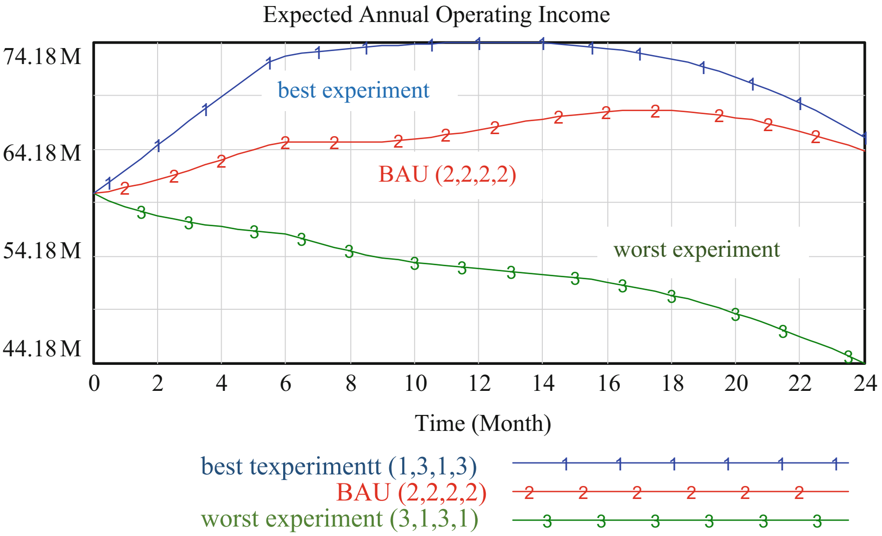


Fig. 6.11 AOI((3,1,3,1),(2,2,1)), AOI((2,2,2,2),(2,2,1)) and AOI((1,3,1,3),(2,2,1)) with surmised worst, BAU and worst experiments in the *best uncertainty regime of (2,2,1)*

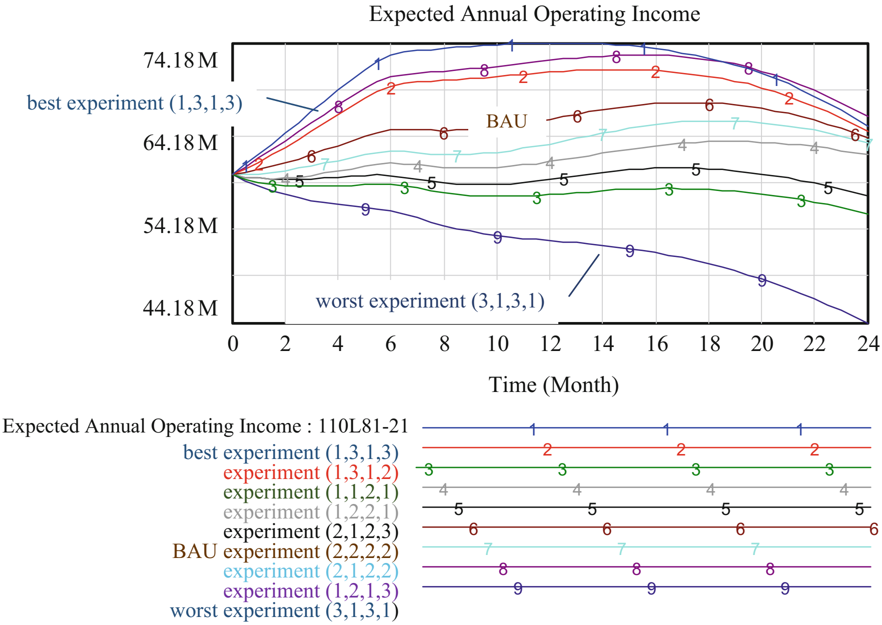


Fig. 6.12 AOI for a variety of treatments in the *best uncertainty regime (2,2,1)*

6.2.7 Summary Discussion

The goal of this section has been to test the adequacy of the ADI systems dynamics model as a surrogate company for our DOE-based decision analysis method. We framed a corporate decision, *maximizing the Annual Operating Income (AOI*). For this objective, we identified four controllable variables that are specified at three levels of performance. This gave us a space of $3^4 = 81$ possible configurations of factor-levels, they span the entire discretized Solution Space. We also simplified the uncertainty space from $3^3 = 27$ sunspaces into $2^3 + 1 = 9$ subspaces. We called these subspaces the *uncertainty regimes*. They span the entire uncertainty space. The size of the outcome space is then $81 \times 9 = 729$ outcomes. It is significant and useful that the entire solutions space and uncertainty space have been discretized into more manageable sets. But for senior-executive decision-making, this remains a very large space of outcomes to consider. In the remainder of this chapter, we will how to systematically cope with this situation of complexity.

Recall, our first task was to test the behavior of the ADI surrogate using our controllable and uncontrollable variables. We tested the sensitivity of the dependent variable AOI against each of the controllable and uncontrollable variables one at a time. We followed this with a systematic set of tests to evaluate the sensitivity of the dependent variable AOI. We used ensemble configurations of structured controllable and uncontrollable variables at different levels. Significantly, the direction of

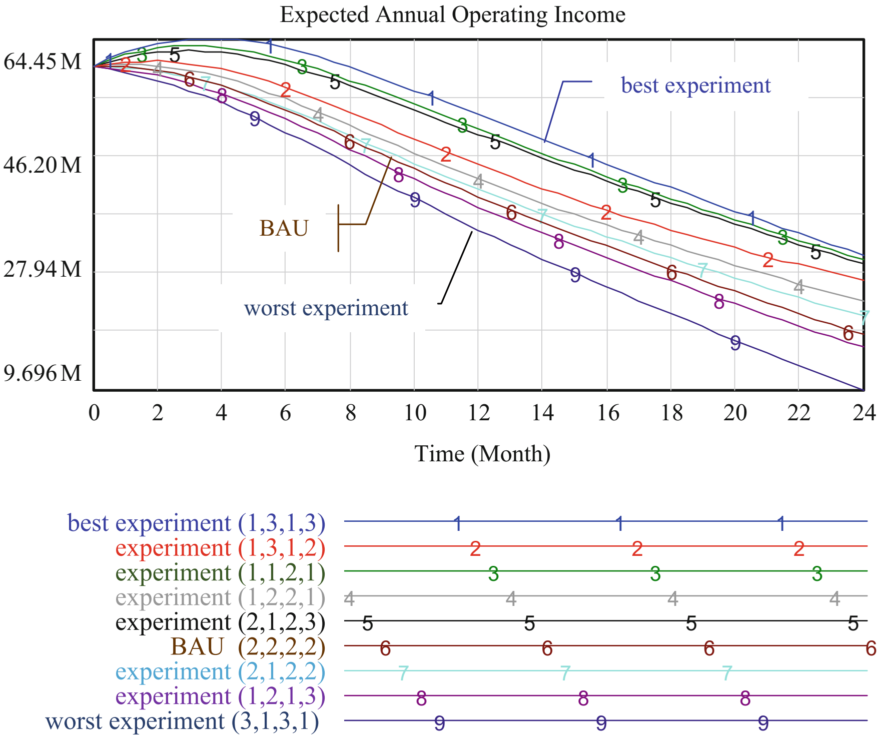


Fig. 6.13 AOI (BAU) and a variety of treatments in the *worst uncertainty regime (1,1,2)*

the AOI movements are consistent with domain knowledge and our understanding of the decision situation. Equally important, outcomes of the dependent variable AOI are also consistent with our understanding of the problem under different uncertainty conditions. Putting all this together, *these tests demonstrate the existence of meaningful causal linkages between the independent and dependent variables*. We find that the ADI surrogate has face, construct, and internal validity. Table 6.7 summarizes the support for X-RL1.

We are now ready to test our decision analysis method for the AOI decision. That is the subject of our next section.

6.3 Engineering the Solution Space

6.3.1 Introduction

In this section, we will show how to engineer the solution space to maximize the Annual Operating Income (AOI) for ADI. In the previous section, Characterizing

Table 6.7 X-RL1 Readiness level specifications for executive-management decisions

Readiness level	Our systematic process for the problem space	Functionality
X-RL1 Characterize Problem space	Sense making—uncomplicate the cognitive load	☑
	Framing problem/opportunity–clarify boundary conditions	☑
	Specify goals and objectives	☑
	Specify essential variables Managerially controllable variables Managerially uncontrollable variables	☑

☑ indicates support is demonstrated

the Problem Space, we have framed the problem, specified the goals and objectives, and identified the controllable and uncontrollable variables. We also systematically verified that the controllable and uncontrollable variables pass our tests of face and construct validity. Behavior of the controllable and uncontrollable variables determine the outcome of AOI. In the previous section we showed the direction of AOI as a function of controllable and uncontrollable variables. *However, we do not yet have any data to support the predictive power of specific configurations of the controllable variables under uncertainty regimes.* This is our next step—to engineer the solution space and the uncertainty regimes by using specifically designed experiments. From these experiments, we will be able to design decision specifications to explore the solution space and analyze their outcomes to determine whether they generate our intended results.

6.3.2 The Subspaces of the Solution Space

In Sect. 3.3.3 (Eq. 3.3), we defined the solutions space as the Cartesian product of two spaces. This is now Eq. (6.2) in this chapter.

$$(controllable\ \ space) \times (uncontrollable\ \ space) = [output\ \ space]. \tag{6.2}$$

We now proceed to construct each of these spaces. We begin with the controllable space, follow with the uncontrollable space, and finally with the output space.

6.3.2.1 Controllable Space = Alternatives Space

The controllable space is the sufficient sample set of alternatives from which we construct any new alternative and be able to predict its outcome and associated standard deviation. **This enables us to design any decision alternative anywhere in the controllable space and be able to predict its outcome. And standard deviation, as well. There is no alternative that cannot be analyzed.** We have four controllable variables, *r&d budget, IC yield, cogs,* and *product price*. We array them in Table 6.8 (previously shown as Table 6.3). For example, *r&d budget* is specified as *more-is-better*. ADI is a high technology company for which r&d is their lifeblood to maintain technology advantages or to develop new competitive advantages.

Using Table 6.8, we are able to construct Table 6.9. It shows a schematic of the *entire* and *complete* set of actionable decision alternatives without uncertainty. It is the full factorial set of all possible combinations of the four variables at three levels, of which there are $3^4 = 81$ alternatives. Each row in Table 6.8 represents a specific decision alternative, as a 4-tuple representing a configuration of the controllable variables. For example, alternative 3 is represented as (1,1,1,3) for *r&d budget* at -10%, *manufacturing yield* at -15%, *cogs* at -10%, and *product price* at -10%. Table 6.8 **shows how the complexity of the entire variety of actionable alternatives has been discretized into a finite set**. The first two columns of the arrays in Appendix 6.1 show a complete list of all 81 4-tuples that specify the entire set of decision alternatives. The set is still large and complicated, but we will show how it can be reduced to a manageable set.

The purpose of having decision alternatives is to predict how they will perform. From that data and information, the objective is to ***engineer*** a decision specifications that will satisfice the stated goals and objectives. The outputs of each alternative are shown by the column identified as **output**, $\boldsymbol{y}_{\boldsymbol{\alpha}} = f(alternative\ \alpha)$. But

Table 6.8 Controllable variables and levels

Controllable factors	Level 1 (%)	Level 2	Level 3 (%)	Characteristic
r&d budget	−10	Current level	+10	More is better
IC yield	−15	Current level	+15	More is better
cogs	−10	Current level	+10	Less is better
Product price	−10	Current level	+10	More is better

Table 6.9 Entire set of alternatives and outputs under NO uncertainty

	(r&d budget, IC yield, *cogs*, Product price)	$y_{\alpha} = f$ (alternative $\boldsymbol{\alpha}$) $1 \le \boldsymbol{\alpha} \le 81$
alternative 1	(1,1,1,1)	$\boldsymbol{y_1}$
alternative 2	(1,1,1,2)	$\boldsymbol{y_2}$
alternative 3	(1,1,1,3)	$\boldsymbol{y_3}$
alternative 4	(1,1,2,2)	$\boldsymbol{y_4}$
…	…	…
alternative 66	(3,2,1,1)	$\boldsymbol{y_{66}}$
alternative 67	(3,2,2,1)	$\boldsymbol{y_{67}}$
…	…	…
alternative 78	(3,3,2,3)	$\boldsymbol{y_{78}}$
alternative 79	(3,3,3,1)	$\boldsymbol{y_{79}}$
alternative 80	(3,3,3,2)	$\boldsymbol{y_{80}}$
alternative 81	(3,3,3,3)	$\boldsymbol{y_{81}}$

these outputs are under ideal conditions **without** any uncertainty. This is not realistic. The question is, therefore, how construct the uncontrollable space. How to address this question of decisions' uncertainties is the topic of the next Sect. 6.3.2.2.

6.3.2.2 Uncontrollable Space: Uncertainty Space

Every alternative will operate under some form of uncertainty, determined by uncontrollable variables. As in the case of controllable variables, we need to ***discretize*** the uncertainty space to make it manageable. We use the uncontrollable variables to represent the space of uncertainty. Our three uncontrollable variables are: *growth rate in industry demand*, *ADI orders*, and *competitors products' attractiveness*. We array these uncontrollable variables in Table 6.10.

Using Table 6.10, we derive the full factorial set of uncertainty conditions. The complexity of the requisite variety of uncertainties has been discretized into a finite set of $3^3 = 27$ uncertainty conditions (Table 6.11). For example, the current state of uncertainty is (2,2,2), uncertainty 14.

6.3.2.3 Solution Space = {Alternatives space} × {Uncertainties}

The *output space* of the solution space is the Cartesian product of two mutually exclusive sets, i.e.

Table 6.10 Uncontrollable factors at three levels each

Uncontrollable factors	Level 1 (%)	Level 2	Level 3 (%)	Characteristic
Industry growth rate	−25	Current level	+10	High is better
ADI orders rate	−25	Current level	+15	Fast is better
Competitors' attractiveness	−10	Current level	+10	Less is better

Table 6.11 Entire set of uncertainties (uncontrollable space)

Uncertainties 1–9		Uncertainties 10–18		Uncertainties 19–27	
1	(1,1,1)	10	(2,1,1)	19	(3,1,1)
2	(1,1,2)	11	(2,1,2)	20	(3,1,2)
3	(1,1,3)	12	(2,1,3)	21	(3,1,3)
4	(1,2,1)	13	(2,2,1)	22	(3,2,1)
5	(1,2,2)	14	(2,2,2)	23	(3,2,2)
6	(1,2,3)	15	(2,2,3)	24	(3,2,3)
7	(1,3,1)	16	(2,3,1)	25	(3,3,1)
8	(1,3,2)	17	(2,3,2)	26	(3,3,2)
9	(1,3,3)	18	(2,3,3)	27	(3,3,3)

$$y((controllable\ space) \times (uncontrollable\ space)) = [output\ space] \tag{6.3}$$

Schematically, the output matrix looks like Table 6.11.

The universe of alternatives under certainty is the set $\{alternative\ \alpha\}$, where $1 \leq \alpha \leq 81$ at each of 27 uncertainty conditions. Therefore, the universe of alternatives under uncertainty is the set of 81 alternatives under the 27 uncertainty conditions. Thus the number of alternatives under uncertainty is $4^3 \times 3^3 = 27 \times 81 = 2187$. This set is shown as follows in shorthand in Table 6.12. **We have discretized the complexity of the entire set of alternatives under the entire set of uncertainties by the Cartesian product of two discrete sets.**

We have shown the following. First, how to represent the entire set of decision alternatives without considering uncertainties (Table 6.8). Second, how to represent the *entire set of uncertainty conditions* (Table 6.11). And finally, how the Cartesian product of the set of alternatives with the set uncertainty space produce the set of alternatives under every uncertainty condition (Table 6.12). In the next section we will show how to reduce the size of this set, how to predict the outcomes for this reduced set, and how to construct the optimally robust decision alternative.

6.3.2.4 Uncertainty Regimes

We discussed, in Sect. 6.2.6.3, how to reduce the size of the uncertainty space, by specifying ***uncertainty regimes*** using configurations of uncontrollable variables. We developed the idea of uncertainty regimes to *uncomplicate* the uncertainty space to enable us to specify a *cognitively tractable* set of uncertainties to exhaustively explore the behavior of the sociotechnical system under any uncertainty condition. This facilitates our ability to systematically explore alternative decision specifications to find and design the decision of choice that can satisfice an organization's prospects. To evaluate any improvement requires a reference point. We specify the reference point as the current state of controllable variables (the BAU state) and the uncontrollable variables as the current *uncertainty regime*. This is reasonable and practical. We can expect the organization to have archival records on organizational performance and historical information on the uncontrollable variables.

However going forward, we cannot assume the uncontrollable environment will remain unchanged. Therefore, in addition to the base-line's specification, we need to complete four additional tasks. They are to specify: (i) the current state of the controllable variables, (ii) one or more specifications of *favorable states* of uncontrollable states, and (iii) specifications of *less favorable states* of uncontrollable states. *More* or *less* favorable conditions are defined relative to the actual state of uncontrollable conditions. In the paragraphs that follow, we will show how to perform these tasks.

Table 6.12 Entire set of alternatives outputs under entire set of uncertainty conditions

$y^j{}_\alpha = f(alternative\ \alpha,$ $uncertainty\ j)$ $1 \leq \alpha \leq 81,\ 1 \leq j \leq 27$		uncertainty **1**	uncertainty **2**	uncertainty **3**	uncertainty **4**	…	uncertainty **25**	uncertainty **26**	uncertainty **27**	$\bar{y}_\alpha$	σ_α
alternative 1	$(1, 1, 1, 1)$	$y^1{}_1$	$y^2{}_1$	$y^3{}_1$	$y^4{}_1$		$y^{25}{}_1$	$y^{26}{}_1$	$y^{27}{}_1$	$\bar{y}_1$	σ_1
alternative 2	$(1, 1, 1, 2)$	$y^1{}_2$	$y^2{}_2$	$y^3{}_2$	$y^4{}_2$		$y^{25}{}_2$	$y^{26}{}_2$	$y^{27}{}_2$	$\bar{y}_2$	σ_2
alternative 3	$(1, 1, 1, 3)$	$y^1{}_3$	$y^2{}_3$	$y3_3$	$y^4{}_3$	…	$y^{25}{}_3$	$y^{26}{}_3$	$y^{27}{}_3$	$\bar{y}_3$	σ_3
alternative 4	$(1, 1, 2, 1)$	$y^1{}_4$	$y^2{}_4$	$y^3{}_4$	$y^4{}_4$		$y^{25}{}_4$	$y^{26}{}_4$	$y^{27}{}_4$	$\bar{y}_4$	σ_4
…	…	…	…	…	…		…	…	…	…	…
alternative 41	$(2, 2, 2, 2)$	$y^1{}_{41}$	$y^2{}_{41}$	$y^3{}_{41}$	$y^4{}_{41}$		$y^{25}{}_{41}$	$y^{26}{}_{41}$	$y^{27}{}_{41}$	$\bar{y}_{41}$	σ_{41}
…	…	…	…	…	…		…	…	…	…	…
alternative 79	$(3, 3, 3, 1)$	$y^1{}_{79}$	$y^2{}_{79}$	$y^3{}_{79}$	$y^4{}_{79}$	…	$y^{25}{}_{79}$	$y^{26}{}_{79}$	$y^{27}{}_{79}$	$\bar{y}_{79}$	σ_{79}
alternative 80	$(3, 3, 3, 2)$	$y^1{}_{80}$	$y^2{}_{80}$	$y^3{}_{80}$	$y^4{}_{80}$		$y^{25}{}_{80}$	$y^{26}{}_{80}$	$y^{27}{}_{80}$	$\bar{y}_{80}$	σ_{80}
alternative 81	$(3, 3, 3, 3)$	$y^1{}_{81}$	$y^2{}_{81}$	$y^3{}_{81}$	$y^4{}_{81}$		$y^{25}{}_{81}$	$y^{26}{}_{81}$	$y^{27}{}_{81}$	$\bar{y}_{81}$	σ_{81}

$\bar{y}_\alpha = average\ (y^1_\alpha, y^2_\alpha, y^3_\alpha, \ldots, y^{26}_\alpha, y^{27}{}_\alpha),\ 1 \leq \alpha \leq 81$

$\sigma_\alpha = stdev\ (y^1_\alpha, y^2_\alpha, y^3_\alpha, \ldots, y^{26}_\alpha, y^{27}{}_\alpha),\ 1 \leq \alpha \leq 81$

6.3.2.5 Business As Usual (BAU) Under Uncertainty Regimes

Table 6.13 establishes the specifications for the **BAU** alternative, which is the do nothing different alternative (2,2,2,2) in the current uncertainty-regime.

The next task is to specify *more favorable* uncontrollable conditions and *less favorable* uncertainty regimes. *More* or *less* favorable are relative to the current state of uncontrollable variables. The BAU(2,2,2) specification in a linearly ordered range of uncertainty conditions, which includes the current uncertainty regime, is called the **base-line**. The base line is useful to bracket the BAU behavior between the current uncertainty regime, more favorable and less favorable regimes.

6.3.2.6 Summary Discussion

The objective of this section has been to represent the solution space and to prescribe how to specify the base line using the current, more favorable, and less favorable uncertainty regimes. This base line is a fundamental building block for us to be able to forecast results of designed alternatives (Table 6.14). We have demonstrated that our methodology is XRL-2 (Table 6.14).

Table 6.13 Values for the BAU state and the current environmental condition

Controllable factors	BAU level	Numeric value
r&d Budget	2	\$28.47 M
Manufacturing yield	2	20%
cogs	2	\$11.28 M
Product price	2	\$17.38

Current uncertainty regime	Condition level	
Growth in demand	2	2%
ADI orders	2	1.487 M
Competitors' products attractiveness	2	4.955e-005 (an index)

Table 6.14 Readiness level specifications for executive decisions

Readiness level	Systematic process for the solution space	Functionality
X-RL2 Engineer Solution space	Specify subspaces of solution space Alternatives space and uncertainty space	☑
	Specify entire solution space	☑
	Specify base line and uncertainty regimes Do-nothing case and choice-decision Estimate base line and dispel bias	☑

The symbol ☑ indicates support is demonstrated

6.4 Exploring the Operations Space

6.4.1 Introduction

We now take the next step and explore the operations space to ***phenomenologically*** extract its system behavior. We explore the operations space using four DOE representation schemas for the ADI sociotechnical system. These representations will be used to analyze its behavior for AOI. The phenomenological data and insights obtained will give us sufficient information to predict outcomes of any designed decision alternatives under any uncertainty-regime. We will use different schemas, of different experimental resolutions, to extract phenomenological data about the sociotechnical system that implements decision specifications. But the methodology for each representation schema is the same, but the size and complexity of each schema is different because they differ in resolution. The volume of extracted volume data and information follows the size and complexity of the schema. We will be discussing the implications of this fact in order to answer the questions: does more information improve our understanding of the sociotechnical system? What information is lost with simpler experiments? Does it matter? To address these questions, DOE is the exploration mechanism (Fig. 6.14) of the operations space.

We will use three representation schemas to investigate the Solution Space. First is the *full-factorial* space $L_{81}(3^4,2^{3+1})$ of four controllable variables under nine plus one uncertainty regimes plus the BAU (Tables 6.8 and 6.5). The uncertainty-regimes are comprised of three uncontrollable variables at two levels. The set of ten uncertainty regimes is denoted by 2^{3+1} (Table 6.5) with the additional current uncertainty-regime.

We start with the full-factorial experiment. This the most complete set of experiments. This set gives us the outcomes over the entire solution space, under all the uncontrollable uncertainty regimes. We use these results as our "gold standard" against which we will compare the results obtained from simpler experiments. And if the simpler tests yield sufficiently close results, then we can

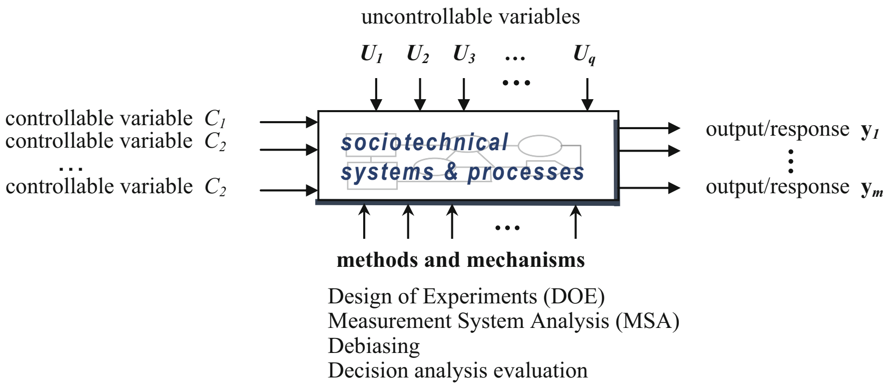


Fig. 6.14 Architecture of the operations space and role of the DOE mechanism

Table 6.15 Progression of experiments for DOE testing of AOI

Experimental design		Number of experiments	Uncertainty regimes	Complexity
$L_{81}(3^4, 2^3{+}1)$	Full factorial	81	9 plus current state	Higher
$L_{27}(3^{4-1}, 2^3{+}1)$	High resolution	27	9 plus current state	Medium
$L_9(3^{4-2}, 2^3{+}1)$	Low resolution	9	9 plus current state	Low

conclude that a simpler experiment will suffice. And if the results are sufficiently close, we want to know the conditions under which this is consistently possible. Naturally, more complex experiments produce more data. With additional data, we would like to know what additional insights we may gain from more complex experiments. And we would like to know what data and information we miss with simpler experiments. We summarize our exploratory approaches in Table 6.15.

The second representation of the solution space is the $L_{27}(3^{4-1},2^{3+1})$ using an *orthogonal* array of 27 rows (Appendix 6.4). Orthogonal means that all three levels, for each of all the three variables, are equally represented in every column. Equally represented means that the levels of the factors appear an equal number of times in the experiments. The experimental structures are designed to collect no more data for any particular variable or level. If an array's the non-orthogonal columns are few, the array is said to be *nearly orthogonal* (Wu and Hamada 2000; 311). There are situations for which constructing nearly orthogonal arrays is useful. The symbol 3^{4-1} means that a subset, of $3^{4-1} = 27$, experiments from the 3^4 full factorial are represented.

The third representation of the solution space is the $L_9(3^{4-2},2^{3+1})$ orthogonal array, which is comprised of ten experiments and ten uncertainty conditions (Appendix 6.9). This is the simplest orthogonal array experiment we can perform.

What is to be gained by proceeding in this way, proceeding from the most complex to successively simpler experiments? And why is it important? This systematic approach is meaningful because we want to know the simplest experiment we can perform that will give us sufficient data for a decision. And we want to go about this task systematically. A systematic approach avoids missing opportunities to explore and learn; moreover, any findings are then more convincing and forceful. The simplest experiment may be meaningful and useful because experiments are costly. The kind of experiments we will be studying—decisions for corporate problems—are generally very expensive. They require corporate staffs to collect data and perform analysis, experts to review, and management time to evaluate and discuss. Invariably new procedures and expertise are required. New equipment may need to be acquired. Specialized expertise may not exist in-house. Occasionally, high-priced consultants need to be engaged to investigate and propose solutions outside the organization's expertise. Simpler experiments mean faster results and more frugal expenditures.

6.4.2 *Solution Space for AOI($L_{81}(3^4, 2^3+1)$)*

6.4.2.1 Analyses of AOI($L_{81}(3^4, 2^3+1)$)

The data set for AOI($L_{81}(3^4,2^3+1)$) is in Appendix 6.1 at the time of t = 12, i.e. 12 months out; t = 0 is the time when the experiment begins, when the decision is committed and implementation begins. The data sets for t = 18 months, and t = 24 months are also available in Appendix 6.1. Since this is the full factorial space, we can find, by *inspection*, the experiment for which AOI reaches its maximum. Table 6.16 shows that the best decision alternative is (1,3,1,3). The maximum revealed by $L_{81}(3^4, 2^3+1)$ full-factorial for the three time periods. The (1,3,1,3) decision-design of is the one in which *r&d* is low, IC manufacturing *yield* is high, *cogs* is low, and *price* is high. In general, one would expect that high r&d would exert a positive impact on the value of a firm since it serves to strengthen product functionality and quality. But as we saw in Fig. 6.6, in ADI at this time it depresses AOI. That the best design has r&d at the lowest level may be counter intuitive, but ADI management emphasis on product quality has led to their current problems (Sect. 5.2.1). The standard deviations increase from t = 12 to t = 24, indicating less precision further out in time, and more risk.

At t = 24 the AOI maximum is (1,3,2,3), which different from that obtained at t = 12 and t = 18. It is also different from the MVF maximum obtained in Table 5.16. The maximum MVF at t = 24 is given by the design specification of (1,3,1,3). For AOI, the maximum at t = 24 is given by (1,3,2,3). The difference between (1,3,1,3) and (1,3,2,3) is the third element in the 4-tuple, *viz. cogs*. Figures 6.3 and 6.5 gives us some insight to explain this difference. The impact of *price* and *cogs* are substantially more forceful at t = 24 than at t = 12. Data of these cases are shown in Fig. 6.15. The Northwest corner of the plots clearly illustrate the iso-influence zones of price and *cogs* on AOI at these times. The effect of price is dramatically more emphatic as shown by the larger dark green region of the contour plots. The nearly parallel color bands indicate a quasi-linear relationship of the two independent variables.

Next we examine the ANOVA tables for $\mathbf{L_{81}(3^4,2^3+1)}$ at t = 12 (Table 6.17). All the controllable variables are statistically significant with p = 0.000. They are strong predictors of the outcome of AOI.

- There are three 2-factor interactions (2-fi) and one 3-factor interaction (3-fi). The 2-fi interactions are *yield*cogs*, *yield*price*, and *cogs*price*. The 3-fi is *yield*cogs*price*. They are also statistically significant, but their contributions are small. Interactions have p = 0.000 except for the 3-fi of *yield*cogs*price*

Table 6.16 Maximum AOI ($L_{81}(3^4, 2^3+1)$) and standard deviation for t = 12, 18, and 24

Period	Experiment	AOI($L_{81}(3^4,2^3+1)$)	Stdev
t = 12	1,3,1,3	$64.53 M	7.84
t = 18	1,3,1,3	$57.96 M	10.61
t = 24	1,3,2,3	$55.38 M	10.09

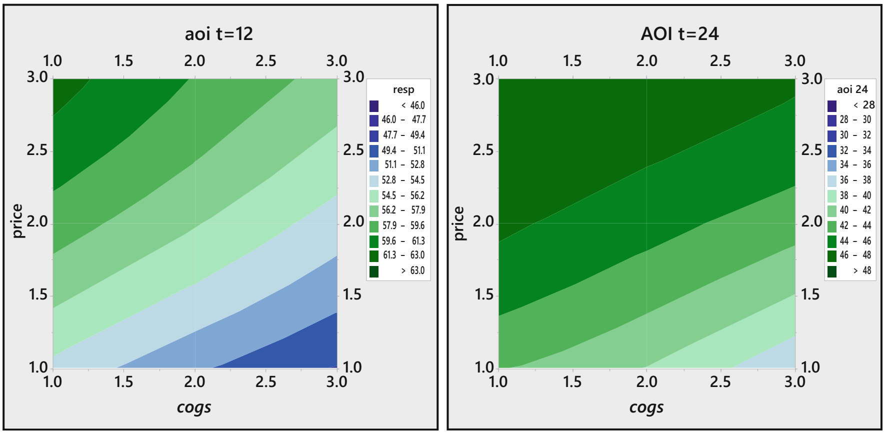


Fig. 6.15 AOI contour plots that show the stronger impact of price relative to *cogs* at t = 24, in comparison to at t = 12

Table 6.17 ANOVA Tables for $L_{81}(3^4,2^3+1)$ at t = 12

Source	DF	Seq SS	Adj SS	Adj MS	F	P
r&d	2	21.123	9.150	4.575	109.52	0.000
yield	2	314.615	353.614	176.807	4232.55	0.000
cogs	2	320.463	347.527	173.763	4159.69	0.000
price	2	908.881	912.325	456.162	10919.99	0.000
yield**cogs*	4	6.967	7.620	1.905	45.60	0.000
yield*price	4	3.384	3.623	0.906	21.68	0.000
*cogs**price	4	2.178	2.209	0.552	13.22	0.000
yield**cogs**price	8	0.918	0.918	0.115	2.75	0.013
Error	51	2.130	2.130	0.042		
Total	79	1580.660				
S = 0.204385, R-Sq = 99.87%, R-Sq(adj) = 99.79%						

with p = 0.013. However, its contribution is very small. Without loss of generality, it can be considered part of the error term.

- The R^2 statistics are very good. R-Sq = 99.87% and R-Sq(adj) = 99.79% for AOI($L_{81}(3^4, 2^3+1)$).

The ANOVA tables for $L_{81}(3^4, 2^3+1)$ for t = 18, and 24 are in Appendix 6.2. Table 6.18 is a summary. And Table 6.19 is a summary of the statistics about the interactions. We have three 2-factor interactions (2-fi) and one 3-factor interaction (3-fi) of *yield*cogs*price*. They are all statistically significant with $p \ll 0.05$ with one exception, the 3-fi at t = 18.

The AOI($L_{81}(3^4, 2^3+1)$) experimental design also exhibits the three key properties, of hierarchy, sparsity, and heredity, stipulated by DOE scholars (Wu and Hamada 2000; Frey and Li 2004, Sect. 3.4.3.2). The hierarchy property states that single variable effects are more important than interactions' effects. The 2-fi are

Table 6.18 AOI($L_{81}(3^4, 2^3+1)$) summary for t = 12, 18, and 24

	t = 12		t = 18		t = 24	
Factors	Adj. MS	p value	Adj. MS	p value	Adj. MS	p value
r&d	4.575	0.000	30.933	0.000	54.908	0.000
yield	176.807	0.000	132.016	0.000	100.264	0.000
cogs	173.763	0.000	139.429	0.000	88.34	0.000
prod. price	456.162	0.000	454.179	0.000	419.899	0.000
yield**cogs*	1.905	0.000	7.013	0.000	15.615	0.000
yield*price	0.906	0.000	5.609	0.000	15.686	0.000
*cogs**price	0.552	0.000	3.533	0.004	12.242	0.000
yield**cogs**price	0.115	0.013	0.492	**0.758**	2.563	0.025
Error	0.042	–	0.796	–	1.045	–
Total	814.827	–	774.00	–	710.562	–
R^2 adj	99.8%		97.5%		96.6%	

Table 6.19 AOI($L_{81}(3^4, 2^3+1)$) interactions for t = 12, 18, and 24

	t = 12		t = 18		**t = 24**	
	Interactions	No interaction	Interactions	No interaction	Interactions	No interaction
ΣMS-adj	3.48	811.31	16.65	756.56	46.11	663.41
Ratio	3.48/811.31 = **0.43%**		16.65/756.56 = **2.20%**		46.11/663.41 = **6.95%**	

more important than 3-fi. And n-fi are more important than (n+1)-fi. Data from Appendix 6.2 show that:

$$\sum(\text{Adj SS})_{\mathbf{me}} = [9.15 + 353.614 + 347.527 + 912.325] = 1622.616 \text{ for main effects}$$

$$\sum(\text{Adj SS})_{\mathbf{fi}} = [7.62 + 3.623 + 2.209 + 0.918)] = 14.37 \text{ for factor} - \text{interactions.}$$

The subscript ***me*** denote main effects and ***fi*** factor-interactions. Total Adj SS of the single variables overwhelm the sum of interactions' SS. This is evidence of sparsity, i.e. relatively few variables dominate the overall effects. This is apparent by the SS contributions of the four controllable variables. Heredity is the property that in order for an interaction to be significant, at least one of its variables should be significant. Each of the variables in the 2-fi and 3-fi is a significant predictor of behavior of AOI($L_{81}(3^4, 2^3+1)$).

These findings of the DOE properties support our choice of variables and constructs. The interactions are a very small percentage of the total Adj. MS, <0.9%. Although 2-fi and 3-fi are present, their contribution to the outcome are small. The behavior of the AOI($L_{81}(3^4, 2^3+1)$) model is quasi-linear and near-decomposable (Simon 1997, 2001).

A summary statistics for the interactions at the time periods of t = 12, t = 18 and t = 24 are in Table 6.19. For each period, we add MS-adj. for two groups, the controllable variables p and for the interactions. We find that the ratio of the ΣMS-adj(interactions) to ΣMS-adj(no interactions) is small. The influence of the interaction on the outputs is weak the system behavior is quasi linear.

The collective contributions of the interactions increase with time although they remain small (Table 6.19). We posit that the explanation lies in the complex system behavior of ADI. In system dynamics models of complex systems, the aggregate of **stocks** and **flows** determine the behavior of the system (e.g. Sterman 2000). A stock is a system element that can accumulate the content of flows. For example, a bathtub accumulates water, a spring stores energy, a capacitor stores charge, a company accrues profit; they are all stocks. Stocks delay many of the responses in the system. It takes time to fully charge a capacitor. There is a lag between the time one turns on the hot water faucet and the time one is able to sense the rise in temperature. Cold water in the pipes delays the arrival of warm water.

Empirical data of the interactions from our experiment point to the phenomenon of the increasing contribution of the interactions at t = 12, 18, and 24. The presence of stocks creates delays and dampen the responses of the system variables. The empirical data of the interactions of our experiment suggests this is the phenomenon of the increasing contribution of the interactions. For example, between *manufacturing yield* and *product price* there are a set of complex causal relations involving stocks and flows. There are many more paths (than the one described below) that include many mediating variables. We limit ourselves to a single chain of events to simplify the illustration. $x \rightarrow y$ indicates $y = f(x)$ where f is analytic construct, which can be algebraic, derivative or an integral. An integral is a stock.

$$\begin{aligned} &\textit{Manufacturing Yield} \rightarrow \textit{Manufacturing Cost of Finished Good}\\ &\rightarrow \textit{Manufacturing Cost of Goods Sold} \rightarrow \textit{Cost of Goods Sold}\\ &\rightarrow \textit{Total per Unit Cost} \rightarrow \textit{Perceived Total Per Unit Cost}\\ &\rightarrow \textit{Target Price} \rightarrow \textit{Product Price}. \end{aligned}$$

There are many stocks, e.g. *Manufacturing Cost of Finished Good*. Stocks cause delays of the interaction effects. They accumulate and are revealed more intensely only as time rolls forward.

Findings

All four controllable variables (*r&d, manufacturing yield, cogs, and product price*) are strong predictors of the AOI($L_{81}(3^4,2^3+1)$) outcomes. They all have $p \ll 0.05$. Each is a strong predictor of the outcome of AOI. The 2-fi interactions of *yield*cogs, yield*price*, *cogs*price* and the 3-fi of *yield*cogs*price* are present. The 3-fi of *yield*cogs*price* has $p = 0.013$, the other interactions have $p = 0.000$. The collective contributions of the interactions to the outcome is small, but statistically significant. The model's variables exhibit the key properties of hierarchy, sparsity, and inheritance, typical of complex DOE experiments. The model AOI ($L_{81}(3^4,2^3+1)$ is very good. All R^2 adj > 99% at t = 12, 18 and 24.

6.4.2.2 $\mathcal{R}$\{AOI($L_{81}(3^4, 2^3+1)$)\}: The Rotated AOI(($L_{81}(3^4, 2^3+1)$) Space

Data for the **controllable** variables *vis à vis* AOI($L_{81}(3^4,2^3+1)$) indicate they are strong predictors of the AOI outcome (Table 6.18). The solutions space is the product of the controllable space and the uncontrollable space, which is used to obtain the output space.

$$\boldsymbol{y}((\textit{controllable space}) \times (\textit{uncontrollable space})) = [\textit{output space}] \tag{6.4}$$

Suppose we "rotate" the controllable space and uncontrollable spaces. i.e.

$$\boldsymbol{y}((\textit{uncontrollable space}) \times (\textit{controllable space}))^{\boldsymbol{T}} = [\textit{output space}]^{\boldsymbol{T}} \tag{6.5}$$

where T indicates the transpose. We identify this **rotated** space by:

$$\mathcal{R}\left\{\mathrm{AOI}\left(\mathrm{L}_{81}\left(3^4, 2^3+1\right)\right)\right\}.$$

Given the role reversal between the controllable and uncontrollable variables, we would like to know whether the ANOVA statistics of this rearranged space provide us with any information that is new and meaningful. We wish to examine the ANOVA statistics of this new construct. The summary statistics for this new construct are in Table 6.20. (The ANOVA tables for the time periods of $t = 18$ and 24 are in Appendix 6.3) Are the **uncontrollable** variables are also statistically significant predictors of AOI?

The answer is in the affirmative. Notably, the ANOVA statistics of the $\mathcal{R}$\{AOI ($L_{81}(3^4,2^3+1)$)\} construct show $p < 0.05$ for all the **uncontrollable** variables; they are statistically significant. This does not mean that we can use them to predict the AOI; rather it means that they are meaningful to include as uncontrollable variables in our DOE formulation. The summary statistics for this new construct are shown in Table 6.21. The residuals are random N(0, 0.6320) (Fig. 6.16). (The ANOVA tables for the time periods of $t = 18$ and 24 are in Appendix 6.3)

Overall, the rotated model is good. The p values for *Long Term Growth* at $t = 18$ and $t = 24$ have $p \ll 0.05$, except for *industry long term growth* with $p = 0.036$ at $t = 12$. The effect of the *Long Term Growth* uncontrollable variable is not instantaneous, there is a delay before the effect is visible. This is discernable by

Table 6.20 $\mathcal{R}$\{AOI($L_{81}(3^4, 2^3+1)$)\} at $t = 12$

Analysis of Variance. $\mathcal{R}$\{AOI ($L_{81}(3^4, 2^3+1)$)\} $t = 12$

Source	DF	Seq SS	Adj SS	Adj MS	F	P
LT growth	1	6.76	6.76	6.76	9.67	0.036
ADI orders	1	336.08	336.08	336.08	480.84	0.000
Competitor	1	70.59	70.59	70.59	101.00	0.001
Error	4	2.80	2.80	0.70		
Total	7	416.22				

S = 0.836030, R-Sq = 99.33%, R-Sq(adj) = 98.82%

Fig. 6.16 Residual plots of $\mathcal{R}\{\mathrm{AOI}(L_{81}(3^4, 2^3{+}1))\}$ at $t = 12$

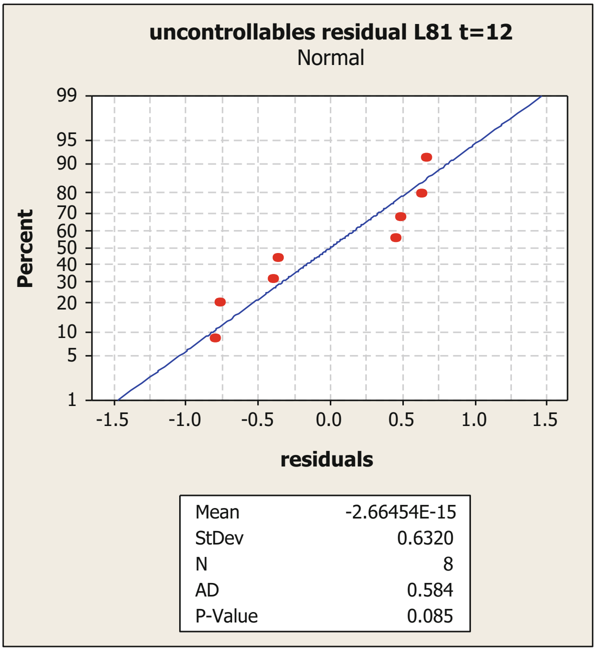


Table 6.21 $\mathcal{R}\{\mathrm{AOI\ F}(L_{81}(3^4, 2^3{+}1))\}$—The rotated $\mathrm{AOI}(L_{81}(3^4, 2^3{+}1))$ space at $t = 12, 18, 24$

$\mathcal{R}\{\mathrm{AOI\ F}(L_{81}(3^4, 2^3{+}1))\}$						
	$t = 12$		$t = 18$		$t = 24$	
Uncontrollable variables	Adj. MS	p value	Adj. MS	p value	Adj. MS	p value
Industry long term growth	6.76	0.036	45.76	0.002	100.04	0.001
ADI orders	336.08	0.000	593.7	0.000	592.22	0.000
Competitors' prod. attractiveness	70.59	0.001	205.67	0.000	298.72	0.000
Error	0.7	–	0.81	–	1.46	–
Total	414.13	–	845.940	–	992.44	–

the rise in SS adj. The same is true for *competitors' products attractiveness*. Moreover, we note, from Figs. 6.7, 6.8 and 6.9, that the influence of *ADI orders* and *competitors' attractiveness* dominates the uncontrollable influences on AOI $(L_{81}(3^4, 2^3{+}1))$.

Consider the Eqs. (6.6) and (6.7) using data from Appendix 6.1 for $t = 12$. Equation (6.6) shows the *average* of $\mathrm{AOI}(L_{81}(3^4, 2^{3-1}))$ for the uncertain regimes in which *Industry Long Term Growth* is **high**. Equation (6.7) is the average of AOI $(L_{81}(3^4, 2^{3-1}))$ outputs for which *Industry Long Term Growth* is **low**.

$$\begin{aligned}&\mathrm{AOI}\big(L_{81}\big(3^4, 100\big)\big) + \mathrm{AOI}\big(\big(L_{81}\big(3^4, 101\big)\big) + \mathrm{AOI}\big(\big(L_{81}\big(3^4, 110\big)\big)\\&\quad + \mathrm{AOI}\big(L_{81}\big(3^4, 111\big)\big) = \$18252.78\,\mathrm{M}\end{aligned} \tag{6.6}$$

$$\begin{aligned} &\mathrm{AOI}\left(\mathrm{L}_{81}\left(3^4,000\right)\right)+\mathrm{AOI}\left(\mathrm{L}_{81}\left(3^4,001\right)\right)+\mathrm{AOI}\left(\mathrm{L}_{81}\left(3^4,010\right)\right) \\ &\quad+\mathrm{AOI}\left(\left(\mathrm{L}_{81}\left(3^4,011\right)\right)=\$17657.41\,\mathrm{M}\right. \end{aligned} \tag{6.7}$$

Difference of these two Eqs. (6.6)–(6.7) is

$$\$18252.78\,\mathrm{M}-\$17657.41\,\mathrm{M}=\$595.37\,\mathrm{M} \tag{6.8}$$

This the difference that *Long Term Industry Growth* makes to AOI at t = 12. Sum of (6.6) and (6.7) is

$$\Sigma^{81}(y-\mathrm{bar})_i=\$35{,}910.19\,\mathrm{M}\ \text{ for the eight uncertainty regimes} \tag{6.9}$$

Although the percentage impact is \$595.37/\$35,910.19 = 1.67%, an executive is unlikely to ignore an improvement on AOI of \$595.37 M.

6.4.2.3 Summary of AOI((L_{81}(3^4,2^3+1)) Surrogate Testing

We populated the full factorial $L_{81}(3^4,2^3+1)$ orthogonal array and we also used a full factorial uncertainty to address a spanning set of uncertainties. We analyzed the L_{81} arrays for the time periods of t = 12, 18, and 24 and by inspection identify the maximum AOI($L_{81}(3^4,2^3+1)$) for each of the time periods. The ANOVA statistics for the controllable variables support them as strong predictors of the output of AOI. The data indicate that statistically significant 2-fi and 3-fi are present for the controllable variables, but their contribution is a small percentage to the outcome of AOI. Without loss of generality, they are therefore pooled into the error term.

The ANOVA statistics of the **rotated** space $\mathcal{R}\{\mathrm{AOI\ F}(L_{81}(3^4,2^3+1))\}$ reveal that the uncontrollable variables are also statistically significant to the outcome of AOI at all three time periods of t = 12, 18 and 24. We discern from Table 6.18 that the experiments using the $L_{81}(3^4,2^3+1)$ design exhibit the properties of hierarchy, sparsity, and inheritance. With these results, we now have our gold standard for the rest of our experiments. All the data for $L_{81}(3^4,2^3+1)$ appear in Appendix 6.1.

6.4.3 Solution Space for AOI(L_{27}(3^{4-1},2^3+1))

6.4.3.1 Analyses of AOI(L_{27}(3^{4-1},2^3+1))

In Sect. 6.4.2, we studied and analyzed the AOI($L_{81}(3^4,2^3+1)$) Solution Space. We used the DOE methodology on a full factorial AOI($L_{81}(3^4,2^3+1)$). There we could find the extremum by inspection.

In this section, we will be using the reduced orthogonal Solution Space of AOI ($L_{27}(3^{4-1},2^3+1)$). Using the $L_{27}(3^{4-1},2^3+1)$ array, instead of $L_{81}(3^{4-1},2^3+1)$, reduces the number of experiments from 81 to 27. This will result in a substantial reduction in data that will be required. Unlike the previous section where we could find the extremum by inspection, we will now use robust design to construct and predict extrema. Given that volume of data will be significantly reduced and will depend predictive analytics, the key questions we will be investigating in this section are:

- Can we design robust decision alternatives anywhere in the Solution Space?
- Will the results be consistent with our "gold standard"

To answer whether the controllable variables remain as strong predictors of the AOI outcomes, we turn our attention to the ANOVA table (Table 6.22). All variables are strong predictors for the AOI outcome have $p \ll 0.05$. We see three 2-fi, *yield*cogs, yield*price* and *cogs*price*. The first two 2-fi have strong p values of $p = 0.003$ and $p = 0.029$, while *cogs*price* has a somewhat weaker p value of $p = 0.06$. The residuals are statistically normal, N(0,0.1031) with $p \gg 0.05$ (Fig. 6.17).

Table 6.22 ANOVA AOI($L_{27}(3^{4-1}, 2^3{+}1)$) at t = 12

Analysis of Variance. AOI $L_{27}(3^{4-1}, 2^3{+}1)$ t = 12						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
r&d	2	4.457	4.457	2.228	48.36	0.000
yield	2	126.065	126.065	63.032	1367.96	0.000
cogs	2	121.000	121.000	60.500	1313.00	0.000
price	2	313.681	313.681	156.840	3403.82	0.000
yield**cogs*	4	2.860	2.860	0.715	15.52	0.003
yield*price	4	1.078	1.078	0.269	5.85	0.029
*cogs**price	4	0.762	0.762	0.190	4.13	0.060
Error	6	0.276	0.276	0.046		
Total	26	570.178				
S = 0.214657, R-Sq = 99.95%, R-Sq(adj) = 99.79%						

Fig. 6.17 AOI($L_{27}(3^{4-1}, 2^3{+}1)$) residuals at t = 12

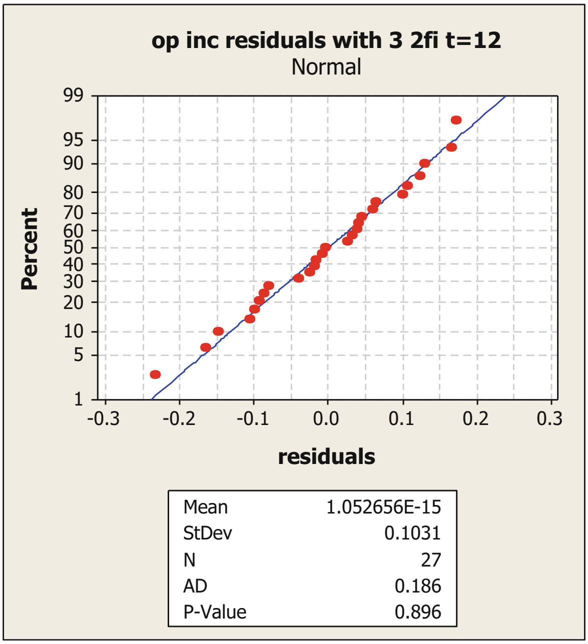


Table 6.23 AOI($L_{27}(3^{4-1}, 2^3+1)$) summary for t = 12, 18, and 24

AOI($L_{27}(3^{4-1}, 2^3+1)$)						
	t = 12		t = 18		t = 24	
Factors	Adj. MS	p value	Adj. MS	p value	Adj. MS	p value
r&d	2.228	0.000	8.064	0.002	18.854	0.003
yield	63.032	0.000	51.66	0.000	35.263	0.001
cogs	60.5	0.000	54.178	0.000	34.704	0.001
product price	156.84	0.000	166.258	0.000	156.48	0.000
yield**cogs*	0.715	0.003	2.728	0.017	8.346	0.014
yield*price	0.269	0.029	2.02	0.033	7.085	0.021
price**cogs*	0.19	**0.060**	1.907	0.038	5.097	0.044
Error	0.046	–	0.368	–	1.053	–
Total	283.82	–	287.183	–	266.882	–

Table 6.24 $L_{27}(3^{4-1}, 2^3+1)$ interactions for AOI for t = 12, 18, and 24

Two-factor interactions	t = 12		t = 18		t = 24	
	Adj. MS	% of total	Adj. MS	% of total	Adj. MS	% of total
	1.17	0.41	6.6	2.32	20.53	7.69

The model is good, $R^2 = 99.35$ and the residuals are random normal with p = 0.896 (Fig. 6.17).

AOI($L_{27}(3^{4-1},2^3+1)$) data are in Appendix 6.4. Table 6.23 summarizes the ANOVA statistics for the three time periods t = 12, 18 and 24. All factors are strong predictors of the outcome of AOI except for price**cogs* at t = 12.

Table 6.24 summarizes the overall impact of the three two-factor interactions.

As in the case of $L_{81}(3^{4-1},2^3+1)$, the intensity of the interactions increase over time in our $L_{27}(3^{4-1}, 2^3+1)$. This phenomenon is due to the presence of stocks in the system dynamics model. Stocks accumulate content of flows and have a tendency to delay effects in the model (See Sect. 6.4.2.1).

Findings

The AOI($L_{27}(3^{4-1},2^3+1)$) model is good. All the controllable variables (*r&d, manufacturing yield, cogs*, and *product price*) are strong predictors of the AOI ($L_{27}(3^{4-1},2^3+1)$) outcomes, with strong p values, $p \ll 0.05$. There are three 2-fi, *yield*cogs, yield*price* and *cogs*price*. Only *cogs*price* has a weaker p value of p = 0.06 for t = 12. But the contribution of the interactions to the overall model is small. AOI($L_{27}(3^{4-1},2^3+1)$) model a near decomposable representation (Simon 1997, 2001). The structure of the AOI($L_{27}(3^{4-1},2^3+1)$) model exhibits the properties of sparsity, hierarchy and inheritance. The controllable variables and the one interaction explain a large percentage of the variations. R^2adj = 99.79% at t = 12, R^2adj = 96.08% at t = 18 and R^2adj = 94.70% at t = 24.

Table 6.25 AOI($L_{27}(3^{4-1}$, 2^3+1)) response table for and stdev for t = 12

Response Table for Means t = 12					Response Table for Std Deviations				
Level	r&d	yield	*cogs*	price	Level	r&d	yield	*cogs*	price
1	56.27	53.13	58.29	51.34	1	7.331	7.163	7.531	7.060
2	55.70	55.69	55.84	56.26	2	7.390	7.412	7.297	7.372
3	55.28	58.43	53.11	59.65	3	7.309	7.455	7.202	7.598
Delta	0.99	5.29	5.18	8.30	Delta	0.080	0.291	0.329	0.539
Rank	4	2	3	1	Rank	4	3	2	1

6.4.3.2 Syntheses

The data from our AOI(($L_{27}(3^{4-1}$,2^3+1)) shows there is support our choice of controllable variables. With this support, we now take the next step to construct decision alternatives.

Using the AOI($L_{27}(3^{4-1}$,2^3+1)) response tables, we can design decisions to explore the solution space to design and engineer robust decisions for a satisficing AOI outcome and improved standard deviation from the current state of BAU. Table 6.25 shows the response tables for t = 12. The tables for t = 18 and t = 24 are in Appendix 6.5. Table 6.25 has two parts. On the left, Response Table for Means, are the predicted responses for each level of the controllable variables. For example, *yield* level 3 has value 58.43. On the right, Response Table for Std. Deviations, are the associated standard deviations for the responses on the left. For example, *yield* level 3 with value 7.455.

Having this information is very useful to design robust decision alternatives. For it tells us that if we specify a design with the *price* variable at level-3, the standard deviation for that outcome will be the highest among the levels for *price* implying the highest risk. This same information is in graphical form in Fig. 6.18. The information for t = 18 and 24 are in Appendices 6.6 and 6.7.

"Delta" in Table 6.25 is the difference between the highest and lowest responses, for a given variable. "Rank" orders the variables by Delta. For example, Rank 3 identifies *cogs* as the third in influence on the output. Inspection of the left-hand-sides (LHS) of Table 6.25 and Fig. 6.18 reveals that *product price* is the dominant contributing factor to the outcomes of AOI(L_{27}); it has rank 1 from both a response of main effects and from the standard deviation.

Table 6.25, Fig. 6.18 and Appendices 6.4, 6.5, 6.6 for AOI(L_{27}) present us with sufficient information to design any decision alternative located anywhere in the Solution Space with a standard deviation we can predict. As designer of alternatives, we can trade off outcome with risk, i.e. standard deviation, if we so desire. In the remainder of this section, we will demonstrate a systematic process to design decisions with these attributes. This the process of **synthesis**.

Appendix 6.4 is the AOI($L_{27}(3^{4-1}$,2^3+1)) at t = 12 in the **o**utput Space, the Cartesian product of the controllable space with the uncontrollable space, Eq. (6.3). The column $\bar{y}_\alpha$, $1 \leq \alpha \leq 27$, is the average values under the set of uncertainty regimes and σ_α is the standard deviation. From the LHS panel of Table 6.25 and

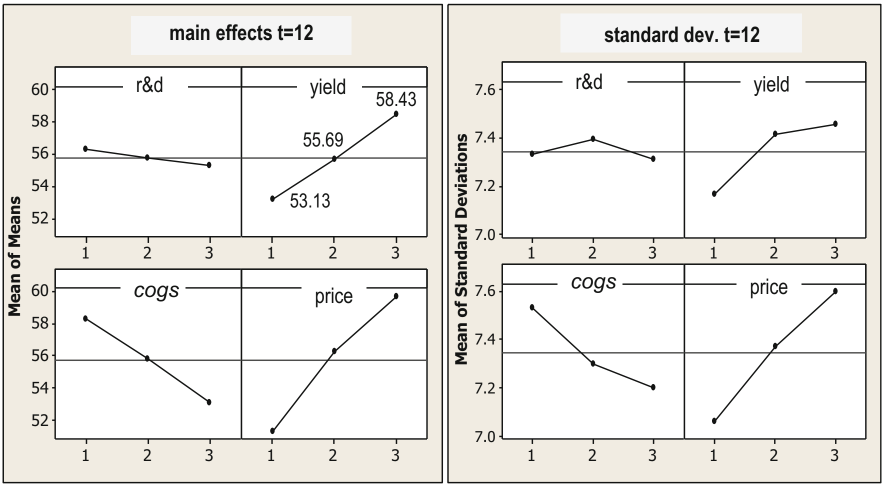


Fig. 6.18 AOI($L_{27}(3^{4-1}$, 2^3+1)) plots for response and stdev at t = 12 under (2,2,2)

Fig. 6.18 we hypothesize that experiment (1,3,1,3) produces the highest AOI ($L_{27}(3^{4-1},2^3+1)$), i.e. *r&d* at level-1 (highest *r&d budget*), *manufacturing yield* at level-3 (highest), product cost *(cogs)* at level-3 (lowest), and highest *product price* at level-3 (highest). And by inspection, L_{81} Table data, in Appendix 6.1, tells us AOI(L_{27}(1,3,1,3),(222)) = \$64.529 M at t = 12. (1,3,1,3) is the decision specification that produces the highest AOI.

But can we predict it? We can predict the outcome using the Analysis of Means (ANOM) by means of Eq. (6.10) (e.g. Phadke 1989; Wu and Wu 2000).

$$\begin{aligned}\mathrm{AOI}(\mathrm{L}_{27}(1{,}3{,}1{,}3),(222)) &= \mathrm{m} + \left(\mathrm{m} - r\&d^1\right) + \left(\mathrm{m} - yield^3\right)\\ &\quad + \left(\mathrm{m} - cogs^1\right) + \left(\mathrm{m} - price^3\right)\end{aligned} \tag{6.10}$$

where the superscripts denote the level of the variable. For example, $r\&d^2$ is the value of *r&d* at level 2. From the LHS of Table 6.25, $r\&d^2 = 55.69$. And,

$$\begin{aligned}\mathrm{m} &= average(r\&d\,\text{responses}) = 1/3(56.27 + 55.70 + 55.28)\\ &= 55.750 \text{ at } \mathrm{t} = 12 = average(yield\,\text{responses})\\ &= average(cogs\,\text{responses}) = average(price\,\text{responses}) \quad = 55.750.\end{aligned} \tag{6.11}$$

Using Eq. (6.10), we get for AOI(L_{27}(1,3,1,3),(222)):

$$\begin{aligned}\mathrm{AOI}(\mathrm{L}_{27}(1{,}3{,}1{,}3),(222)) &= 55.75 + \left(r\&d^1 - 55.75\right) + \left(yield^3 - 55.75\right)\\ &\quad + \left(cogs^1 - 55.75\right) + \left(price^3 - 55.75\right)\\ &= 55.75 + (56.27 - 55.75) + (58.43 - 55.75)\\ &\quad + (58.29 - 55.75) + (59.65 - 55.75) = \$65.393\,\mathrm{M}\end{aligned}$$

This is a fundamental procedure in our methodology. We can predict the outcome of any decision alternative that has been designed. As the AOI (L_{27}(1,3,1,3),(222)) case illustrates, the predictions are persuasive. Our Gold Standard of AOI(L_{81}(1,3,1,3),(222)) tells us the AOI outcome is $64.529.1 M. Our calculations predict $65.393 M at $t = 12$.

But, can we **predict the standard deviation** of the AOI(L_{27}(1,3,1,3),(222)) outcome? The answer is in the affirmative. The procedure is not as direct as Eq. (6.10). We must make a simple detour. Table 6.25 shows standard deviations at $t = 12$. Standard deviations are not additive; but variances are additive. Variance is defined as: $variance = (stdev)^2$. Therefore we can simply transform the stdevs to variances, $\boldsymbol{\nu}$, and apply our analyses-of-means approach as before. We get a quantity for variance. Take the root of that quantity to get the stdev. We first calculate $\boldsymbol{\nu}$,

$$\begin{aligned}\boldsymbol{\nu} &= average(r\&d \text{ variances}) = 1/3(53.74 + 54.61 + 53.42) = 53.93\\ &= average(yield \text{ variances}) = average(cogs \text{ variances})\\ &= average(price \text{ variances}) = 10619.46\end{aligned}$$

Then using the analyses-of-means, the *variance* (AOI(L_{27}(1,3,1,3),(222))) =

$$\begin{aligned}&= 53.93 + \left(\boldsymbol{\nu}\mathrm{r\&d}^1 - 53.93\right) + \left(\boldsymbol{\nu}yield^3 - 53.93\right) + \left(\boldsymbol{\nu}cogs^1 - 53.93\right)\\ &\quad + \left(\boldsymbol{\nu}price^3 - 53.93\right)\\ &= 53.93 + (53.74.35 - 53.93) + (55.58 - 53.93) + (56.72 - 53.93)\\ &\quad + (57.73 - 53.93) = 61.91\end{aligned}$$

Therefore, stdev = $\sqrt{61.91}$ = **7.87**.

The standard deviation of the decision design for the (1,3,1,3) output is also higher than each of the individual standard deviations of the highest levels of the controllable variables. This is a case where the stdevs of “stack up”.

This is a second key procedure in our methodology. **We can predict the standard deviation of any decision alternative that has been designed.**

As the AOI(L_{27}(1,3,1,3),(222)) case illustrates, the predictions for standard deviations are also persuasive. Our Gold Standard in Appendix 6.1 for AOI (L_{81}(1,3,1,3),(222)) tells us the AOI outcome’s stdev is 7.84. Our calculations predict 7.87.

The quintessential question of the prudent executive question is: Can we design a decision alternative that has a satisficing output and is also less risky, i.e. with a lower standard deviation? We seek a **robust design**.

To improve robustness, make the response have less variation. We direct our attention to the variables *r&d* and *cogs* (RHS Fig. 6.18). Instead of the (1,3,1,3) design, we adopt a “greedy cheap-skate strategy” of a (2,2,3,3) design. In other words, *r&d* at the medium level-2, keep *manufacturing yield* at the current level-2 to not pressure *r&d*, drive *cogs* down to the lowest level-3 through belt tightening, but consistent with greed, raise *price*s. Predicted output is:

$$\begin{aligned}&\mathrm{AOI}(\mathrm{L}_{27}(2,2,3,3),(222)) =\\ &\quad= 55.75 + \left(\mathrm{r\&d}^2 - 55.75\right) + \left(\mathit{yield}^2 - 55.75\right) + \left(\mathit{cogs}^3 - 55.75\right) + \left(\mathit{price}^3 - 55.75\right)\\ &\quad= 55.75 + (55.70 - 55.75) + (55.69 - 55.75) + (53.11 - 55.75) + (59.65 - 55.75)\\ &\quad= \$56.903\,\mathrm{M}\end{aligned}$$

The *variance* (AOI(L_{27}(2,2,3,3),(222)) is given by:

$$\begin{aligned}\mathit{variance}\left(\mathrm{AOI}(\mathrm{L}_{27}(2,2,3,3),(222))\right) &= \boldsymbol{\nu} + \left(\boldsymbol{\nu}\mathrm{r\&d}^2 - \boldsymbol{\nu}\right) + \left(\boldsymbol{\nu}\mathit{yield}^2 - \mu\right)\\ &\quad+ \left(\boldsymbol{\nu}\mathit{cogs}^3 \ - \boldsymbol{\nu}\right) + \left(\boldsymbol{\nu}\mathit{price}^3 - \boldsymbol{\nu}\right)\\ = 53.93 + (54.61 - 53.93) + (54.94 - 53.93) &+ (51.87 - 53.93)\\ \quad + (57.73 - 53.93) = 157.29 &\end{aligned} \tag{6.12}$$

Therefore, stdev = √57.29 = **7.57** at t = 12.

This is a third key procedure in our methodology. We can design decision alternatives that can satisfice and have less risk. These are the decision alternatives that are more robust.

AOI(L_{27}(2,2,3,3),(222)) = \$56.903 M is less than AOI(L_{27}(1,3,1,3),(222)) = \$65.393 M. But it is also less risky. *Stdev*(AOI(L_{27}(2,2,3,3),(222))) = 7.57, which is less than the best alternative that has stdev(AOI(L_{27}(1,3,1,3),(222))) = 7.87.

Using the above procedures, we get the following for AOI(L_{27}(2,2,2,2),(222)), the BAU:

$$\begin{aligned}\mathrm{AOI}(\mathrm{L}_{27}(2,2,2,2),(222)) &= \$56.243\,\mathrm{M}\ \text{and}\,\mathrm{stdev}(\mathrm{AOI}\ (\mathrm{L}_{27}(2,2,2,2),(222)))\\ &= 7.57\end{aligned}$$

And for the worst AOI(L_{27}(3,1,3,1),(222)), we get:

$$\begin{aligned}\mathrm{AOI}\ (\mathrm{L}_{27}(3,1,3,1),(222)) &= \$45.61\ \ \text{and}\ \ \mathit{stdev}(\mathrm{AOI}(\mathrm{L}_{27}(3,1,3,1),(222)))\\ &= 6.68\end{aligned}$$

We take a slight pause and briefly summarize the key points of this section.

- This section is about designing decision alternatives that will produce an intended outcome.
- The decision alternative is expressed as a decision specification. The specification has two parts.
- One part, is a configuration of controllable variables, each of which is specified at a level. The second part is a configuration of uncontrollable variables, each of which is also specified at a level.
- To simplify the discussion, we have considered the configuration of the uncontrollable variables to remain as-is at their current levels. In other words, we temporarily suspended considering different uncertainty regimes.

- We use the orthogonal array L_{27} array of 27 rows. Each row represents a decision alternative, which is used to experiment. From experiment we can calculate the AOI, annual operating income, of the firm. In this section, these values have been obtained from simulations of the ADI surrogate.
- The structure, of this array of 27 rows of alternative decision specifications, is not an arbitrarily constructed array, but it is a statistically rigorous framework. It is grounded on rigorous and proven mathematical statistical methods. It is an orthogonal array from which we calculate predictions over the entire solution space.
- From this set of 27 experiments, we can systematically make predictions about outcomes of any different configurations, which are **not** included in the 27. This is an extremely useful capability, for we can now predict the outcome of any decision specification.
- In addition, we can also predict the mean and the standard deviation of the data of any decision alternative. We use the response Table 6.25 and Fig. 6.18. We follow the widely accepted approach of using the standard deviation of a predicted outcome as a proxy for risk. Because the wider the spread of a possible outcome the less likely you may get what you want; it is more risky.
- These statistical insights permits us to construct any decision alternative of any configuration of controllable variables. Executives can specify any hypothetical alternative, predict its outcome, under any uncertainty regime. In this way, executives can explore the entire Solution Space, without any constraints.
- These statistical insights also give us the ability to know the uncertainty of any decision specification, by predicting its standard deviation, as a proxy for risk.
- We showed in detail how to construct alternatives endowed with two key attributes. One is a desirable outcome. Two is, design alternatives with a predictable uncertainty, i.e. standard deviation. These two tasks when integrated, constitute the method of ***engineering robust decision-alternatives***.
- As concrete examples, we showed how to design and engineer decisions for the BAU, for the worse design, for the best design, and the improved-BAU design. We showed how to calculate their predicted outcomes.
- There are two unstated and untested assumptions. One is that there are other decision alternatives, which produce more desirable results, and which are also less risky. The other is the converse, *viz.* there are worse alternatives that produce less desirable results with also more risk. We can state and show that these kinds of alternatives exist and can be designed. The following two plots, Figs. 6.19 and 6.20 are examples that illustrate this assertion.

Now we try to put together a while view of what we have learned. Figure 6.19 is a plot of AOI versus standard deviation for all points of the L_{27} experiments. We added the *best* AOI(L_{27}(1,3,1,3),(222)), *worst* AOI(L_{27}(3,1,3,1),(222)), BAU experiment of AOI(L_{27}2,2,2,2),(222)), and an equidistant *midpoint* between the *bes*t and *worst* experiment. We define *best* as the design that based on the controllable variables' configuration, we judge will produce the highest AOI, independent of the magnitude of the standard deviation. *Worst* is analogously defined as the decision specification that based on the configuration of the controllable variables,

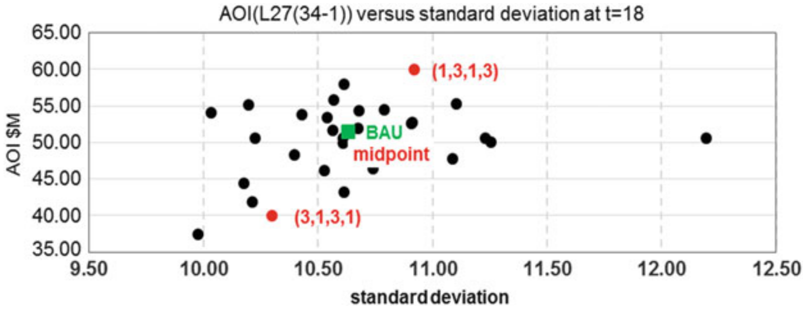


Fig. 6.19 L_{27} experiments with the *best, worst* AOI and *midpoint* experiments at t = 12

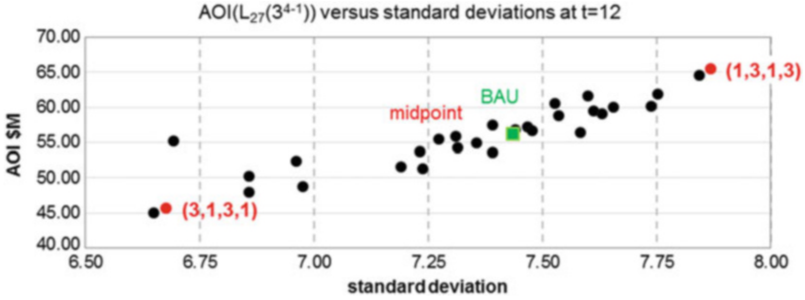


Fig. 6.20 L_{27} experiments with the *best, worst* AOI and *midpoint* experiments at t = 18

we judge will produce the lowest AOI. The plots clearly demonstrate that there are many alternatives that can be designed to produce near or better results than BAU. Likewise, there are other worse alternatives.

Of course, there are many more alternatives can be constructed beyond the 27 of the L_{27} array (e.g. Montgomery 2001; Otto and Wood 2001). Executives do not have to settle for the status quo. Alternatives above and to the left of the midpoint are better alternatives. The have better AOI outcomes and lower risk. It is interesting to note that there is an alternative at the bottom of the left-hand corner of Fig. 6.19 that has a lower AOI than our purported worst. Possibly interactions among the variables both controllable and uncontrollable cause this phenomenon. This case shows the value of the ability to explore and predict outcomes of different decision designs. Notably BAU outperforms the midpoint in both outcome and standard deviations.

Figure 6.20 is similar to Fig. 6.19, but at t = 18. It also demonstrates the existence of alternative designs that are superior to the BAU alternative and alternatives that are inferior as well. Both examples illustrated in Figs. 6.19 and 6.20 highlight the utility and importance of having the ability to design decision alternatives that can cover the entire solution space, to predict their outcomes, and to predict their standard deviation as a proxy for risk.

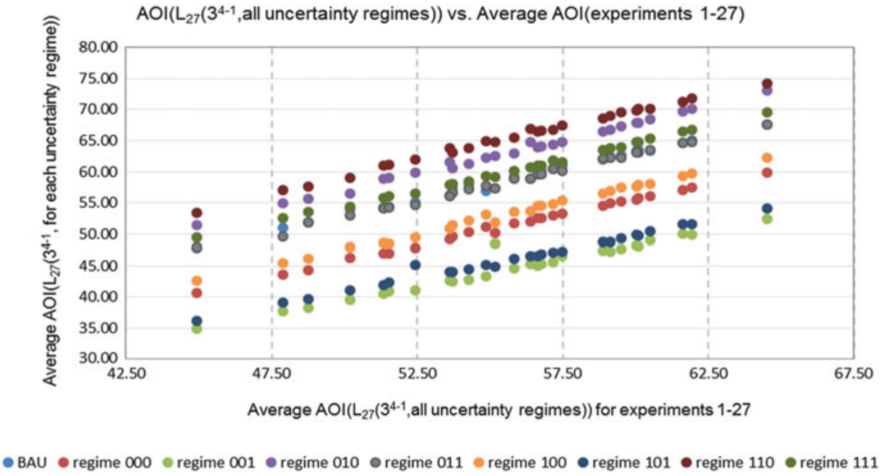


Fig. 6.21 AOI(L27(3^{4-1}, all uncertainty regimes)) versus Average AOI(experiment 1–27) for t = 12

The next topic is ***uncertainty*** and its effect on AOI. Uncertainty is inexorably and inextricably connected in all decisions. “Uncertainty appears as the fundamental problem for complex organizations, and coping with uncertainty, as the essence of the administrative process (Thompson 2004, 159).”

We take a closer look at the set of uncertainty regimes. From Appendix 6.4 data, we add the responses of each column of outputs for each uncertainty regime, this is labeled as “Σexpmt output”. These are identified in Table 6.26.

We have discretized the uncertainty spectrum into a monotonically increasing set of uncertainty regimes. This is illustrated graphically in Fig. 6.21. On the vertical axis is the average of AOI(L_{27}(3^{4-1}, for each uncertainty regime)) including the BAU. Hence there are nine data points for each vertical column. Since we have 27 experiments in a L_{27}, there are 27 vertical columns. These plots show that the range of decision alternatives is very broad and they span over the range of uncertainty regimes.

The AOI(L_{27}(1,3,1,3),(222)) output for the three time periods are shown in Table 6.27 where we also show a comparison of the **derived** values for AOI (L_{27}(1,3,1,3),(222)) versus the values from our “gold standard” the AOI(L_{81}(3^4, 2^3+1)). The AOI(L_{27}(3^{4-1},2^3+1)) were calculated using the procedures discussed in this section. The |%Δ| differences of L_{27} versus L_{81} are small, average of 3.4%. The predicted values compare favorably with our “gold standard”. The correlation is 99%. These data are support for the ability of our method for predicting the output of decision designs.

Findings

Significantly, we have demonstrated how to design any decision alternative and how to predict its outcome and its standard deviation, which is a measure of its

Table 6.26 Sum of y-bar for current state of uncertainty and each uncertainty regime at t = 12

	Uncertainty regimes								Uncontrollable variables
Current	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	• Industry growth
Current	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	• ADI orders
Current	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	• Competitors
	000	**001**	**010**	**011**	**100**	**101**	**110**	**111**	
BAU	…	Worst case	…	…	…	…	Best case		
4775.98	**4170.08**	**3617.65**	**5115.92**	**4753.76**	**4330.98**	**3736.43**	**5300.54**	**4884.83**	**Σexpmt output**
	3	**1**	7	5	4	2	**8**	6	***r***: 1 ≤ order ≤ 8

Table 6.27 AOI for t = 12, 18, and 24, L_{27} versus L_{81}

Period	Experiment	AOI($L_{27}(3^{4-1}, 2^3+1)$)	AOI($L_{81}(3^4, 2^3+1)$) Firm annual op. income by inspection gold standard	$\lvert\%\Delta\rvert$ of $[L_{27} - L_{81}]/L_{81}$
t = 12	1,3,1,3	\$65.39 M	\$64.53 M	1.3%
t = 18	1,3,1,3	\$59.89 M	\$57.94 M	3.4%
t = 24	1,3,1,3	\$51.27 M	\$48.58 M	5.5%
		Conf. interval (46,56)	Conf. interval (48,57)	
				Average = 3.4%

uncertainty. The predicted outcomes of the hypothesized best experiment of AOI (L_{27}((1,3,1,3)) experiments yield results that are close at t = 12 to the "gold standard" for AOI(L_{81}((1,3,1,3),(2,2,2))), but the predictions drift slightly apart for t = 18, and for t = 24. Because the model AOI(L_{27}((1,3,1,3)) is of lower fidelity than the equivalent L_{81} model, the three 2-fi interactions that were evident for the L_{81} model are not all visible with the L_{27} model. However, the predicted results for the maximum AOI are very close to the gold standard. We judge that the more parsimonious L_{27} model is useful in predicting results, albeit with some loss of information about the interactions. They are derived values that are all within the 95% CI. The contributions of the interactions, which are no longer visible, are small. We judge the functionality of the L_{27} model to be good.

6.4.3.3 $\mathcal{R}$\{AOI($L_{27}(3^{4-1},2^3+1)$)\} = The Rotated AOI($L_{27}(3^{4-1},2^3+1)$) Space

The analysis of rotated space $\mathcal{R}$\{AOI($L_{27}(3^4,2^3+1)$)\} proceeds as in Sect. 6.4.2. The ANOVA statistics of this rearranged space $\mathcal{R}$\{AOI($L_{27}(3^4,2^3+1)$)\} (Table 6.28), show all uncontrollable variables are strong predictors of the AOI outcomes with $p \ll 0.05$. Data for t = 18, 24 appear in Appendix 6.7. The residuals at t = 12 have mean ≈0(−2.66E-15) with stdev = 0.632, they are normal and do not carry information, N(0,0.632) with $p > 0.05$. The residuals at t = 18 are also acceptable with p = 0.007. However at t = 18, 24 the residuals do not behave as well, p = 0.05

Table 6.28 $\mathcal{R}$\{AOI($L_{27}(3^{4-1},2^3+1)$)\} at t = 12 for uncontrollable variables

Analysis of Variance. AOI $L_{81}(3^4, 2^3+1)$ t = 12						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
LT growth	1	6.76	6.76	6.76	9.67	0.036
ADI orders	1	336.08	336.08	336.08	480.84	0.000
Competitor	1	70.59	70.59	70.59	101.00	0.001
Error	4	2.80	2.80	0.70		
Total	7	416.22				
S = 0.836030, R-Sq = 99.33%, R-Sq(adj) = 98.82%						

Table 6.29 $\mathcal{R}\{\text{AOI}(L_{27}(3^{4-1},2^3+1))\}$for t = 12, 18, and 24

Rotated $L_{27}(3^{4-1},2^3+1)$						
	t = 12		t = 18		t = 24	
Factors	Adj. MS	p value	Adj. MS	p value	Adj. MS	p value
Industry long term growth	6.76	0.033	45.76	0.001	100.04	0.001
ADI orders	336.08	0.000	593.7	0.000	592.22	0.000
Competitors' attractiveness	70.59	0.000	205.67	0.000	298.72	0.000
Error	0.70	–	0.81	–	1.46	–

and 0.012 respectively. We surmise that there are not enough degrees of freedom as in the L_{81} case. There is support for the statistical significance of the uncontrollable variables for AOI($L_{27}(3^{4-1},2^3+1)$) at t = 12 and qualified support at t = 18 and 24. Summary are shown in Table 6.29.

Findings

Previously, we found that data for the **controllable** variables *vis à vis* AOI ($L_{27}(3^{4-1},2^3+1)$) support construct validity. They are strong predictors of the outcome. In this section, we explore whether the same is true for the **uncontrollable** variables. Again, we "rotate" the positions of the controllable variable and the uncontrollable variables of the $L_{27}(3^{4-1},2^3+1)$ array. The ANOVA table for that construct is shown in Table 6.28 and Appendix 6.6. There is support for the statistical significance of the uncontrollable variables for AOI($L_{27}(3^{4-1},2^3+1)$ at t = 12 and qualified support at t = 18 and 24.

6.4.3.4 Summary of the AOI($L_{27}(3^{4-1},2^3+1)$)

The original questions in Sect. 6.4.3 were:

- Can we design robust decision alternatives?
- Will the results be consistent with our "gold standard"

We can now confidently answer all the questions in the affirmative. *Most significantly, we have shown the systematic design synthesis for robust decisions.*

We populated the AOI($L_{27}(3^{4-1},2^3+1)$) orthogonal array using a full factorial noise array to be able to address the uncertain environments of the decision. The ANOVA tables for **both** the controllable variables **and** uncontrollable variables support our belief that they are strong predictors of the output of AOI. The data indicate the presence of three statistically significant 2-fi of controllable variables, but their total contribution to the outcome of AOI is small (Table 6.23).

For decision-making, we are able to design the hypothesized decision that yields the maximum AOI for each of the time periods of t = 12, 19, and 24. Except for t = 24, using the $L_{27}(3^{4-1},2^3+1)$, the treatments that yield the maximum AOI are identical to the one revealed by the L_{81} full factorial array. There at t = 12, although the treatments are different, their AOI values are within each other's 95% CI (Table 6.27). In addition, we know precisely the extent to which each controllable and uncontrollable variable contributes to AOI (Table 6.28 and Appendix 6.6). And we find that each variable's (controllable and uncontrollable) relative contribution to AOI remains consistent between L_{81} and L_{27} and the time periods t = 12, 18, and 24.

6.4.4 Solution Space for AOI($L_9(3^{4-2},2^3+1)$)

6.4.4.1 Analyses of AOI($L_9(3^{4-2},2^3+1)$)

The key questions we will be investigating in this section are:

- Can we design robust decision alternatives?
- Will the results be consistent with our "gold standard"

These are the same questions of Sects. 6.4.2 and 6.4.3. We will continue to use AOI(($L_{81}(3^{4-2},2^3+1)$) full factorial as our gold standard. In Sect. 6.4.3 we used AOI (($L_{27}(3^{4-2},2^3+1)$). We will now use a very lean and parsimonious model, AOI (($L_9(3^{4-2},2^3+1)$). This is the simplest orthogonal array we can use. Simpler experiments are noteworthy because they imply lower cost and are simpler to perform.

First, we want to know whether analysis of the AOI($L_9(3^{4-2},2^3+1)$) will continue to support the predictive power for our outputs as in the previous chapter using our controllable variables, under a variety of uncertainty regimes. Second, we want to know whether our designed decision specifications have the predictive power that is consistent with our "gold standard" and our L_{27} experiments. This is important because if so, it will demonstrate an overall consistent functionality of our methodology. An L_9 array does not have enough degrees of freedom (dof's) to obtain the F statistic and p values for four controllable variables. Therefore, we add two experiments to our $L_9(3^{4-2},2^3+1)$ array as shown in Appendix 6.8. We denote this new array as $\boldsymbol{L}'_9(3^{4-2},2^3+1)$. The array is *nearly orthogonal*).

Table 6.30 summarizes the ANOVA statistics for each of the time periods ending at t = 12, 18, and 24. Details are in Appendix 6.9. Overall, the AOI($\boldsymbol{L}'_9(3^{4-2}$,

Table 6.30 AOI($L'_9(3^{4-2}+2,2^3+1)$) summary for t = 12, 18, and 24

AOI($L'_9(3^{4-2}+2,2^3+1)$)						
	t = 12		t = 18		t = 24	
Factors	Adj. MS	p value	Adj. MS	p value	Adj. MS	p value
r&d	1.415	**0.085**	6.37	0.050	22.317	**0.058**
Yield	21.68	0.006	16.445	0.020	11.824	**0.104**
cogs	23.784	0.006	23.632	0.014	22.697	0.057
Product price	55.067	0.002	56.854	0.006	36.524	0.036
Error	0.132	–	0.337	–	1.375	–

Table 6.31 Comparison of p values of AOI($L_{27}(3^{4-1},2^3+1)$) versus AOI($L'_9(3^{4-2}+2,2^3+1)$)

	t = 12		t = 18		t = 24	
	L_{27}	**L'_9**	**L_{27}**	**L'_9**	**L_{27}**	**L'_9**
Factors	p value	p value	p value	p value	p value	p value
r&d	0.000	0.085	0.002	0.050	0.003	0.058
Manufacturing yield	0.000	0.006	0.000	0.020	0.001	0.104
cogs	0.000	0.006	0.000	0.014	0.001	0.001
Product price	0.000	0.002	0.000	0.006	0.000	0.000
Yield**cogs*	0.003	–	0.017	–	0.014	–
Yield*price	0.029	–	0.033	–	0.021	–
Price**cogs*	**0.060**	–	0.038	–	0.044	–
Error	–	–	–	–	–	–

2^3+1)) is a low fidelity model. At t = 12 *r&d* is not a strong predictors of the AOI outcome. At t = 18 and 24 it is only an adequate predictor of the AOI outcome with p = 0.05 and p = 0.058 respectively. At t = 18, *cogs* is not statistically significant. At t = 24, only *product price* is statistically significant.

The statistical significance of the controllable variables and their interactions for the L_{27} model and L'_9 model show a sharp contrast (Table 6.31). The interactions are clearly visible in the L_{27} model. The p values of the L'_9 are less significant than in the L_{27} model. The AOI($L'_9(3^{4-2},2^3+1)$) is a low fidelity model. The model is to be used with caution for t = 18, and not advisable for t = 24. The model is excessively lean and parsimonious.

6.4.4.2 Synthesis in the AOI (L_9 (uncertainty regimes)) Space

We proceed to test our decision synthesis procedure to determine the extent to which our low fidelity model can predict outcomes. *We now revert to our* $L_9(3^{4-2},2^3+1)$. The response tables for t = 12 are shown in Table 6.32. The LHS shows the means for the main effects and the RHS for the standard deviations. Figure 6.22 shows these tables as graphs. (Data for t = 18 and t = 24 are in Appendix 6.11)

The LHS panels of Fig. 6.22 and Table 6.32 suggest that experiment (1,3,1,3) produces the highest AOI($L_9(3^{4-2},2^3+1)$), i.e. *r&d* at level 1 (highest *r&d budget*),

Table 6.32 AOI($L_9(3^{4-2},2^3+1)$) response table for stdev at t = 12

Response Table for Means t = 12					Response Table for stdev t = 12				
Level	r&d	yield	*cogs*	price	Level	r&d	yield	*cogs*	price
1	56.55	53.37	58.27	51.54	1	7.383	7.070	7.409	7.086
2	55.58	55.52	56.01	55.95	2	7.320	7.347	7.403	7.316
3	55.17	58.42	53.02	59.82	3	7.283	7.569	7.174	7.584
Delta	1.38	5.06	5.25	8.28	Delta	0.100	0.499	0.235	0.498
Rank	4	1	3	2	Rank	4	3	2	1

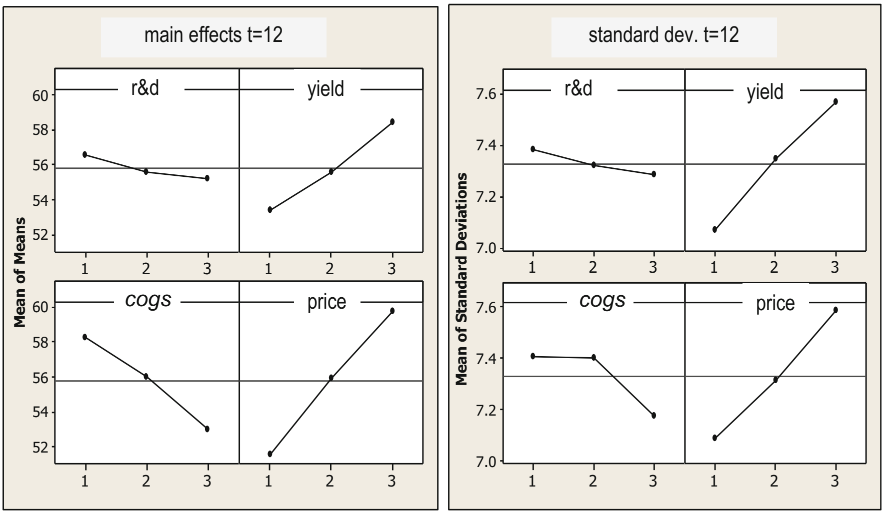


Fig. 6.22 AOI($L_9(3^{4-2}, 2^3+1)$) graphs for response and stdev at t = 12

manufacturing yield at level 3 (highest), product cost (*cogs*) at level 3 (lowest), and highest *product price* at level 3 (highest). These are the points (1,3,1,3) which can produce the highest AOI($L_9(3^{4-2},2^3+1)$). But what is its predicted value? The predicted the value is:

$$\mathrm{AOI}(\mathrm{L}_9(1,3,1,3),(222)) = \mathrm{m} + \left(\mathrm{m} - r\&d^1\right) + \left(\mathrm{m} - yield^3\right) + \left(\mathrm{m} - cogs^1\right) + \left(\mathrm{m} - price^3\right)$$

where the superscripts denote the level of the variable, e.g. $r\&d^2$ is the value of r&d at level-2 from the LHS of the response table. Thus, for example, $r\&d^1 = 56.55$ at t = 12.

$$\begin{aligned}\mathrm{m} &= \mathrm{average}(r\&d\,\mathrm{responses}) = 1/3(56.55 + 55.58 + 55.17) = 55.77 \text{ at t} = 12\\ &= \mathrm{average}(yield\,\mathrm{responses}) = \mathrm{average}(cogs\,\mathrm{responses})\\ &= \mathrm{average}(price\,\mathrm{responses}) = 55.77\end{aligned}$$

To get for AOI(L_{27}(1,3,1,3),(222)) =

$$\begin{aligned}&= 55.77 + (\mathrm{m}^1{}_{\mathrm{r\&d}} - 55.77) + \left(\mathrm{m}^3{}_{\mathrm{yield}} - 55.77\right) + \left(\mathrm{m}^1{}_{cogs} - 55.77\right) + \left(\mathrm{m}^3{}_{\mathrm{price}} - 55.77\right)\\ &= 55.77 + (56.55 - 55.77) + (58.42 - 55.77) + (58.27 - 55.77)\\ &\quad + (59.82 - 55.77) = \$65.75\,\mathrm{M}\end{aligned}$$

AOI($L_9(3^{4-2},2^3+1)$) relative to our "gold standard" AOI($L_{81}(3^4,2^3+1)$) is shown in Table 6.33. We derive the hypothesized maximum AOI experiments (Table 8.11). Using our array $L_9(3^{4-2},2^3+1)$ for t = 24, we derive the identical treatment (1,3,2,3)

Table 6.33 AOI for t = 12, 18, and 24, L_9 versus L_{27} and L_{81}

		Annual operating income (AOI)				
		AOI(L_{81})	AOI(L_{27})	AOI(L_9)		
	Experiment	by inspection gold standard	Derived	Derived	$\lvert[\mathrm{AOI}(L_{27})\text{-}\mathrm{AOI}(L_{81})]\rvert/\mathrm{AOI}(L_{81})$	$\lvert[\mathrm{AOI}(L_9)\text{-}\mathrm{AOI}(L_{81})]\rvert/\mathrm{AOI}(L_{81})$
t = 12	1,3,1,3	\$64.53 M	\$65.39 M	\$65.75 M	1.3%	1.8%
t = 18	1,3,1,3	\$57.94 M	\$59.89 M	\$60.56 M	3.4%	4.5%
t = 24	1,3,1,3	\$48.88 M	\$51.27 M	\$52.42 M	5.5%	7.2%
					Average = 3.4%	Average = 4.6%
t = 24	$\alpha = 0.05$	(48,57)	(46,56)	(46,62)		

revealed by $L_{81}(3^4,2^3+1)$. Recall that the revealed maximum of $L_{81}(3^4,2^3+1)$ and the derived maximum from $L_{27}(3^{4-1},2^3+1)$ are different but within each other's 95% CI ($\alpha = 0.05$). The derived value from the $L_9(3^{4-2},2^3+1)$ for the hypothesized maximum AOI(1,3,1,3) is "close" to its counterparts L_{27} and L_{81}.

The RHS of Fig. 6.22 shows the standard deviations of AOI($L_9(3^{4-2},2^3+1)$) output responses at t = 12. Thus we can predict standard deviations of designed alternatives. Since standard deviations are ***not*** additive, but variances are additive, we calculate the variances first. Then using means analyses, we predict the variances, which we then convert to standard deviations $\boldsymbol{v}$.

Using ANOM, the variance of $\boldsymbol{v}$ (AOI(L_9(1,3,1,3),(222))) is given by:

$$\begin{aligned}\boldsymbol{v}\big(\mathrm{AOI}(L_9(1,3,1,3),(222)\big) &= \mu + (v^1{}_{r\&d} - \mu) + \left(v^3{}_{yield} - \mu\right) + \left(v^1{}_{cogs} - \mu\right)\\ &\quad + \left(v^3{}_{price} - \mu\right) = 53.93 + (53.74 - 53.93) + (55.58 - 53.93)\\ &\quad + (56.72 - 53.93) + (57.73 - 53.93) = 61.980\end{aligned}$$

Therefore, stdev = $\sqrt{}61.980 = 7.87$ at t = 12.

Table 6.33 shows that AOI(L_9(1,3,1,3),(222)) and AOI(L_{27}(1,3,1,3),(222)) the predicted outcomes are close. Is still true for other decision designs? There is support for the assertion that the answer is affirmative. We picked 12 experiments from AOI(L_{27}) then we predicted their outcomes and standard deviations using the AOI(L_{27}) response tables data and the ANOM procedure. We then went through the exact same steps for AOI(L_9). The results are plotted in Fig. 6.23. The AOI(L_{27}) points are in red, and the AOI(L_9) points are shown in blue. The trend line, which takes into account both L_9 and L_{27} points, shows $R^2 = 95\%$. The correlation between the AOI(L_{27}) and the AOI(L_9) data sets shows a correlation of 99%. The predictive power of AOI(L_9) is good, but we are unable to detect the presence of the 2-fi of *yield*cogs* and *yield*price*. The AOI(L_9) model is a *low-resolution* model, with corresponding *lower fidelity*.

Findings

Using the $L_9(3^{4-2},2^3+1)$ we are able to design the experiment that we surmise yields the maximum AOI. The experimental result is nearly identical to the one revealed by the L_{81} full factorial array and derived values (Table 8.11). Notably we

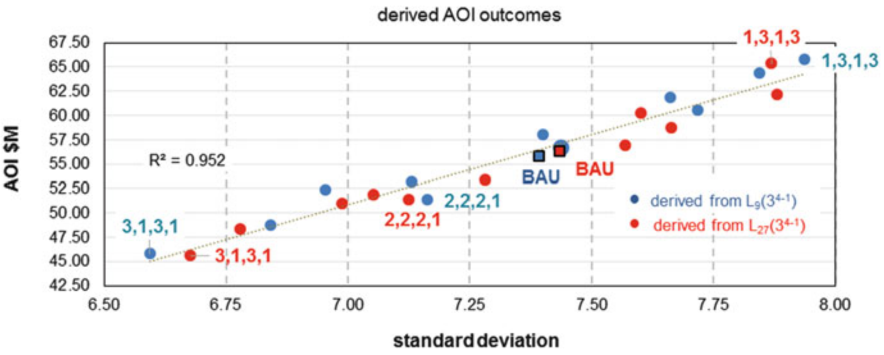


Fig. 6.23 Correlation between AOI($L_9(3^{4-2}, 2^3+1)$) and AOI($L_{27}(3^{4-2}, 2^3+1)$) subsets at t = 12

have shown that we can design, construct and predict the outcome and standard deviation of any designed decision alternative. Comparison of the results, for predictions using the $L_9(3^{4-2},2^3+1)$ response tables for means and standard deviations versus the predictions using the $L_{27}(3^{4-2},2^3+1)$ response tables, show a high degree of correlation (Fig. 6.23). However, given that $L_9(3^{4-2},2^3+1)$ is a low resolution model, the interactions are not visible.

6.4.4.3 $\mathcal{R}\{\text{AOI}(L_9(3^{4-2}, 2^3+1))\}$: The Rotated AOI($L_9(3^{4-2}, 2^3+1)$) Space

We ask whether the **uncontrollable** variables in our $L_9(3^{4-2},2^3+1)$ array have strong predictive power with respect to AOI. As before, we swap the positions between the controllable and uncontrollable variables to obtain the "rotated array" of $\mathcal{R}\{\text{AOI}(L_9(3^{4-2},2^3+1))\}$. As before, we swap relative positions of the controllable and uncontrollable variables of $L_9(3^{4-2}, 2^3+1)$. We examine the ANOVA statistics (Table 6.34). With exception of *long term growth* for t = 12, with $p < 0.05$, all the uncontrollable variables have $p \ll 0.05$. The residuals are N(7.185) with $p \gg 0.05$ (Fig. 6.24).

The ANOVA statistics for each of the time periods ending at t = 12, 18, and 24 (Table 6.35). The data for t = 18 and t = 24 are in Appendix 6.10.

Findings

For AOI($L_9(3^{4-2},2^3+1)$), we changed places of the controllable and uncontrollable variables. We there is support for uncontrollable variables as strong predictors for the AOI($L_9(3^{4-2},2^3+1)$) model.

6.4.4.4 Summary of the AOI($L_9(3^{4-2},2^{3+1})$)

We constructed the $L_9(3^{4-2},2^3+1)$ orthogonal array using a full factorial noise-array of uncontrollable variables to address the uncertain environments of our decision.

Table 6.34 $\mathcal{R}\{AOI(L_9(3^{4-2}, 2^3+1))\}$ at t = 12

Analysis of Variance Rotated. AOI $L_9(3^{4-2}, 2^3+1)$ t = 12						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
LT growth	1	6.93	6.93	6.93	11.59	0.027
ADI orders	1	337.58	337.58	337.58	564.11	0.000
Competitor	1	70.31	70.31	70.31	117.49	0.000
Error	4	2.39	2.39	0.60		
Total	7	417.22				
S = 0.773580, R-Sq = 99.43%, R-Sq(adj) = 99.00%						

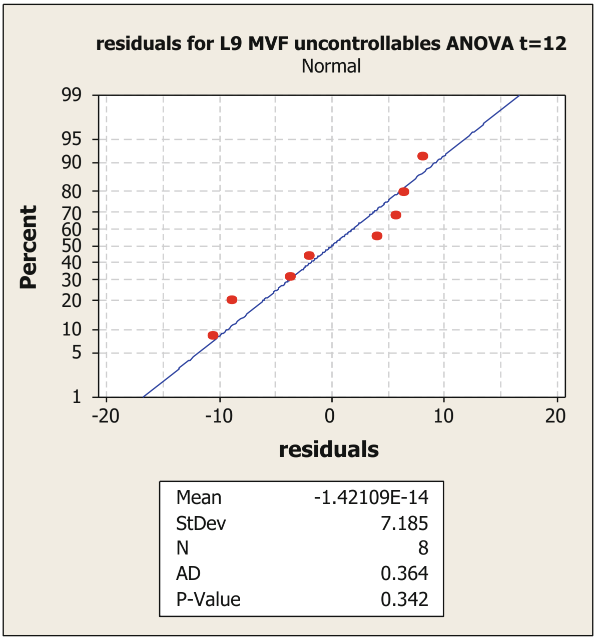


Fig. 6.24 $\mathcal{R}[AOI(L_9(3^{4-2}, 2^3+1))]$ residuals ANOVA at t = 12

Table 6.35 $\mathcal{R}[AOI(L_9(3^{4-2}, 2^3+1))]$ summary for AOI for t = 12, 18, and 24

$\mathcal{R}[AOI(L_9(3^{4-2}, 2^3+1))]$						
	t = 12		t = 18		t = 24	
Variables	Adj. MS	p value	Adj. MS	p value	Adj. MS	p value
Long term growth	6.93	0.027	43.30	0.001	125.72	0.002
ADI orders	337.58	0.000	599.85	0.000	647.40	0.000
Competitors' attractiveness	70.31	0.000	214.59	0.000	271.60	0.000
Error	0.60	–	0.68	–	2.20	–

The ANOVA tables for **both** the controllable variables **and** uncontrollable variables support our belief that they are predictors of the output of AOI in the time periods t = 12 and t = 18. There is support for all the controllable variables as predictors of the AOI outcome.

Using the $L_9(3^{4-2},2^3{+}1)$ data we are able to design the decision for the hypothesized maximum AOI at $t = 12$, 18, and 24 and predict the outcome values. The predicted values are in the 95% confidence interval.

We randomly selected a set of 12 decision designs and predicted their AOI output and standard deviations at $t = 12$. These were plotted in Fig. 6.23 and notably the correlation between the predictions using the L_9 and L_{27} results are 99%. However, the L_9 as low fidelity model does not reveal any interactions.

6.4.5 Summary of the Analyses of the Operations Space

There are two important results we developed in these sections. First, we have shown there is support for **construct validity**. One is our tests on behavior of the ADI surrogate using our controllable and uncontrollable variables. *These tests reveal the existence of demonstrable causal linkages between the independent and dependent variables for the time periods marked by $t = 12$, 18 and 24.* The dependent variables are the controllable and uncontrollable variables are linked by the sociotechnical working mechanisms of the firm. The independent variable was AOI **and** its associated standard deviation. We find that the experiments in this chapter support the functional validity of using the ADI surrogate to maximize the value of the firm, AOI.

Second, building on support of construct validity, we presented algorithms for **decision syntheses**. Paraphrasing Pahl and Beitz (1999), syntheses is the putting together of controllable and uncontrollable variables to produce intended results from the ensemble. Synthesis is engineered construction. In contrast to analyses, it is arguably the most important part of decision engineering. We presented three fundamental processes related to synthesis of our methodology. How to: (i) predict the outcome of any decision alternative that has been designed, (ii) predict the standard deviation of any decision alternative that has been designed, and (iii) therefore, design decision and construct alternatives that can satisfice and have less risk. These are decisions alternatives that are robust.

For rigorous systematic construction, we used our DOE-based executive decision methodology using *gedanken* experiments. We proceeded through a progressively demanding series beginning with the most thorough using L_{81}, then L_{27}, and L_9 orthogonal arrays. We used this sequence of experiments to find simpler experiments that will can potentially give us sufficient information for intelligent decisions. The corporate problems we intend to study are complicated, messy, and wicked. Therefore, simplicity is important because complex experiments are costly. They are costly because they require corporate staffs to collect data and perform analysis, experts to review, and management time to evaluate. The simpler the experiment, the smaller the cost incurred.

We started with the AOI $L_{81}(3^4,2^3{+}1)$ full-factorial experiment. This is the most complete experiment consisting of $3^4 \times 2^3 + 1 = 2188$ experiments. We used its results for our "gold standard" against which we compared the results obtained from simpler experiments. We wanted to know what additional insights we may

Table 6.36 p values for controllable factors for AOI for t = 12, 18, and 24

	Controllable factors' p values								
	L_{81}			L_{27}			L_{9}		
	t = 12	t = 18	t = 24	t = 12	t = 18	t = 24	t = 12	t = 18	t = 24
r&d	0.000	0.000	0.000	0.000	0.002	0.003	**0.085**	0.050	**0.058**
yield	0.000	0.000	0.000	0.000	0.000	0.001	0.006	0.020	**0.104**
cogs	0.000	0.000	0.000	0.000	0.000	0.001	0.006	0.014	**0.057**
prod. price	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.006	0.036
yield**cogs*	0.000	0.000	0.000	0.003	0.017	0.014	–	–	–
yield*price	0.000	0.000	0.000	0.029	0.033	0.021	–	–	–
*cogs**price	0.000	0.004	0.000	**0.060**	0.038	0.044	–	–	–
yield**cogs** price	0.013	**0.758**	0.025	–	–	–	–	–	–

Table 6.37 % contribution of interaction to AOI

	% contribution of interactions to the outcome of AOI								
	L_{81}			L_{27}			L_{9}		
	t = 12	t = 18	t = 24	t = 12	t = 18	t = 24	t = 12	t = 18	t = 24
Interactions	0.43%	2.2%	6.5%	0.41%	2.3%	7.7%	–	–	**–**

Table 6.38 p values for uncontrollables for AOI for t = 12, 18, 24

	Uncontrollable factors' p values for AOI outcome								
	L_{81}			L_{27}			L_{9}		
	t = 12	t = 18	t = 24	t = 12	t = 18	t = 24	t = 12	t = 18	t = 24
ind.demand	0.033	0.001	0.001	0.027	0.001	0.002	0.027	0.001	0.002
ADI orders	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Competiveness	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

gain from more effort. Next, we used the L_{27} medium resolution and the L_9 low-resolution arrays, respectively, for testing. Table 6.36 presents the results from our three experimental designs (Tables 6.18, 6.23 and 6.30). The data demonstrate that our variables have high explanatory power (high R^2) and are also strong predictors ($p \ll 0.05$) except for few exceptions, at t = 24 of the AOI outcome.

Table 6.37 shows that the % contributions of the interactions are small.

We also tested the statistical significance of the uncontrollable variables on our AOI outcome (Table 6.38). Data indicate that the uncontrollable variables do create significant uncertainty conditions that have a strong influence on AOI.

The data from these analyses suggest that the controllable and uncontrollable variables have predictive and explanatory power. We summarize our findings for AOI maxima for each of the time periods in our progression of experimental designs in Table 6.39.

We find that there is support for X-RL3T (Table 6.40)

Table 6.39 AOI for t = 12, 18, and 24, L_9 versus L_{27} and L_{81}

		Annual operating income (AOI)				
		AOI(L_{81})	AOI(L_{27})	AOI(L_9)	|[AOI(L_{27})-AOI (L_{81})]|/AOI(L_{81})	|[AOI(L_9)-AOI (L_{81})]|/AOI(L_{81})
	Experiment	Inspection	Derived	Derived		
t = 12	1,3,1,3	$64.53 M	$65.39 M	$65.75 M	1.3%	1.8%
t = 18	1,3,1,3	$57.94 M	$59.89 M	$60.56 M	3.4%	4.5%
t = 24	1,3,1,3	$48.88 M	$51.27 M	$52.42 M	5.5%	7.2%
t = 24					Average = 3.4%	Average = 4.6%
Conf. interval α = 0.05		(48,57)	(46,56)	(46,62)		

Table 6.40 Readiness level specifications for executive decisions

Prescriptive phases	Our systematic process	
X-RL3 Explore operations space	Specify	
	Sample orthogonal array	☑
	Do-nothing case and choice decision-alternative	☑
	Predict outcomes	☑
	Design and implement robust alternative	☑
	Design and implement any what-if alternative	☑

☑ indicates support for Readiness

6.4.6 Summary Discussion

The conclusions that follow are nearly identical to those of Chap. 5. These results suggest to us that the findings from Chap. 5 are not simply fortuitous. They suggest to us that our DOE-based decision prescriptive method is functional and ready-**to**-work. In summary:

- The ADI system dynamics model is a valid company surrogate for the decision-synthesis and analysis to maximize AOI.
- Our controllable and uncontrollable variables have strong explanatory and predictive power for our outcome of annual operating income (AOI).
- At the scale of our decision analysis, the interactions among the controllable variables are small.
- From a very small sample L_9 of the entire solution space L_{81}, we can design a decision that yields the maximum outcome. The L_9 statistics reveal consistent relative importance of the controllable and uncontrollable variables to the outcome vis à vis results obtained from our L_{27} and L_{81}. The desirable property of AOI equifinality, within the bounds of 95% confidence intervals, between L_9, L_{27} and L_{81} is maintained for all three time periods of t = 12, 18, and 24.
- With a larger sample L_{27} we can also find the influence of 2-fi. Moreover, the derived maxima are identical to the one revealed by the full-factorial space

specified by our L_{81} array; in the one exception though the maxima are different, the values are within the 95% CI.

- The outcomes can be analyzed over the entire uncertainty space. Unconstrained exploration is indeed possible and demonstrated.

The data from our ADI-surrogate simulations of the AOI corporate decision suggest there is support for our DOE-based methodology for decision syntheses. Our methodology is able to parametrize the system behavior of the corporation for the AOI outcome. It is also able to parametrize the set of uncontrollable uncertainties. Therefore, using our DOE-based prescriptive paradigm, we can explore the entire solution space over the entire space of environmental uncertainty. The data show that the interactions are small and their contribution to the outcome is very small. Therefore the data indicates that system behavior of the ADI corporation for the AOI outcome is "nearly-decomposable" (Simon 1997) at our scale of analysis (Bar-Yam 1997), which says that we can represent that emergent system behavior with a linear model. Significantly, the socio behavior of ADI was revealed phenomenologically using gedanken experiments.

6.5 Evaluating the Performance Space

The discussions have concentrated on the use of DOE methods to construct decision alternatives using DOE experiments to predict performance. Experiments depend on data, but how do we know the data are "good enough"? What is good enough? How do we know the quality of those performing the experiments or of the mechanisms? These are the questions we explore and discuss by considering the sociotechnical system that implements a decision specification as a **production system**. We evaluate performance through this lens using the science and technology of a measurement system and use Gage R&R (AIAG 2002).

Because this chapter is a simulation, we cannot address the questions or repeatability and reproducibility. We will discuss them in Part III where we report the results and our findings from real enterprises from the business and national defense sectors. Full discussion of conformance to X-RL4 is deferred to Part III. Table 6.41 summarizes the X-RL4 situation at this point.

Table 6.41 Readiness level specifications for executive decisions

Readiness Level	Systematic process for the performance space	Functionality
X-RL4 Evaluating performance space	Evaluate performance: analyze 4R	☐
	Robustness	☑
	Repeatability, reproducibility, reflect	☐

The symbol ☐ indicates functionality and efficacy will be shown in Part III

6.6 Enacting in the Commitment Space

Hans J. Morgenthau (1970) writes “The statesman must commit himself to a particular course of action to the exclusion of all others. He must cross the Rubison or refrain from crossing it, but he cannot have it both ways.” This rule that must govern all decisions. Teddy Roosevelt famously said that at any moment of decision, the worst thing one can do is to do nothing. He also said that doing the “wrong thing” is preferable to doing nothing. Our experiences tells us the “wrong thing” means acting on a less than ideal alternative, which then provides us with information that supports or refutes the undertaken action. This is an effective learning mechanism. As a general principle, we agree that being “wrong” is better than being indecisive. Indecisiveness breeds uncertainty, doubt that propagates rapidly in an organization and erodes confidence.

Taking a decision means committing to a decision specification and gaining senior executive approval to act. Approval must include a plan with well-defined checkpoints and work products to implement the decision-specifications. A plan that is buttressed with funds, organizations and skilled experts to do the work. Because this chapter is a simulation, we cannot address this question of execution—the production of a decision specification. We will discuss these topics in Part III where we report the results and our findings from real enterprises from the business and national defense sectors. Full discussion of conformance to X-RL5 is deferred to Part III. Table 6.42 summarizes the X-RL5 situation at this point.

6.7 Discussion

> Macroscopic behavior of physical [and social systems] systems can be described or determined by only a few relevant parameters. It is not always necessary to describe the behavior is terms of the finest scale . . . the wealth of behavior [of lower level objects] is not relevant at the larger scale. (Bar-Yam)

Data from our ADI-surrogate simulations of our AOI corporate decision provide support for our DOE-based methodology for decision analysis. Our method is able to parametrize the system behavior of the ADI corporation for the AOII outcome. It is also able to parametrize the entire space of uncontrollable uncertainties it faces. Using our DOE-based method using *gedanken* experiments, we can explore the entire solution space over the entire space of environmental uncertainty. Simulation

Table 6.42 Readiness level specifications for executive decisions

Readiness Level	Systematic process for the Commitment Space	Functionality
X-RL5 Enacting commitment space	Decisive executive	☐
	Approval of plan	☐
	Commit funds, equipment, organizations	☐

The symbol ☐ indicates functionality and efficacy will be shown in Part III data show that the interactions are small and their overall contribution to the outcome is very small. Therefore the data show that system behavior of ADI for the AOI outcome is "nearly-decomposable" (Simon 1997) at our scale of analysis (Bar-Yam 1997). This supports our belief that we can represent that emergent system behavior with a quasi-linear model. "Simon (1997) writes that "If we are interested only in certain aggregated aspects of behavior, it may be that we can predict those aggregates by use of an appropriately aggregated model." And that "the dynamic behavior of a nearly-decomposable system can be analyzed without examining simultaneously all the interactions of the elementary parts (Simon 1997)." Bar-Yam (1997, 2000, 2003) makes a similar argument, that by looking at complex systems at the appropriate scale, i.e. at a level where the descriptions are self-consistent, "the wealth of behavior [of lower level objects] is not relevant at the larger scale." Bar-Yam makes a very insightful observation: "The existence of multiple levels implies that simplicity can also be an emergent property. This means that the collective behavior of many elementary parts can behave simply on a much larger scale (Bar-Yam 1997)." He writes: "The central point is: When the independence of the components is reduced, scale of behavior is increased."

In the next chapter, we will use the same approach for a different outcome to determine whether the findings will continue to consistently support the findings of this chapter.

6.8 Chapter Summary

- We stipulated that our methodology ***works***, if and only if, it simultaneously satisfies two conditions, *viz*. it is ready-to-work for users in general ***and*** ready-for-work by a user for a specific set of needs. The former condition is demonstration of **functionalit**y, the latter is **efficacy**. The goal in this chapter has been to develop evidence that the methodology is ***ready-to-work*** for users; that it is functional. In other words, the methodology "works" as designed by us.
- We used the ADI surrogate as a test object to present evidence that our methodology is ready-to-work by demonstrating that it will satisfy the X-RL conditions. We played the role of a DMU. We applied our systematic decision life-cycle process. We used the ADI surrogate for the specific corporate objective of maximizing ADI's.
- First, we demonstrated though exhaustive analyses the construct validity of our decision using the AOI($L_{81}(3^4,2^3+1)$) model, under a wide range of uncertainty regimes. We established as the "gold standard" the results from AOI($L_{81}(3^4,2^3+1)$) under a spectrum of uncertainty regimes.
- We stepped through every step of our systematic process to demonstrate the *functionality* of our method and readiness levels, from X-RL1 to X-RL5. Our experiments with ADI demonstrate there is support for the following:

X-RL1 The *Problem Space* is very clearly characterized with controllable and uncontrollable variables, at three levels for each, to achieve the objective of annual operating income (AOI). The controllable and uncontrollable variables were exhaustively analyzed to be construct valid.

X-RL2 The specifications for *Solution Space* is thoroughly specified using two elements. They are the controllable and uncontrollable spaces. These building blocks are used to engineer the entire space of solutions' alternatives, as well as, the uncertainty space.

X-RL3 Exploration of the *Operations Space* is exhaustively executed and analyzed. Three strategies are used to explore the operations space. First, a "gold standard" is specified for the entire solution space, uncertainty space, and outcomes space. The gold standard is obtained from full factorial experiments. Second, we used three experimental models of varying degrees of fidelity ad complexity to test the functionality of our methodology. We find that the controllable and uncontrollable variables are all strong predictors of the outcomes under a wide range of uncertainty conditions. The predicted outcomes are quite close to the "gold standard". Two-factor and three-factor interactions are revealed more prominently in the high fidelity models. Fewer are revealed in the lesser fidelity models, but the results are very consistent with our gold standard.

X-RL4 Evaluation of the *Performance Space* of the 4-R (robustness, repeatability, reproducibility, and reflection) is only partly completed. We demonstrated robustness by using the response tables that show the standard deviations for the behavior of each controllable variable and by constructing a robust output. Reflection is demonstrated with the detailed discussions of our analyses and findings. Repeatability and repeatability remain untested because we are acting as DMU without a quorum. This will be tested in Part III.

X-RL5 Enacting the Commitment Space remains untested because these experiments are simulations. This will be tested in Part III.

- The X-RL readiness demonstrated in this chapter is summarized in the Table 6.43.

Overall, the results reported in this chapter are evidence for the claim of functionality for our methodology. We conclude that there is strong support for the functionality of our methodology. This conclusion will be strengthened with the field experiments that will be presented in Part III.

Table 6.43 Readiness level specifications for executive decisions

Readiness level	Our systematic process	Functionality
X-RL1 Characterize Problem space	Sense making—uncomplicate cognitive-load	☑
	Frame problem/opportunity and clarify boundary conditions	☑
	Specify goals and objectives	☑
	Specify essential variables Managerially controllable variables Managerially uncontrollable variables	☑
X-RL2 Engineer Solution space	Specify subspaces of solution space Alternatives space and uncertainty space	☑
	Specify entire solution space	☑
	Specify base line and uncertainty regimes Do-nothing case and choice-decision Estimate base line and dispel bias	☑
X-RL3 Explore Operations space	Specify	
	Sample orthogonal array	☑
	Do-nothing case and choice decision-alternative	☑
	Predict outcomes	☑
	Design and implement robust alternative	☑
	Design and implement any what-if alternative	☑
X-RL4 Evaluate Performance space	Evaluate performance: analyze 4R	☐
	Robustness	☑
	Repeatability, reproducibility, reflect	☐
X-RL5 Enact Commitment space	Decisive executive	☐
	Approval of plan	☐
	Commit funds, equipment, organizations	☐

☑ indicates support has been demonstrated
☐ indicates support will be demonstrated in Part III

Appendix 6.1 AOI(L_{81}(3^4,2^3+1)) Experiment Data Under Uncertainty Regimes

Appendix 6.1.1 AOI(L_{81}(3^4,2^3+1)) at t = 12

		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	← Industry growth	
		Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	← ADI order rate	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	← Competitors' attractiveness	
			000	**001**	**010**	**011**	**100**	**101**	**110**	**111**		
	Experiments		. . .	**Worst case**	. . .	. . .	. . .	. . .	**Best case**		$\bar{y}$	σ
1	**1,1,1,1**	55.05	47.81	41.03	59.82	54.73	49.55	45.21	62.03	56.56	52.421	6.96
2	**1,1,1,2**	60.50	53.06	45.27	64.42	60.05	55.02	46.89	66.91	61.43	57.061	7.53
3	**1,1,1,3**	63.82	56.15	48.26	68.39	63.30	58.44	50.01	70.57	65.02	60.440	7.79
4	**1,1,2,1**	51.90	44.50	38.18	55.83	51.77	46.33	39.62	57.90	53.44	48.830	7.02
5	**1,1,2,2**	57.98	50.36	42.76	61.24	57.14	52.20	44.42	63.78	58.49	54.263	7.31
6	**1,1,2,3**	61.49	53.74	45.81	65.31	60.64	55.88	47.58	67.91	62.16	57.836	7.65
7	**1,1,3,1**	53.68	50.91	50.04	56.24	55.30	51.18	50.20	56.42	55.58	53.283	2.70
8	**1,1,3,2**	54.97	47.15	40.11	57.49	54.09	48.97	41.73	59.97	55.44	51.102	6.99
9	**1,1,3,3**	56.93	51.18	43.30	62.20	57.76	53.18	45.09	64.92	59.28	54.871	7.35
10	**1,2,1,1**	57.12	50.08	43.16	62.43	56.98	51.81	44.58	64.64	58.84	54.404	7.51
11	**1,2,1,2**	62.33	54.91	47.29	66.78	62.22	56.92	48.85	69.01	63.74	59.117	7.63
12	**1,2,1,3**	65.58	57.91	50.27	70.63	65.35	60.26	51.93	72.29	67.29	62.390	7.82
13	**1,2,2,1**	54.77	47.34	40.81	59.25	54.54	49.04	42.26	61.41	56.31	51.748	7.28
14	**1,2,2,2**	60.22	52.65	45.06	63.93	59.83	54.56	46.66	66.40	61.15	56.718	7.46
15	**1,2,2,3**	63.51	55.74	48.06	67.91	63.06	57.97	49.75	70.13	64.73	60.096	7.74

(continued)

		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	← Industry growth	
		Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	← ADI order rate	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	← Competitors' attractiveness	
			000	**001**	**010**	**011**	**100**	**101**	**110**	**111**		
	Experiments		. . .	**Worst case**	. . .	. . .	. . .	. . .	**Best case**		$\bar{y}$	$\boldsymbol{\sigma}$
16	**1,2,3,1**	51.87	44.29	38.24	55.64	51.87	46.08	39.65	57.67	53.50	48.757	6.98
17	**1,2,3,2**	57.91	50.13	42.77	61.05	57.21	51.91	44.39	63.55	58.50	54.158	7.28
18	**1,2,3,3**	61.39	53.51	45.80	65.12	60.67	55.59	47.53	67.88	62.15	57.738	7.65
19	**1,3,1,1**	59.30	52.36	45.48	65.18	59.40	54.10	46.83	67.21	61.18	56.782	7.63
20	**1,3,1,2**	64.34	56.92	49.54	69.40	64.53	58.99	51.02	71.02	66.32	61.342	7.69
21	**1,3,1,3**	67.54	59.89	52.49	73.11	67.60	62.28	54.06	74.17	69.62	64.529	7.84
22	**1,3,2,1**	57.37	50.22	48.47	62.58	57.35	51.89	44.86	64.74	59.14	55.180	6.69
23	**1,3,2,2**	62.50	54.97	47.61	66.90	62.54	56.95	49.11	69.05	64.05	59.298	7.59
24	**1,3,2,3**	65.71	51.94	51.52	60.26	65.63	60.26	52.15	72.29	67.55	60.812	7.62
25	**1,3,3,1**	55.31	47.80	41.43	59.87	55.23	49.42	42.84	61.99	56.97	52.318	7.30
26	**1,3,3,2**	60.63	52.96	45.62	64.39	60.50	54.81	47.15	66.79	61.77	57.180	7.47
27	**1,3,3,3**	63.88	55.99	48.59	68.35	63.63	58.19	50.21	70.39	65.32	60.506	7.72
28	**2,1,1,1**	54.79	47.38	40.75	59.43	54.29	49.21	42.21	61.65	56.12	51.759	7.33
29	**2,1,1,2**	60.00	52.60	44.97	63.98	59.56	54.54	46.57	66.48	60.93	56.626	7.48
30	**2,1,1,3**	63.28	55.67	47.97	67.89	62.77	57.93	49.67	70.08	64.48	59.971	7.72
31	**2,1,2,1**	51.44	44.07	37.89	55.44	51.32	45.90	39.31	57.52	52.99	48.431	6.98
32	**2,1,2,2**	57.48	49.89	42.46	60.80	56.65	51.72	44.09	63.35	58.00	53.827	7.26
33	**2,1,2,3**	60.95	53.24	46.48	64.81	60.11	55.36	47.24	67.42	61.62	57.470	7.39
34	**2,1,3,1**	47.88	40.69	34.86	51.46	47.95	42.57	36.22	53.39	49.48	44.944	6.65
35	**2,1,3,2**	54.46	46.68	39.80	57.06	53.60	48.49	41.39	59.54	54.94	50.662	6.94

36	**2,1,3,3**	58.38	50.67	42.96	61.71	57.22	52.65	44.73	64.44	58.73	54.610	7.40
37	**2,2,1,1**	56.67	49.66	42.89	62.04	56.54	51.38	44.29	64.26	58.40	54.014	7.47
38	**2,2,1,2**	61.84	54.46	47.01	66.33	61.74	56.44	48.53	68.57	63.25	58.686	7.57
39	**2,2,1,3**	65.05	57.44	49.97	70.13	64.83	59.75	51.60	71.80	66.75	61.924	7.75
40	**2,2,2,1**	54.31	46.92	40.53	58.86	54.10	48.61	41.96	61.02	55.87	51.353	7.24
41	**2,2,2,2**	59.72	52.19	44.76	63.49	59.34	54.08	46.34	65.96	60.66	56.282	7.41
42	**2,2,2,3**	62.98	55.25	47.75	67.41	62.54	57.45	49.41	69.64	64.19	59.624	7.67
43	**2,2,3,1**	51.41	43.86	37.95	55.26	51.43	45.64	39.34	57.28	53.06	48.359	6.94
44	**2,2,3,2**	57.40	49.66	42.47	60.62	56.71	51.43	44.07	63.12	58.01	53.721	7.23
45	**2,2,3,3**	60.85	53.01	45.48	64.42	60.13	55.07	47.18	67.19	61.60	57.214	7.53
46	**2,3,1,1**	58.86	51.96	45.22	64.79	58.96	53.67	46.54	66.83	60.74	56.397	7.58
47	**2,3,1,2**	63.86	56.49	49.27	68.95	64.05	58.53	50.72	70.58	65.83	60.920	7.63
48	**2,3,1,3**	67.02	59.45	52.20	72.61	67.09	61.79	53.75	73.68	69.09	64.076	7.76
49	**2,3,2,1**	56.92	49.80	43.20	62.19	56.91	51.46	44.57	64.35	58.70	54.233	7.44
50	**2,3,2,2**	62.01	54.52	47.32	66.46	62.06	56.47	48.80	68.62	63.56	58.869	7.53
51	**2,3,2,3**	65.19	57.48	50.26	70.24	65.11	59.75	51.82	71.80	67.02	62.074	7.71
52	**2,3,3,1**	54.86	47.38	41.15	59.48	54.79	48.99	42.54	61.61	56.63	51.937	7.27
53	**2,3,3,2**	60.14	52.50	45.33	63.95	60.01	54.34	46.83	66.35	61.28	56.748	7.41
54	**2,3,3,3**	63.35	55.50	48.28	67.85	63.11	57.67	49.88	69.90	64.78	60.036	7.66
55	**3,1,1,1**	54.13	46.98	40.52	58.99	53.82	48.68	41.95	61.21	55.64	51.324	7.24
56	**3,1,1,2**	59.50	52.18	44.72	63.48	59.06	54.07	46.30	65.98	60.41	56.189	7.38
57	**3,1,1,3**	62.74	55.24	47.71	67.35	62.23	57.45	49.40	69.55	63.92	59.510	7.61
58	**3,1,2,1**	50.97	43.66	37.65	55.00	49.70	45.45	39.05	57.09	52.52	47.899	6.86
59	**3,1,2,2**	56.97	49.45	42.20	60.30	56.13	51.23	43.81	62.85	57.46	53.378	7.17
60	**3,1,2,3**	60.39	52.79	45.22	64.26	59.56	54.84	46.95	66.87	61.04	56.880	7.47
61	**3,1,3,1**	47.40	40.27	34.62	51.03	47.47	42.13	35.95	52.96	49.00	44.537	6.58
62	**3,1,3,2**	53.94	46.22	39.53	56.56	53.07	47.99	41.10	59.05	54.41	50.208	6.86

(continued)

		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	← Industry growth	
		Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	← ADI order rate	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	← Competitors' attractiveness	
			000	**001**	**010**	**011**	**100**	**101**	**110**	**111**		
	Experiments		. . .	**Worst case**	. . .	. . .	. . .	. . .	**Best case**		$\bar{y}$	$\boldsymbol{\sigma}$
63	**3,1,3,3**	57.82	50.20	42.69	61.15	56.66	52.12	44.43	63.89	58.15	54.123	7.29
64	**3,2,1,1**	56.22	49.28	42.66	61.60	56.08	50.94	44.04	63.82	57.93	53.619	7.39
65	**3,2,1,2**	61.34	54.06	46.76	65.84	61.25	55.99	48.27	68.07	62.73	58.257	7.47
66	**3,2,1,3**	64.52	57.03	49.72	69.59	64.30	59.30	51.33	71.25	66.20	61.471	7.64
67	**3,2,2,1**	53.85	46.52	40.29	58.42	53.63	48.17	41.70	60.59	55.39	50.951	7.16
68	**3,2,2,2**	59.21	51.77	44.52	62.99	58.84	53.60	46.07	65.46	60.13	55.843	7.31
69	**3,2,2,3**	62.43	54.82	47.49	66.87	62.00	56.97	49.12	69.08	63.63	59.157	7.56
70	**3,2,3,1**	50.94	43.44	37.71	54.82	50.95	45.20	39.08	56.85	52.58	47.952	6.87
71	**3,2,3,2**	56.89	49.22	42.21	60.12	56.20	50.94	43.78	62.62	57.48	53.273	7.14
72	**3,2,3,3**	60.29	52.56	45.22	64.07	59.58	54.55	46.89	66.64	61.03	56.759	7.44
73	**3,3,1,1**	58.41	51.59	45.00	64.35	58.52	53.26	46.31	66.38	60.28	56.011	7.50
74	**3,3,1,2**	63.37	56.11	49.03	68.46	63.57	58.11	50.47	70.08	65.33	60.503	7.53
75	**3,3,1,3**	66.50	59.05	51.95	72.07	66.58	61.36	53.48	73.14	68.56	63.632	7.65
76	**3,3,2,1**	56.46	49.41	42.98	61.75	56.46	51.03	44.33	63.91	58.22	53.839	7.36
77	**3,3,2,2**	61.51	54.13	47.08	65.97	61.56	56.02	48.54	68.11	63.05	58.441	7.43
78	**3,3,2,3**	64.65	57.07	50.00	69.70	64.59	59.30	51.55	71.25	66.47	61.620	7.60
79	**3,3,3,1**	54.40	46.98	40.92	59.04	54.33	48.55	42.28	61.17	56.05	51.524	7.19
80	**3,3,3,2**	59.63	52.08	45.08	63.45	59.21	53.86	46.57	65.85	60.76	56.277	7.30
81	**3,3,3,3**	62.80	55.08	48.02	67.31	62.57	57.20	49.50	69.35	64.22	59.561	7.56
Σcolumn		4775.98	4170.08	3617.65	5115.92	4753.76	4330.98	3736.43	5300.54	4884.83	4520.686	

Appendix 6.1.2 AOI(L_{81}(3^4,2^3+1)) at $t = 18$

		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	← Industry growth	
		Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	← ADI order rate	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	← Competitors' attractiveness	
			000	**001**	**010**	**011**	**100**	**101**	**110**	**111**		
	Experiments	**Current**	. . .	**Worst case**	. . .	. . .	. . .	. . .	**Best case**		$\bar{y}$	$\boldsymbol{\sigma}$
1	**1,1,1,1**	53.91	41.04	30.62	58.24	48.55	45.78	34.09	64.33	53.34	47.767	11.09
2	**1,1,1,2**	58.96	47.13	35.27	62.45	53.73	51.87	39.07	69.18	57.86	52.836	10.92
3	**1,1,1,3**	61.46	49.66	37.76	65.78	56.22	54.44	41.74	72.03	60.89	55.553	11.09
4	**1,1,2,1**	50.01	36.47	26.60	52.53	44.97	41.33	30.04	58.46	49.42	43.314	10.64
5	**1,1,2,2**	57.98	57.20	44.43	32.56	59.86	51.00	49.42	36.54	66.80	50.643	11.23
6	**1,1,2,3**	60.17	47.89	35.51	63.35	53.96	52.95	39.74	70.55	58.55	53.630	11.19
7	**1,1,3,1**	48.34	41.12	35.15	51.84	48.40	43.01	36.53	53.77	49.92	45.342	6.68
8	**1,1,3,2**	53.57	40.05	28.90	54.86	47.47	45.27	32.76	61.67	51.81	46.262	10.73
9	**1,1,3,3**	58.25	45.47	32.85	60.88	51.28	50.42	32.21	68.35	56.08	50.643	12.19
10	**1,2,1,1**	54.82	43.67	33.01	60.44	50.34	48.06	36.34	66.46	55.18	49.813	10.89
11	**1,2,1,2**	59.70	48.37	36.99	64.22	55.42	52.74	41.53	70.25	59.63	54.317	10.68
12	**1,2,1,3**	62.13	50.75	39.43	67.34	57.69	55.29	43.13	72.39	67.62	57.308	11.32
13	**1,2,2,1**	53.72	40.38	30.25	57.47	48.34	45.13	33.69	63.55	53.04	47.286	11.02
14	**1,2,2,2**	58.71	46.78	34.96	61.99	53.46	51.52	38.75	68.76	57.54	52.497	10.90
15	**1,2,2,3**	61.23	49.29	37.44	65.34	55.95	54.04	41.39	71.79	60.55	55.224	11.10
16	**1,2,3,1**	49.96	36.11	26.59	52.27	45.11	40.96	29.98	58.16	49.50	43.182	10.61
17	**1,2,3,2**	57.08	44.07	32.45	59.70	51.01	48.99	36.37	66.62	55.22	50.168	11.06
18	**1,2,3,3**	60.02	47.61	35.36	63.20	53.92	52.60	39.54	70.42	58.45	53.458	11.22

(continued)

		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	← Industry growth	
		Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	← ADI order rate	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	← Competitors' attractiveness	
			000	**001**	**010**	**011**	**100**	**101**	**110**	**111**		
	Experiments	**Current**	...	**Worst case**	...	...	...	...	**Best case**		$\bar{y}$	**σ**
19	**1,3,1,1**	55.67	42.25	34.96	62.55	62.07	49.13	38.03	67.96	56.66	52.142	11.68
20	**1,3,1,2**	60.44	49.63	38.81	66.10	57.02	53.68	42.07	70.61	61.58	55.549	10.61
21	**1,3,1,3**	62.87	51.89	41.16	68.99	59.26	56.17	44.57	72.55	64.22	57.964	10.61
22	**1,3,2,1**	54.85	43.73	33.17	60.51	50.54	48.00	36.43	68.46	55.27	50.107	11.26
23	**1,3,2,2**	59.67	48.36	37.13	64.25	55.55	52.63	40.58	70.19	59.77	54.237	10.80
24	**1,3,2,3**	62.06	50.69	39.53	55.12	57.79	55.12	43.12	72.31	62.71	55.383	10.09
25	**1,3,3,1**	53.93	40.94	30.93	58.23	48.86	45.57	34.30	64.29	53.53	47.842	11.02
26	**1,3,3,2**	58.88	46.88	35.31	62.33	53.99	51.47	38.97	69.02	57.94	52.754	10.91
27	**1,3,3,3**	61.26	49.34	37.76	65.66	56.29	53.97	41.57	71.86	60.92	55.403	11.08
28	**2,1,1,1**	52.80	40.23	30.24	57.32	47.58	44.80	33.66	63.44	52.30	46.930	10.89
29	**2,1,1,2**	57.80	46.30	34.89	61.41	52.73	50.86	38.62	68.16	56.71	51.942	10.67
30	**2,1,1,3**	60.28	48.88	37.38	64.61	55.21	53.45	41.28	70.87	59.70	54.629	10.79
31	**2,1,2,1**	48.89	35.64	26.2	51.62	43.96	40.33	29.59	57.57	48.42	42.469	10.44
32	**2,1,2,2**	55.96	43.52	32.15	58.83	49.93	48.33	36.06	65.8	54.11	49.410	10.81
33	**2,1,2,3**	58.90	47.01	35.10	62.18	52.88	51.86	39.26	69.4	57.29	52.653	10.91
34	**2,1,3,1**	43.84	30.84	21.80	46.11	39.07	35.43	25.03	51.47	43.30	37.432	9.98
35	**2,1,3,2**	52.32	39.11	28.47	53.84	46.35	44.16	32.28	60.67	50.66	45.318	10.49
36	**2,1,3,3**	56.91	44.50	32.41	59.72	50.12	49.24	36.70	67.22	54.80	50.180	11.06
37	**2,2,1,1**	53.76	42.90	32.63	59.53	49.42	47.11	33.92	65.55	54.14	48.773	11.01
38	**2,2,1,2**	58.61	47.63	36.63	63.18	54.47	51.81	40.10	69.21	58.53	53.352	10.57

39	**2,2,1,3**	61.03	50.03	39.06	66.18	56.74	54.39	42.70	71.22	61.51	55.873	10.57
40	**2,2,2,1**	52.60	39.56	29.87	56.55	47.36	44.14	33.25	62.25	52.00	46.398	10.74
41	**2,2,2,2**	57.33	45.94	34.38	60.95	52.45	50.49	38.3	67.74	56.39	51.552	10.67
42	**2,2,2,3**	60.05	48.50	37.06	64.17	54.94	53.04	40.93	70.62	59.35	54.296	10.80
43	**2,2,3,1**	48.84	35.27	26.2	51.36	44.10	39.95	29.54	57.27	48.48	42.334	10.41
44	**2,2,3,2**	55.84	43.16	32.04	58.67	49.94	47.90	35.9	65.61	54.06	49.236	10.82
45	**2,2,3,3**	58.75	46.73	34.96	62.03	52.84	51.51	39.05	69.28	57.19	52.482	10.93
46	**2,3,1,1**	54.67	44.56	34.63	61.64	51.22	48.26	37.63	67.05	55.67	50.592	10.61
47	**2,3,1,2**	59.44	48.65	38.47	64.06	56.15	52.84	41.68	69.57	6.057	48.546	18.81
48	**2,3,1,3**	61.87	51.23	40.81	67.84	58.38	55.37	44.18	71.39	63.21	57.142	10.31
49	**2,3,2,1**	53.79	42.97	32.82	59.59	49.64	47.05	36.02	65.56	54.24	49.076	10.65
50	**2,3,2,2**	58.58	47.62	36.78	63.21	54.62	51.7	40.16	69.15	58.68	53.389	10.54
51	**2,3,2,3**	60.97	49.97	39.17	66.19	56.86	54.23	42.70	71.14	61.61	55.871	10.54
52	**2,3,3,1**	52.83	40.13	30.56	57.31	47.90	44.58	33.87	63.39	52.49	47.007	10.81
53	**2,3,3,2**	57.73	46.06	34.93	61.29	53.00	50.46	38.52	67.99	56.80	51.864	10.66
54	**2,3,3,3**	60.09	48.57	37.38	64.49	55.3	52.98	41.11	70.69	59.74	54.483	10.79
55	**3,1,1,1**	51.77	39.61	29.96	56.27	46.69	43.98	33.31	62.40	51.23	46.136	10.60
56	**3,1,1,2**	56.77	45.67	34.59	60.24	51.84	50.04	38.27	66.96	55.65	51.114	10.35
57	**3,1,1,3**	59.28	48.26	37.07	63.34	54.33	52.71	40.94	69.54	58.67	53.793	10.43
58	**3,1,2,1**	47.82	34.98	25.91	50.58	44.98	39.49	29.23	56.55	47.35	41.877	10.21
59	**3,1,2,2**	54.84	42.87	31.84	37.64	48.97	47.43	35.69	64.62	52.93	46.314	10.42
60	**3,1,2,3**	57.79	46.34	34.78	60.88	51.94	50.99	38.89	68.07	56.14	51.758	10.54
61	**3,1,3,1**	42.74	30.17	21.50	45.18	38.11	34.58	24.67	50.49	42.21	36.628	9.71
62	**3,1,3,2**	51.13	38.28	28.15	52.66	45.31	43.22	31.88	59.52	49.47	44.402	10.18
63	**3,1,3,3**	55.71	43.77	32.08	58.40	49.10	48.27	36.30	65.90	53.53	49.229	10.69
64	**3,2,1,1**	52.80	42.32	32.38	58.48	48.60	46.33	35.60	64.50	53.16	48.241	10.39
65	**3,2,1,2**	57.66	47.04	36.34	62.02	53.65	51.08	39.78	68.01	57.56	52.571	10.24

(continued)

		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	← Industry growth	
		Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	← ADI order rate	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	← Competitors' attractiveness	
			000	**001**	**010**	**011**	**100**	**101**	**110**	**111**		
	Experiments	**Current**	. . .	**Worst case**	. . .	. . .	. . .	. . .	**Best case**		$\bar{y}$	$\boldsymbol{\sigma}$
66	**3,2,1,3**	60.12	49.46	38.76	64.95	55.92	53.71	42.37	69.92	60.55	55.084	10.22
67	**3,2,2,1**	51.56	38.93	29.58	55.50	46.48	43.31	32.91	61.62	50.92	45.646	10.53
68	**3,2,2,2**	56.50	45.30	34.28	59.78	51.57	49.65	37.95	66.54	53.22	50.532	10.22
69	**3,2,2,3**	59.04	47.88	36.75	62.90	54.05	52.28	40.59	69.29	58.31	53.454	10.44
70	**3,2,3,1**	47.77	34.62	25.90	50.32	43.16	39.10	29.18	56.25	47.41	41.523	10.13
71	**3,2,3,2**	54.72	42.46	31.73	57.48	48.99	46.99	35.52	64.43	52.88	48.356	10.49
72	**3,2,3,3**	57.65	46.06	34.64	60.73	51.90	50.62	38.68	67.94	56.05	51.586	10.57
73	**3,3,1,1**	53.80	44.02	34.36	60.60	50.46	47.59	37.34	65.98	54.79	49.882	10.32
74	**3,3,1,2**	58.59	48.41	38.19	63.95	55.39	52.20	41.37	68.39	59.68	54.019	10.03
75	**3,3,1,3**	61.05	50.70	40.52	66.69	57.62	54.75	43.86	70.14	62.33	56.407	9.98
76	**3,3,2,1**	52.84	42.38	32.55	58.54	48.83	46.28	35.70	64.50	53.27	48.321	10.36
77	**3,3,2,2**	57.65	47.04	36.49	62.06	53.81	50.98	39.84	67.75	57.72	52.593	10.17
78	**3,3,2,3**	60.08	49.40	38.87	64.96	56.05	53.56	42.37	69.84	60.67	55.089	10.20
79	**3,3,3,1**	51.81	39.51	30.27	56.26	47.03	43.76	33.53	62.35	51.42	46.216	10.53
80	**3,3,3,2**	56.71	45.44	34.64	30.11	52.14	49.64	38.18	66.80	55.76	47.713	11.78
81	**3,3,3,3**	59.11	47.95	37.07	63.22	54.44	52.24	40.77	69.36	58.73	53.654	10.43
Σcolumn		4551.4	3611.2	2748.6	4785.8	4181.6	3962.2	3032.72	5337.47	4473.1	4076.0	

Appendix 6.1.3 AOI(L_{81}(3^4,2^3+1)) at t = 24

		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	← Industry growth	
		Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	← ADI order rate	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	← Competitors' attractiveness	
			000	**001**	**010**	**011**	**100**	**101**	**110**	**111**		
	Experiments	**Current**	. . .	**Worst case**	. . .	. . .	. . .	. . .	**Best case**		$\bar{y}$	σ
1	**1,1,1,1**	51.81	34.10	21.65	53.19	41.56	41.80	26.90	62.54	48.57	42.458	13.18
2	**1,1,1,2**	55.68	41.08	27.54	55.59	45.46	49.19	33.71	65.76	51.60	47.290	11.83
3	**1,1,1,3**	57.10	42.57	25.19	57.21	46.69	50.57	35.03	67.02	53.24	48.291	12.66
4	**1,1,2,1**	47.47	28.15	16.21	46.14	36.71	35.75	21.39	55.87	43.16	36.761	12.95
5	**1,1,2,2**	55.17	38.05	23.84	54.64	43.66	46.35	29.93	65.28	50.22	55.270	13.04
6	**1,1,2,3**	57.19	42.04	27.75	56.33	45.35	50.53	34.09	67.40	52.10	48.087	12.24
7	**1,1,3,1**	44.96	31.68	22.20	46.88	40.08	36.47	25.48	52.34	44.31	38.267	10.16
8	**1,1,3,2**	51.24	32.31	18.67	48.51	39.07	40.59	24.51	59.52	46.04	40.051	13.09
9	**1,1,3,3**	56.40	39.32	24.12	55.43	43.59	47.63	30.84	67.00	50.83	46.129	13.34
10	**1,2,1,1**	51.26	37.41	24.96	54.27	42.36	44.87	30.07	63.45	49.33	44.220	12.08
11	**1,2,1,2**	55.22	41.29	28.48	56.24	46.29	48.75	33.93	65.59	52.53	47.591	11.60
12	**1,2,1,3**	56.53	42.69	30.01	57.68	47.27	49.94	35.43	66.27	54.05	48.874	11.42
13	**1,2,2,1**	51.80	33.24	21.12	52.65	41.38	40.98	26.37	62.12	48.40	42.007	13.29
14	**1,2,2,2**	55.58	40.92	27.16	55.50	45.21	48.98	32.93	65.85	51.42	47.061	12.02
15	**1,2,2,3**	57.11	42.38	28.87	57.11	46.44	50.50	34.71	67.23	53.02	48.597	11.94
16	**1,2,3,1**	47.41	27.68	16.11	45.93	36.89	35.33	21.25	55.65	48.73	37.220	13.45
17	**1,2,3,2**	55.06	37.56	23.64	54.71	43.59	45.76	29.65	65.37	50.18	45.058	13.17
18	**1,2,3,3**	57.10	41.81	27.48	56.43	45.26	50.23	33.80	67.61	52.02	47.971	12.39

(continued)

		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	← Industry growth	
		Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	← ADI order rate	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	← Competitors' attractiveness	
			000	**001**	**010**	**011**	**100**	**101**	**110**	**111**		
	Experiments	**Current**	. . .	**Worst case**	. . .	. . .	. . .	. . .	**Best case**		$\bar{y}$	σ
19	**1,3,1,1**	50.53	37.77	26.15	55.07	42.98	44.50	30.75	63.54	49.46	44.528	11.77
20	**1,3,1,2**	54.54	41.40	29.32	56.89	46.90	47.97	34.12	64.71	53.24	47.667	11.26
21	**1,3,1,3**	55.88	42.78	30.74	58.17	47.87	49.25	35.67	62.25	54.63	48.582	10.54
22	**1,3,2,1**	51.07	37.40	25.12	54.43	42.36	44.79	30.07	63.64	49.28	44.240	12.09
23	**1,3,2,2**	55.10	41.22	28.43	56.35	46.25	48.57	33.59	65.71	52.38	47.511	11.68
24	**1,3,2,3**	56.38	42.58	30.63	57.76	47.19	49.73	35.20	66.37	54.05	48.877	11.35
25	**1,3,3,1**	51.68	33.96	22.04	53.50	41.54	41.63	27.20	63.01	48.63	42.577	13.19
26	**1,3,3,2**	55.57	40.79	27.31	55.76	45.50	48.79	32.82	66.06	51.56	47.129	12.08
27	**1,3,3,3**	56.9	42.23	28.85	57.38	46.50	50.19	34.54	67.32	53.17	48.564	12.00
28	**2,1,1,1**	49.99	33.15	21.26	51.47	40.30	40.45	26.43	60.87	46.89	41.201	12.67
29	**2,1,1,2**	54.01	40.12	27.14	53.69	44.37	47.87	32.72	63.85	49.99	45.973	11.35
30	**2,1,1,3**	55.59	41.72	28.81	55.24	45.63	49.40	34.55	64.84	51.76	47.504	11.19
31	**2,1,2,1**	45.57	27.16	15.80	44.50	35.34	34.38	20.92	54.24	42.10	35.557	12.49
32	**2,1,2,2**	53.16	36.97	23.42	52.71	42.37	44.88	29.42	63.42	48.38	43.859	12.47
33	**2,1,2,3**	55.39	41.06	27.33	54.19	44.16	49.11	33.57	65.26	50.38	46.717	11.63
34	**2,1,3,1**	38.91	20.93	9.99	37.49	28.63	28.00	14.81	46.02	35.34	28.902	11.88
35	**2,1,3,2**	49.10	31.20	18.22	46.64	37.56	39.06	24.00	57.70	44.18	38.629	12.53
36	**2,1,3,3**	54.29	38.20	23.67	53.26	42.19	46.05	30.30	64.92	48.87	44.639	12.71
37	**2,2,1,1**	49.37	36.53	24.60	52.57	41.28	43.61	29.61	61.76	47.82	43.017	11.57
38	**2,2,1,2**	53.78	40.46	28.12	54.43	45.28	47.61	33.27	63.63	50.93	46.390	11.07
39	**2,2,1,3**	55.22	41.92	29.65	55.87	46.00	48.93	35.00	64.13	52.75	47.719	10.86

40	**2,2,2,1**	49.94	32.29	20.79	50.93	40.12	39.93	25.90	60.46	46.57	40.770	12.76
41	**2,2,2,2**	53.87	39.96	26.77	53.57	44.00	47.62	32.44	63.95	49.79	45.774	11.47
42	**2,2,2,3**	55.57	41.51	28.49	55.10	45.36	49.29	34.23	65.05	51.51	47.346	11.34
43	**2,2,3,1**	45.50	26.69	15.71	44.27	35.52	33.95	20.77	54.01	42.12	35.393	12.51
44	**2,2,3,2**	53.06	36.49	23.21	52.77	42.32	44.29	29.14	63.51	48.34	43.681	12.60
45	**2,2,3,3**	55.30	40.83	27.01	54.28	44.07	48.81	33.28	65.48	50.30	46.596	11.78
46	**2,3,1,1**	49.21	37.01	25.83	53.46	42.04	43.44	30.33	61.82	48.17	43.479	11.29
47	**2,3,1,2**	53.33	40.68	28.99	55.25	45.99	47.02	33.72	62.80	52.04	46.647	10.75
48	**2,3,1,3**	54.75	42.10	30.40	56.55	46.99	48.40	35.28	63.30	53.51	47.920	10.55
49	**2,3,2,1**	49.51	36.53	24.76	52.72	41.31	43.55	29.63	61.95	47.80	43.084	11.59
50	**2,3,2,2**	53.69	40.41	28.80	54.54	45.25	47.44	33.14	63.76	50.99	46.447	10.99
51	**2,3,2,3**	55.06	41.82	29.54	55.95	46.23	48.73	34.78	64.23	52.78	47.680	10.93
52	**2,3,3,1**	48.89	33.00	21.65	51.78	40.36	40.28	26.74	61.34	49.97	41.557	12.81
53	**2,3,3,2**	53.93	39.86	26.93	53.84	44.40	47.47	32.34	64.15	49.98	45.878	11.52
54	**2,3,3,3**	55.41	41.39	28.48	55.39	45.44	49.01	34.07	65.13	51.71	47.337	11.40
55	**3,1,1,1**	48.64	32.47	20.97	49.60	39.29	39.47	26.06	38.90	45.54	37.882	9.83
56	**3,1,1,2**	52.77	39.42	26.85	51.83	43.48	46.93	32.36	61.62	48.76	44.891	10.75
57	**3,1,1,3**	54.47	41.06	28.51	53.49	44.77	48.58	34.20	62.55	50.65	46.476	10.60
58	**3,1,2,1**	44.11	26.45	15.51	42.72	39.84	33.38	20.55	52.30	40.93	35.088	12.07
59	**3,1,2,2**	51.68	36.21	23.11	50.60	41.31	43.80	29.02	6.190	46.92	36.538	14.87
60	**3,1,2,3**	54.07	40.33	27.01	52.18	43.20	48.11	33.19	62.77	49.08	45.549	10.96
61	**3,1,3,1**	37.40	20.22	9.696	36.47	27.50	26.97	14.43	44.18	33.90	27.863	11.39
62	**3,1,3,2**	47.48	30.40	17.90	44.57	36.37	37.94	23.58	55.52	42.86	37.402	11.90
63	**3,1,3,3**	52.75	37.41	23.34	50.98	41.08	44.90	29.88	62.43	47.35	43.347	12.00
64	**3,2,1,1**	48.40	35.89	24.32	50.85	40.39	42.67	29.27	39.77	45.65	39.690	8.69
65	**3,2,1,2**	52.71	39.83	27.84	52.77	44.48	46.81	32.95	61.53	49.86	45.420	10.52
66	**3,2,1,3**	54.24	41.34	29.37	54.31	45.51	48.20	34.67	62.11	51.75	46.833	10.34

(continued)

		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	← Industry growth	
		Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	← ADI order rate	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	← Competitors' attractiveness	
			000	**001**	**010**	**011**	**100**	**101**	**110**	**111**		
	Experiments	**Current**	...	**Worst case**	...	...	...	...	**Best case**		$\bar{y}$	$\boldsymbol{\sigma}$
67	**3,2,2,1**	48.56	31.60	20.44	49.04	39.11	38.64	25.53	58.49	46.31	39.747	12.25
68	**3,2,2,2**	52.61	39.25	26.47	51.67	43.21	46.64	32.07	61.70	48.53	44.683	10.85
69	**3,2,2,3**	54.43	40.85	28.18	53.30	44.50	48.45	33.89	62.70	50.38	46.298	10.73
70	**3,2,3,1**	44.04	25.97	15.41	42.46	34.43	32.93	20.39	52.08	40.94	34.294	11.95
71	**3,2,3,2**	51.58	35.72	22.90	50.65	41.29	43.21	28.74	61.28	46.87	42.471	11.95
72	**3,2,3,3**	53.97	40.11	26.74	52.24	43.12	47.79	32.90	62.98	49.00	45.428	11.10
73	**3,3,1,1**	48.22	36.44	25.56	51.93	41.26	42.70	30.03	59.91	47.20	42.583	10.77
74	**3,3,1,2**	52.42	40.13	28.72	53.79	42.26	46.34	33.42	60.94	51.10	45.458	10.33
75	**3,3,1,3**	53.91	41.57	30.14	55.18	46.26	47.76	34.98	91.59	57.62	47.668	17.79
76	**3,3,2,1**	48.36	35.90	24.48	51.00	40.45	42.63	29.29	59.95	46.65	42.079	11.03
77	**3,3,2,2**	52.64	39.79	27.79	52.88	44.45	46.65	32.82	61.64	49.94	45.400	10.58
78	**3,3,2,3**	54.13	41.24	29.26	54.39	45.45	48.01	34.45	62.21	51.79	46.770	10.42
79	**3,3,3,1**	48.55	32.32	21.37	49.89	39.39	39.29	26.38	59.36	45.63	40.242	12.09
80	**3,3,3,2**	52.71	39.18	26.63	51.98	43.54	46.52	31.99	61.91	48.78	44.804	10.91
81	**3,3,3,3**	54.30	40.74	28.18	53.62	44.60	48.20	33.73	62.84	50.62	46.314	10.80
Σcolumn		4222.4	3016.2	2005.7	4246.6	3447.0	3611.7	2445.14	4945.51	3965.7	3569.04	

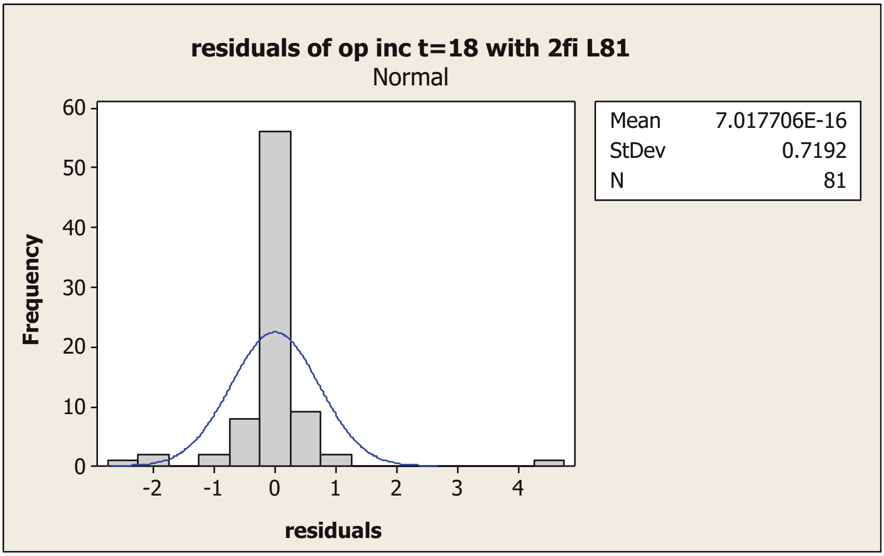
Appendix 6.2 AOI(L_{81}(3^4,2^3+1)) Controllable Variables Statistics

Appendix 6.2.1 AOI(L_{81}(3^4,2^3+1)) Controllable Variables ANOVA and Residuals at t = 18

Analysis of Variance L_{81}(3^4, 2^3+1) AOI t = 18

Source	DF	Seq SS	Adj SS	Adj MS	F	P
r&d	2	61.866	61.866	30.933	38.87	0.000
yield	2	264.031	264.031	132.016	165.88	0.000
cogs	2	278.859	278.859	139.429	175.19	0.000
price	2	908.297	908.297	454.149	570.63	0.000
yield**cogs*	4	28.051	28.051	7.013	8.81	0.000
yield*price	4	22.435	22.435	5.609	7.05	0.000
*cogs**price	4	14.132	14.132	3.533	4.44	0.004
yield**cogs**price	8	3.938	3.938	0.492	0.62	0.758
Error	52	41.385	41.385	0.796		
Total	80	1622.995				

S = 0.892113, R-Sq = 97.45%, R-Sq(adj) = 96.08%

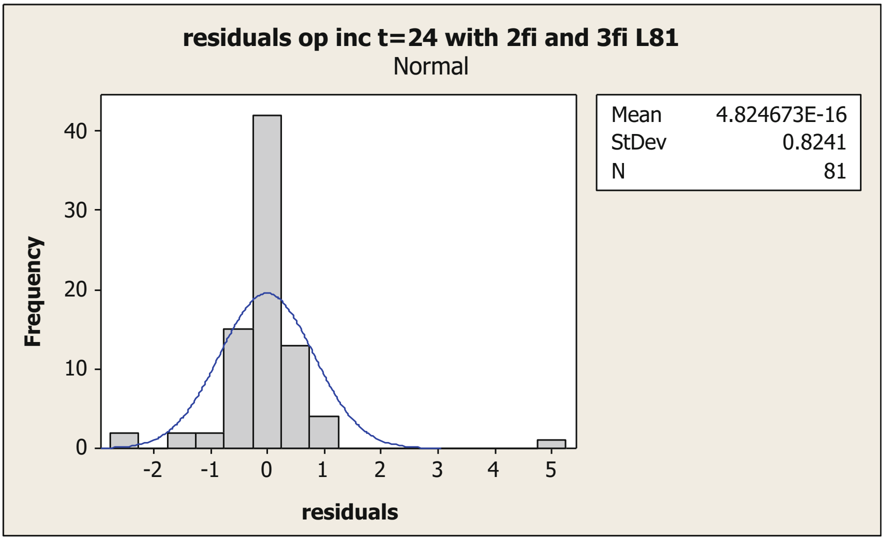


Appendix 6.2.2 AOI($L_{81}(3^4,2^3+1)$) Controllable Variables ANOVA and Residuals at t = 24

Analysis of Variance: $L_{81}(3^4,2^3+1)$ AOI t = 24

Source	DF	Seq SS	Adj SS	Adj MS	F	P
r&d	2	109.815	109.815	54.908	52.55	0.000
yield	2	200.528	200.528	100.264	95.96	0.000
cogs	2	176.609	176.609	88.304	84.51	0.000
price	2	839.797	839.797	419.899	401.87	0.000
yield**cogs*	4	62.460	62.460	15.615	14.94	0.000
yield*price	4	62.744	62.744	15.686	15.01	0.000
*cogs**price	4	48.967	48.967	12.242	11.72	0.000
yield**cogs**price	8	20.508	20.508	2.563	2.45	0.025
Error	52	54.333	54.333	1.045		
Total	80	1575.761				

S = 1.02218, R-Sq = 96.55%, R-Sq(adj) = 94.70%



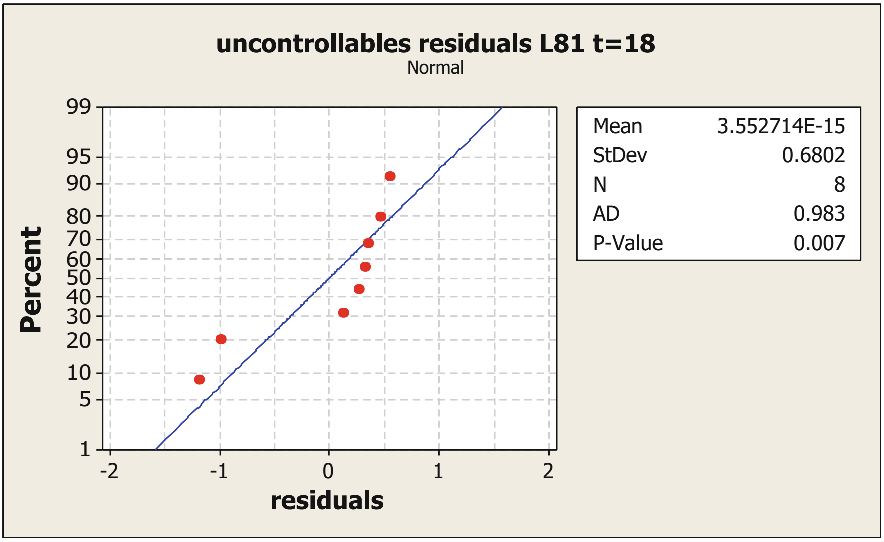
Appendix 6.3 AOI(L_{81}(3^4,2^3+1)) Uncontrollable Variables Statistics

Appendix 6.3.1 Uncontrollable Variables ANOVA Table and Residuals at t = 18

Analysis of Variance. AOI L_{81}(3^4,2^3+1) t = 18

Source	DF	Seq SS	Adj SS	Adj MS	F	P
LT growth	1	45.79	45.79	45.79	56.55	0.002
ADI orders	1	593.70	593.70	593.70	733.25	0.000
Competitor	1	205.67	205.67	205.67	254.01	0.000
Error	4	3.24	3.24	0.81		
Total	7	848.40				

S = 0.899824, R-Sq = 99.62%, R-Sq(adj) = 99.33%

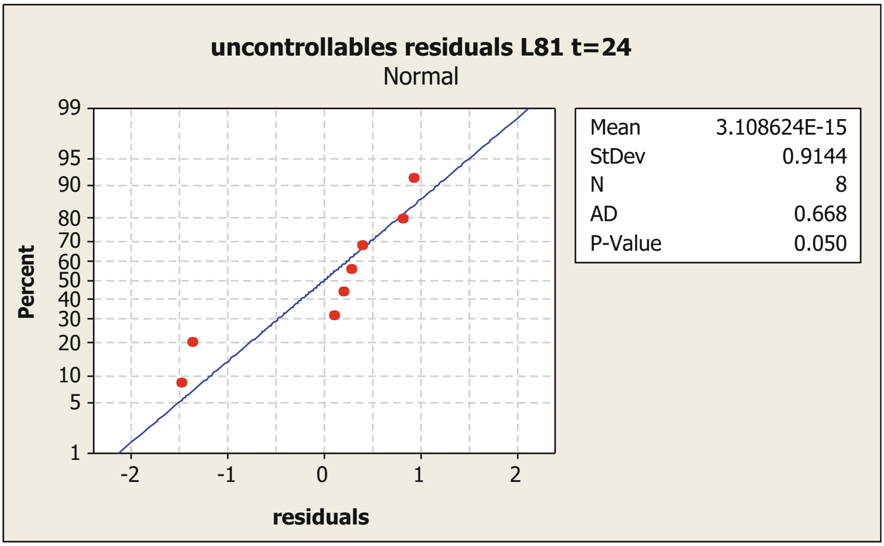


Appendix 6.3.2 Uncontrollable Variables ANOVA Table and Residuals at t = 24

Analysis of Variance. AOI $L_{81}(3^4, 2^3+1)$ t = 24 uncontrollable variables

Source	DF	Seq SS	Adj SS	Adj MS	F	P
LT growth	1	100.04	100.04	100.04	68.36	0.001
ADI orders	1	592.22	592.22	592.22	404.72	0.000
Competitor	1	298.72	298.72	298.72	204.15	0.000
Error	4	5.85	5.85	1.46		
Total	7	996.84				

S = 1.20966, R-Sq = 99.41%, R-Sq(adj) = 98.97%



Appendix 6.4 AOI($L_{27}(3^{4-1},2^3+1)$) Experiment Data Under Uncertainty Regimes

Appendix 6.4.1 AOI($L_{27}(3^{4-1},2^3+1)$) at t = 12

		AOI($L_{27}(3^{4-1}, 2^3+1)$)										
		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	← Industry growth	
		Same	Worse	Worse	Better	Better	Worse	Worse	Better	Better	← ADI order rate	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	← Competitors’ attractiveness	
	Experiments	**Current**	**000**	**001** **Worst regime**	**010**	**011**	**100**	**101**	**110** **Best regime**	**111**	$\bar{y}$ **AOI $M**	σ
1	**1,1,1,1**	55.05	47.810	41.030	59.820	54.730	49.550	45.210	62.030	56.560	52.421	6.96
2	**1,1,2,2**	57.98	50.360	42.760	61.240	57.140	52.200	44.420	63.780	58.490	54.263	7.31
3	**1,1,3,3**	56.93	51.180	43.300	62.200	57.760	53.180	45.090	64.920	59.280	54.871	7.35
4	**1,2,1,2**	62.33	54.910	47.290	66.780	62.220	56.920	48.850	69.010	63.740	59.117	7.63
5	**1,2,2,3**	63.510	55.740	48.060	67.910	63.060	57.970	49.750	70.130	64.730	60.096	7.74
6	**1,2,3,1**	51.870	44.290	38.240	55.640	51.870	46.080	39.650	57.670	53.500	48.757	6.98
7	**1,3,1,3**	67.540	59.890	52.490	73.110	67.600	62.280	54.060	74.170	69.620	64.529	7.84
8	**1,3,2,1**	57.370	50.220	48.470	62.580	57.350	51.890	44.860	64.740	59.140	55.180	6.69
9	**1,3,3,2**	60.630	52.960	45.620	64.390	60.500	54.810	47.150	66.790	61.770	57.180	7.47
10	**2,1,1,2**	60.000	52.600	44.970	63.980	59.560	54.540	46.570	66.480	60.930	56.626	7.48
11	**2,1,2,3**	60.950	53.240	46.480	64.810	60.110	55.360	47.240	67.420	61.620	57.470	7.39
12	**2,1,3,1**	47.880	40.690	34.860	51.460	47.950	42.570	36.220	53.390	49.480	44.944	6.65
13	**2,2,1,3**	65.050	57.440	49.970	70.130	64.830	59.750	51.600	71.800	66.750	61.924	7.75
14	**2,2,2,1**	54.310	46.920	40.530	58.860	54.100	48.610	41.960	61.020	55.870	51.353	7.24
15	**2,2,3,2**	57.400	49.660	42.470	60.620	56.710	51.430	44.070	63.120	58.010	53.721	7.23

(continued)

		AOI($L_{27}(3^{4-1}, 2^3+1)$)										
		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	← Industry growth	
		Same	Worse	Worse	Better	Better	Worse	Worse	Better	Better	← ADI order rate	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	← Competitors' attractiveness	
	Experiments	**Current**	**000**	**001 Worst regime**	**010**	**011**	**100**	**101**	**110 Best regime**	**111**	$\bar{y}$ **AOI $M**	σ
16	**2,3,1,1**	58.860	51.960	45.220	64.790	58.960	53.670	46.540	66.830	60.740	56.397	7.58
17	**2,3,2,2**	62.010	54.520	47.320	66.460	62.060	56.470	48.800	68.620	63.560	58.869	7.53
18	**2,3,3,3**	63.350	55.500	48.280	67.850	63.110	57.670	49.880	69.900	64.780	60.036	7.66
19	**3,1,1,3**	62.740	55.240	47.710	67.350	62.230	57.450	49.400	69.550	63.920	59.510	7.61
20	**3,1,2,1**	50.970	43.660	37.650	55.000	49.700	45.450	39.050	57.090	52.520	47.899	6.86
21	**3,1,3,2**	53.940	46.220	39.530	56.560	53.070	47.990	41.100	59.050	54.410	50.208	6.86
22	**3,2,1,1**	56.220	49.280	42.660	61.600	56.080	50.940	44.040	63.820	57.930	53.619	7.39
23	**3,2,2,2**	59.210	51.770	44.520	62.990	58.840	53.600	46.070	65.460	60.130	55.843	7.31
24	**3,2,3,3**	60.290	52.560	45.220	64.070	59.580	54.550	46.890	66.640	61.030	56.759	7.44
25	**3,3,1,2**	63.370	56.110	49.030	68.460	63.570	58.110	50.470	70.080	65.330	60.503	7.53
26	**3,3,2,3**	64.650	57.070	50.000	69.700	64.590	59.300	51.550	71.250	66.470	61.620	7.60
27	**3,3,3,1**	54.400	46.980	40.920	59.040	54.330	48.550	42.280	61.170	56.050	51.524	7.19
Σcolumn		1588.9	1388.8	1204.6	1707.4	1581.6	1440.9	1242.8	1765.9	1626.4		

Appendix 6.4.2 AOI($L_{27}(3^{4-1},2^3+1)$) at $t = 18$

		AOI($L_{27}(3^{4-1}, 2^3+1)$)										
		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	← Industry growth	
		Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	← ADI order rate	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	← Competitors' attractiveness	
	Experiments	**Current**	**000**	**001 Worst regime**	**010**	**011**	**100**	**101**	**110 Best regime**	**111**	$\bar{y}$ **AOI $M**	σ
1	**1,1,1,1**	53.91	41.04	30.62	58.24	48.55	45.78	34.09	64.33	53.34	47.767	11.09
2	**1,1,2,2**	57.98	57.20	44.43	32.56	59.86	51.00	49.42	36.54	66.80	50.643	11.23
3	**1,1,3,3**	58.25	45.47	32.85	60.88	51.28	50.42	32.21	68.35	56.08	50.643	12.19
4	**1,2,1,2**	59.70	48.37	36.99	64.22	55.42	52.74	41.53	70.25	59.63	54.317	10.68
5	**1,2,2,3**	61.23	49.29	37.44	65.34	55.95	54.04	41.39	71.79	60.55	55.224	11.10
6	**1,2,3,1**	49.96	36.11	26.59	52.27	45.11	40.96	29.98	58.16	49.50	43.182	10.61
7	**1,3,1,3**	62.87	51.89	41.16	68.99	59.26	56.17	44.57	72.55	64.22	57.964	10.61
8	**1,3,2,1**	54.85	43.73	33.17	60.51	50.54	48.00	36.43	68.46	55.27	50.107	11.26
9	**1,3,3,2**	58.88	46.88	35.31	62.33	53.99	51.47	38.97	69.02	57.94	52.754	10.91
10	**2,1,1,2**	57.80	46.30	34.89	61.41	52.73	50.86	38.62	68.16	56.71	51.942	10.67
11	**2,1,2,3**	58.90	47.01	35.10	62.18	52.88	51.86	39.26	69.40	57.29	52.653	10.91
12	**2,1,3,1**	43.84	30.84	21.80	46.11	39.07	35.43	25.03	51.47	43.30	37.432	9.98
13	**2,2,1,3**	61.03	50.03	39.06	66.18	56.74	54.39	42.70	71.22	61.51	55.873	10.57
14	**2,2,2,1**	52.60	39.56	29.87	56.55	47.36	44.14	33.25	62.25	52.00	46.398	10.74
15	**2,2,3,2**	55.84	43.16	32.04	58.67	49.94	47.90	35.90	65.61	54.06	49.236	10.82
16	**2,3,1,1**	54.67	44.56	34.63	61.64	51.22	48.26	37.63	67.05	55.67	50.592	10.61

(continued)

		AOI($L_{27}(3^{4-1}, 2^3+1)$)										
		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	← Industry growth	
		Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	← ADI order rate	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	← Competitors' attractiveness	
	Experiments	**Current**	**000**	**001** **Worst regime**	**010**	**011**	**100**	**101**	**110** **Best regime**	**111**	$\bar{y}$ **AOI $M**	σ
17	**2,3,2,2**	58.58	47.62	36.78	63.21	54.62	51.70	40.16	69.15	58.68	53.389	10.54
18	**2,3,3,3**	60.09	48.57	37.38	64.49	55.30	52.98	41.11	70.69	59.74	54.483	10.79
19	**3,1,1,3**	59.28	48.26	37.07	63.34	54.33	52.71	40.94	69.54	58.67	53.793	10.43
20	**3,1,2,1**	47.82	34.98	25.91	50.58	44.98	39.49	29.23	56.55	47.35	41.877	10.21
21	**3,1,3,2**	51.13	38.28	28.15	52.66	45.31	43.22	31.88	59.52	49.47	44.402	10.18
22	**3,2,1,1**	52.80	42.32	32.38	58.48	48.60	46.33	35.60	64.50	53.16	48.241	10.39
23	**3,2,2,2**	56.50	45.30	34.28	59.78	51.57	49.65	37.95	66.54	53.22	50.532	10.22
24	**3,2,3,3**	57.65	46.06	34.64	60.73	51.90	50.62	38.68	67.94	56.05	51.586	10.57
25	**3,3,1,2**	58.59	48.41	38.19	63.95	55.39	52.20	41.37	68.39	59.68	54.019	10.03
26	**3,3,2,3**	60.08	49.40	38.87	64.96	56.05	53.56	42.37	69.84	60.67	55.089	10.20
27	**3,3,3,1**	51.81	39.51	30.27	56.26	47.03	43.76	33.53	62.35	51.42	46.216	10.53
Σcolumn		25462	1516.6	1210.3	919.87	1596.5	1395.0	1319.6	1013.8	1759.6	1512.0	

Appendix 6.4.3 AOI($L_{27}(3^{4-1},2^3+1)$) at $t = 24$

		AOI($L_{27}(3^{4-1}, 2^3+1)$)										
		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	← Industry demand	
		Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	← ADI orders	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	← Competitiveness	
	Experiments	**Current**	**000**	**001** **Worst regime**	**010**	**011**	**100**	**101**	**110** **Best regime**	**111**	**$\bar{y}$ AOI $M**	**σ**
1	**1,1,1,1**	51.81	34.10	21.65	53.19	41.56	41.80	26.90	62.54	48.57	42.458	13.18
2	**1,1,2,2**	55.17	38.05	23.84	54.64	43.66	46.35	29.93	65.28	50.22	45.238	13.04
3	**1,1,3,3**	56.40	39.32	24.12	55.43	43.59	47.63	30.84	67.00	50.83	46.129	13.34
4	**1,2,1,2**	55.22	41.29	28.48	56.24	46.29	48.75	33.93	65.59	52.53	47.591	11.60
5	**1,2,2,3**	57.11	42.38	28.87	57.11	46.44	50.50	34.71	67.23	53.02	48.597	11.94
6	**1,2,3,1**	47.41	27.68	16.11	45.93	36.89	35.33	21.25	55.65	48.73	37.220	13.45
7	**1,3,1,3**	55.88	42.78	30.74	58.17	47.87	49.25	35.67	62.25	54.63	48.582	10.54
8	**1,3,2,1**	51.07	37.40	25.12	54.43	42.36	44.79	30.07	63.64	49.28	44.240	12.09
9	**1,3,3,2**	55.57	40.79	27.31	55.76	45.50	48.79	32.82	66.06	51.56	47.129	12.08
10	**2,1,1,2**	54.01	40.12	27.14	53.69	44.37	47.87	32.72	63.85	49.99	45.973	11.35
11	**2,1,2,3**	55.39	41.06	27.33	54.19	44.16	49.11	33.57	65.26	50.38	46.717	11.63
12	**2,1,3,1**	38.91	20.93	9.99	37.49	28.63	28.00	14.81	46.02	35.34	28.902	11.88
13	**2,2,1,3**	55.22	41.92	29.65	55.87	46.00	48.93	35.00	64.13	52.75	47.719	10.86
14	**2,2,2,1**	49.94	32.29	20.79	50.93	40.12	39.93	25.90	60.46	46.57	40.770	12.76
15	**2,2,3,2**	53.06	36.49	23.21	52.77	42.32	44.29	29.14	63.51	48.34	43.681	12.60
16	**2,3,1,1**	49.21	37.01	25.83	53.46	42.04	43.44	30.33	61.82	48.17	43.479	11.29
17	**2,3,2,2**	53.69	40.41	28.80	54.54	45.25	47.44	33.14	63.76	50.99	46.447	10.99

(continued)

		AOI(L$_{27}$(3$^{4-1}$, 2^3+1))										
		Uncertainty regimes										
		Same	Lower	Lower	Lower	Lower	Higher	Higher	Higher	Higher	← Industry demand	
		Same	Weaker	Weaker	Stronger	Stronger	Weaker	Weaker	Stronger	Stronger	← ADI orders	
		Same	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	Weaker	Stronger	← Competitiveness	
	Experiments	**Current**	**000**	**001** **Worst regime**	**010**	**011**	**100**	**101**	**110** **Best regime**	**111**	$\bar{y}$ **AOI $M**	$\boldsymbol{\sigma}$
18	**2,3,3,3**	55.41	41.39	28.48	55.39	45.44	49.01	34.07	65.13	51.71	47.337	11.40
19	**3,1,1,3**	54.47	41.06	28.51	53.49	44.77	48.58	34.20	62.55	50.65	46.476	10.60
20	**3,1,2,1**	44.11	26.45	15.51	42.72	39.84	33.38	20.55	52.30	40.93	35.088	12.07
21	**3,1,3,2**	47.48	30.40	17.90	44.57	36.37	37.94	23.58	55.52	42.86	37.402	11.90
22	**3,2,1,1**	48.40	35.89	24.32	50.85	40.39	42.67	29.27	39.77	45.65	39.690	8.69
23	**3,2,2,2**	52.61	39.25	26.47	51.67	43.21	46.64	32.07	61.70	48.53	44.683	10.85
24	**3,2,3,3**	53.97	40.11	26.74	52.24	43.12	47.79	32.90	62.98	49.00	45.428	11.10
25	**3,3,1,2**	52.42	40.13	28.72	53.79	42.26	46.34	33.42	60.94	51.10	45.458	10.33
26	**3,3,2,3**	54.13	41.24	29.26	54.39	45.45	48.01	34.45	62.21	51.79	46.770	10.42
27	**3,3,3,1**	48.55	32.32	21.37	49.89	39.39	39.29	26.38	59.36	45.63	40.242	12.09
Σcolumn		25462	1406.6	1002.3	666.26	1412.8	1147.3	1201.9	811.62	1646.5	1319.8	

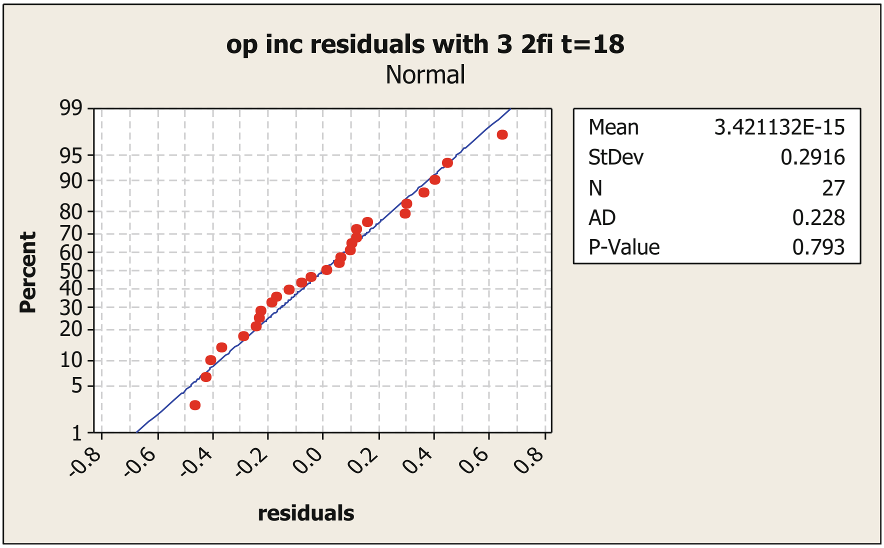
Appendix 6.5 AOI($L_{27}(3^{4-1},2^3+1)$) Controllable Variables Statistics

Appendix 6.5.1 Controllable Variables ANOVA and Residuals at $t = 18$

Analysis of Variance. AOI $L_{27}(3^{4-1},2^3+1)$ $t = 18$

Source	DF	Seq SS	Adj SS	Adj MS	F	P
r&d	2	16.127	16.127	8.064	21.89	0.002
yield	2	103.321	103.321	51.660	140.25	0.000
cogs	2	108.357	108.357	54.178	147.08	0.000
price	2	332.517	332.517	166.258	451.36	0.000
yield**cogs*	4	10.914	10.914	2.728	7.41	0.017
yield*price	4	8.080	8.080	2.020	5.48	0.033
*cogs**price	4	7.628	7.628	1.907	5.18	0.038
Error	6	2.210	2.210	0.368		
Total	26	589.153				

$S = 0.606917$, R-Sq = 99.62%, R-Sq(adj) = 98.37%

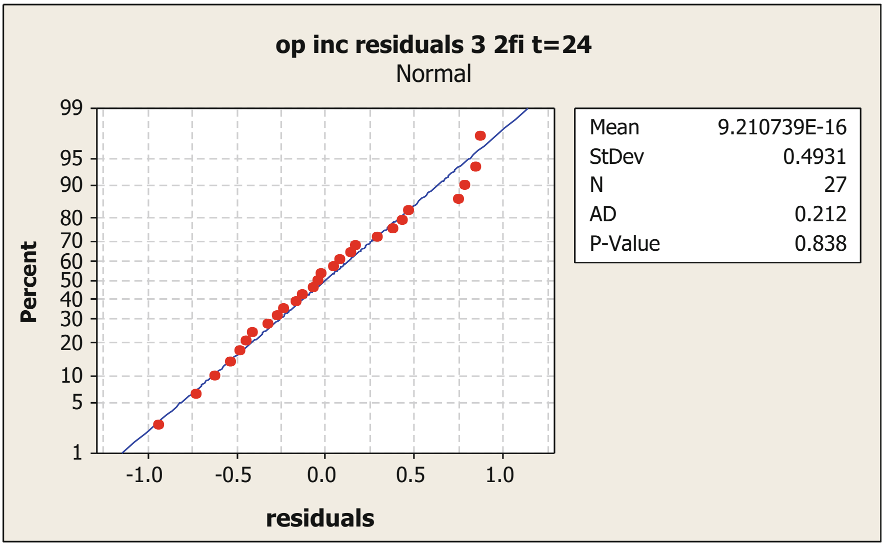


Appendix 6.5.2 Controllable Variables ANOVA and Residuals at $t = 24$

Analysis of Variance. AOI $L_{27}(3^{4-1},2^{3}+1)$ t = 24

Source	DF	Seq SS	Adj SS	Adj MS	F	P
r&d	2	37.707	37.707	18.854	17.90	0.003
yield	2	70.527	70.527	35.263	33.47	0.001
cogs	2	69.407	69.407	34.704	32.94	0.001
price	2	312.960	312.960	156.480	148.54	0.000
yield**cogs*	4	33.383	33.383	8.346	7.92	0.014
yield*price	4	28.342	28.342	7.085	6.73	0.021
*cogs**price	4	20.388	20.388	5.097	4.84	0.044
Error	6	6.321	6.321	1.053		
Total	26	579.035				

S = 1.02638 R-Sq = 98.91% R-Sq(adj) = 95.27%



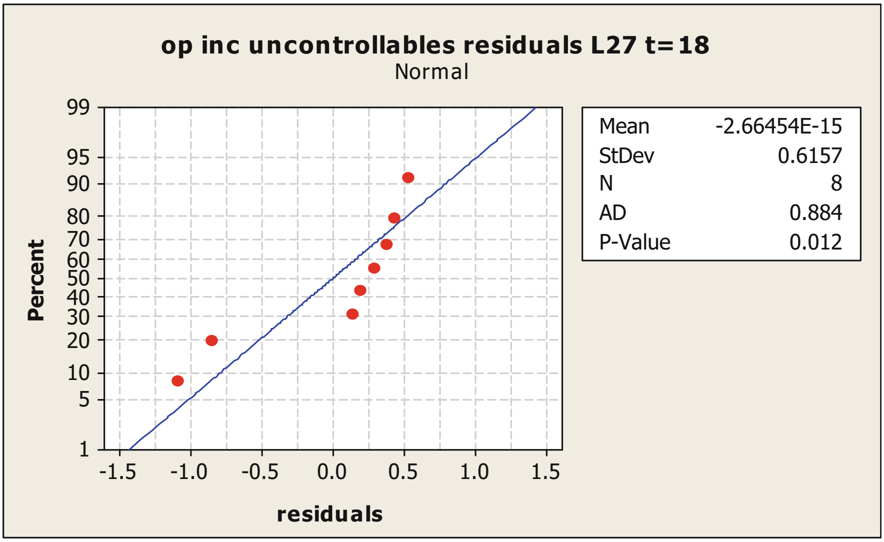
Appendix 6.6 AOI($L_{27}(3^{4-1},2^3+1)$) Uncontrollable Variables Statistics

Appendix 6.6.1 Uncontrollable Variables. Table and Residuals Graph at t = 18

Analysis of Variance. $L_{27}(3^{4-1},2^3+1)$ t = 18, uncontrollable variables

Source	DF	Seq SS	Adj SS	Adj MS	F	P
LT growth	1	42.51	42.51	42.51	64.07	0.001
ADI orders	1	599.48	599.48	599.48	903.54	0.000
Competitor	1	217.22	217.22	217.22	327.39	0.000
Error	4	2.65	2.65	0.66		
Total	7	861.87				

S = 0.814545, R-Sq = 99.69%, R-Sq(adj) = 99.46%

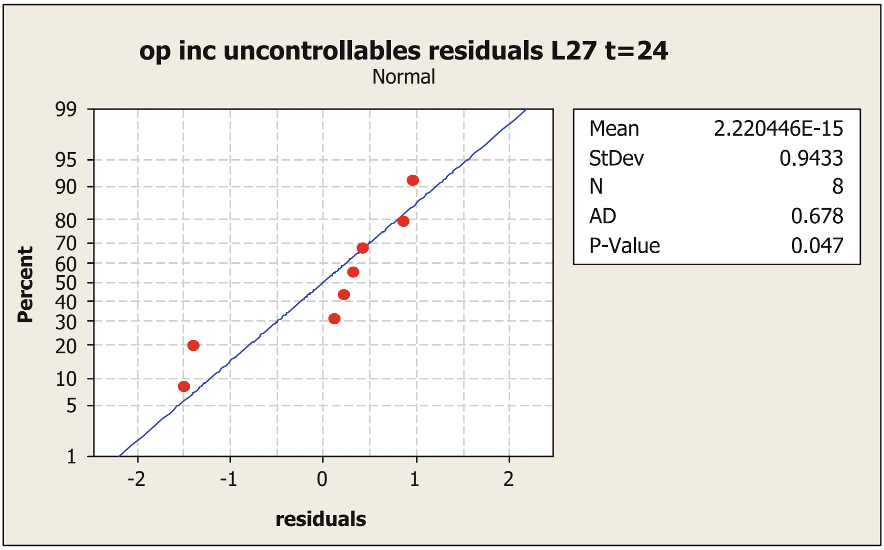


Appendix 6.6.2 Uncontrollable Variables. Table and Residuals Graph at t = 24

Analysis of Variance. AOI($L_{27}(3^{4-1}, 2^3+1)$)t = 24, uncontrollable variables

Source	DF	Seq SS	Adj SS	Adj MS	F	P
LT growth	1	96.20	96.20	96.20	61.77	0.001
ADI orders	1	586.63	586.63	586.63	376.69	0.000
Competitor	1	296.40	296.40	296.40	190.33	0.000
Error	4	6.23	6.23	1.56		
Total	7	985.46				

S = 1.24793, R-Sq = 99.37%, R-Sq(adj) = 98.89%

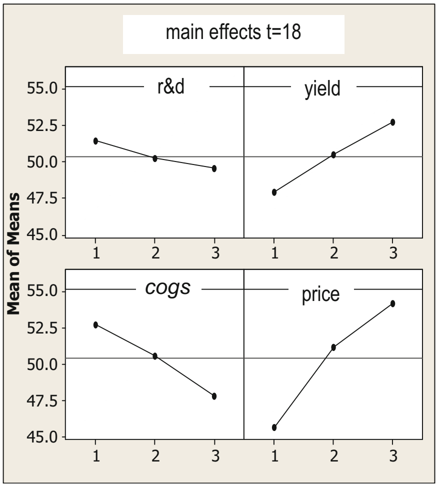


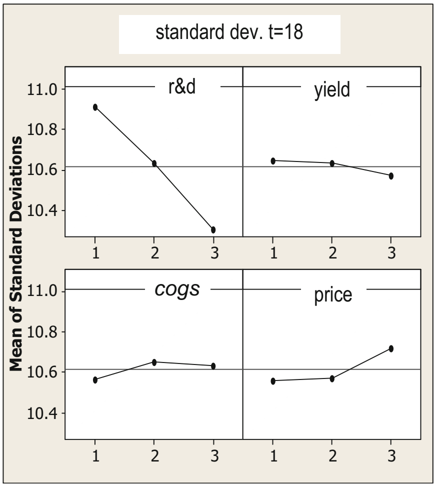
Appendix 6.7 AOI($L_{27}(3^{4-1},2^3+1)$) Experiment Responses. Means and Standard Deviations

Appendix 6.7.1 Response Tables AOI($L_{27}(3^{4-1},2^3+1)$) at $t = 18$

Response Table for Means t = 18				
Level	r&d	yield	*cogs*	price
1	51.40	47.94	52.72	45.73
2	50.23	50.51	50.61	51.23
3	49.53	52.72	47.83	54.21
Delta	1.87	4.79	4.89	8.47
Rank	4	3	2	1

Response Table for Standard Deviations t = 18				
Level	r&d	yield	*cogs*	price
1	10.91	10.65	10.57	10.56
2	10.63	10.63	10.65	10.57
3	10.31	10.57	10.63	10.72
Delta	0.61	0.07	0.09	0.16
Rank	1	4	3	2

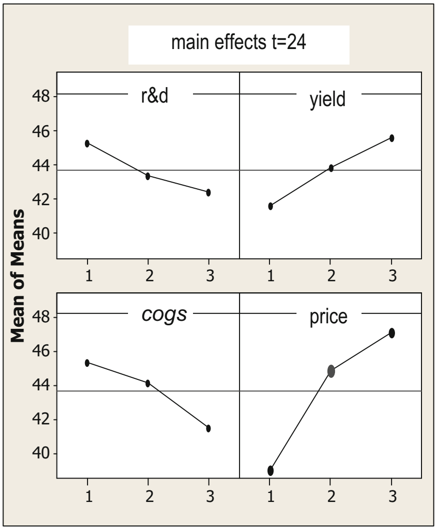


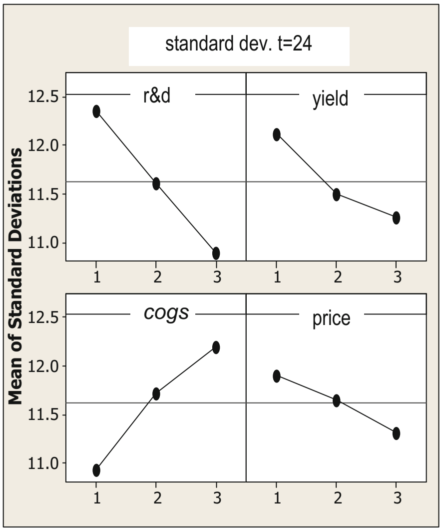


Appendix 6.7.2 Response Tables AOI($L_{27}(3^{4-1},2^3+1)$) at $t = 24$

Response Table for Means t = 24				
Level	r&d	yield	*cogs*	price
1	45.24	41.60	45.32	39.02
2	43.33	43.83	44.16	44.87
3	42.41	45.55	41.49	47.09
Delta	2.84	3.95	3.83	8.07
Rank	4	2	3	1

Response Table for Standard Deviations t = 24				
Level	r&d	yield	*cogs*	price
1	12.36	12.11	10.94	11.90
2	11.60	11.50	11.72	11.65
3	10.90	11.25	12.20	11.31
Delta	1.47	0.86	1.26	0.59
Rank	1	3	2	4





Appendix 6.8 Data Set for $L'_9(3^{4-2},2^3+1)$ for t = 12

		Annual operating income $M										
		Uncontrollable variables										
		Same	Lower	Lower	Lower	Lower	**Higher**	**Higher**	**Higher**	**Higher**	← Industry demand	
		Same	Weaker	Weaker	**Stronger**	**Stronger**	Weaker	Weaker	Stronger	**Stronger**	← ADI orders	
		Same	Weaker	**Stronger**	Weaker	**Stronger**	Weaker	**Stronger**	Weaker	**Stronger**	← Competitiveness	
		Current	000	001	010	011	100	101	110	111		
	Experiments	Current	. . .	**Worst case**	. . .	. . .	. . .	. . .	**Best case**		$\bar{y}$ **AOI $M**	**σ**
1	1,1,1,1	55.05	47.81	41.03	59.82	54.73	49.55	45.21	62.03	56.56	52.421	6.962
2	1,1,2,2	57.98	50.36	42.76	61.24	57.14	52.20	44.42	63.78	58.49	54.263	7.314
3	1,1,3,3	56.93	51.18	43.30	62.20	57.76	53.18	45.09	64.92	59.28	54.871	7.355
4	1,2,1,2	62.33	54.91	47.29	66.78	62.22	56.92	48.85	69.01	63.74	59.117	7.630
5	1,2,2,3	63.51	55.74	48.06	67.91	63.06	57.97	49.75	70.13	64.73	60.096	7.738
6	1,2,3,1	51.87	44.29	38.24	55.64	51.87	46.08	39.65	57.67	53.50	48.757	6.976
7	1,3,1,3	67.54	59.89	52.49	73.11	67.60	62.28	54.06	74.17	69.62	64.529	7.843
8	1,3,2,1	57.37	50.22	48.47	62.58	57.35	51.89	44.86	64.74	59.14	55.18	6.692
9	1,3,3,2	60.63	52.96	45.62	64.39	60.50	54.81	47.15	66.79	61.77	57.18	7.467
10[a]	2,1,2,3	60.95	53.24	46.48	64.81	60.11	55.36	47.24	67.42	61.62	57.47	7.391
11[a]	2,1,3,1	47.88	40.69	34.86	51.46	47.95	42.57	36.22	53.39	49.48	44.944	6.648

[a] Rows 10, 11 only used for $L'_9(3^{4-2}+2, 3^2+1)$, a one-time use array to obtain F and p values for controllable variables

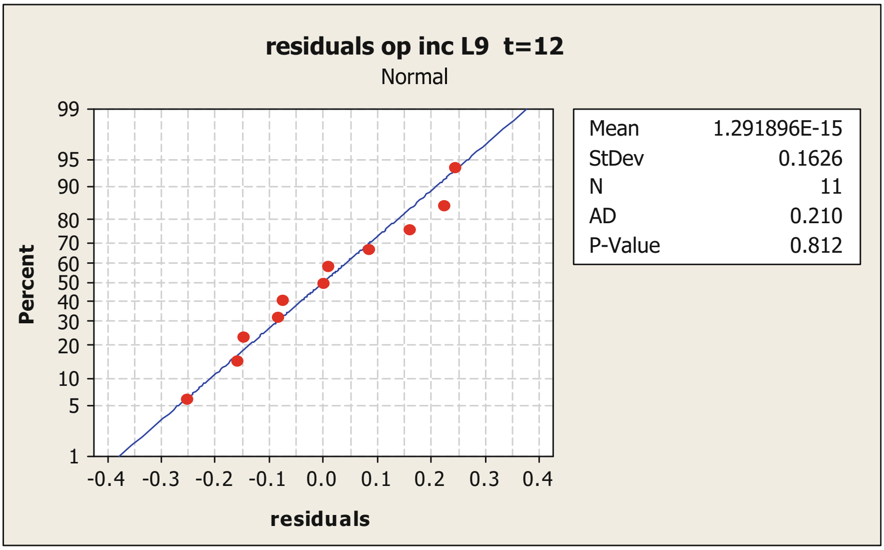
Appendix 6.9 ANOVA AOI($L_9(3^{4-2},2^3+1)$) Controllable Variables Statistics

Appendix 6.9.1 ANOVA Table and Residuals t = 12

Analysis of Variance. AOI L9(3^{4-2}, 2^3+1) t = 12

Source	DF	Seq SS	Adj SS	Adj MS	F	P
r&d	2	1.572	2.829	1.415	10.70	0.085
yield	2	40.110	43.361	21.680	164.06	0.006
cogs	2	35.022	47.568	23.784	179.97	0.006
price	2	110.133	110.133	55.067	416.69	0.002
Error	2	0.264	0.264	0.132		
Total	10	187.101				

S = 0.363529, R-Sq = 99.86%, R-Sq(adj) = 99.29%

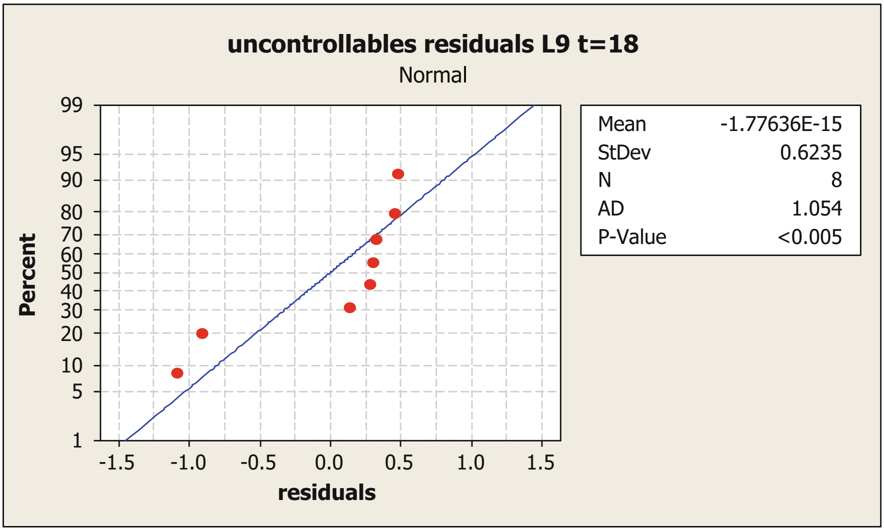


Appendix 6.9.2 ANOVA Table and Residuals t = 18

Analysis of Variance. AOI L9(3^{4-2},2^3+1) t = 18

Source	DF	Seq SS	Adj SS	Adj MS	F	P
r&d	2	10.462	12.741	6.370	18.89	0.050
yield	2	29.960	32.890	16.445	48.76	0.020
cogs	2	34.383	47.264	23.632	70.08	0.014
price	2	113.709	113.709	56.854	168.59	0.006
Error	2	0.674	0.674	0.337		
Total	10	189.188				

S = 0.580720, R-Sq = 99.64%, R-Sq(adj) = 98.22%

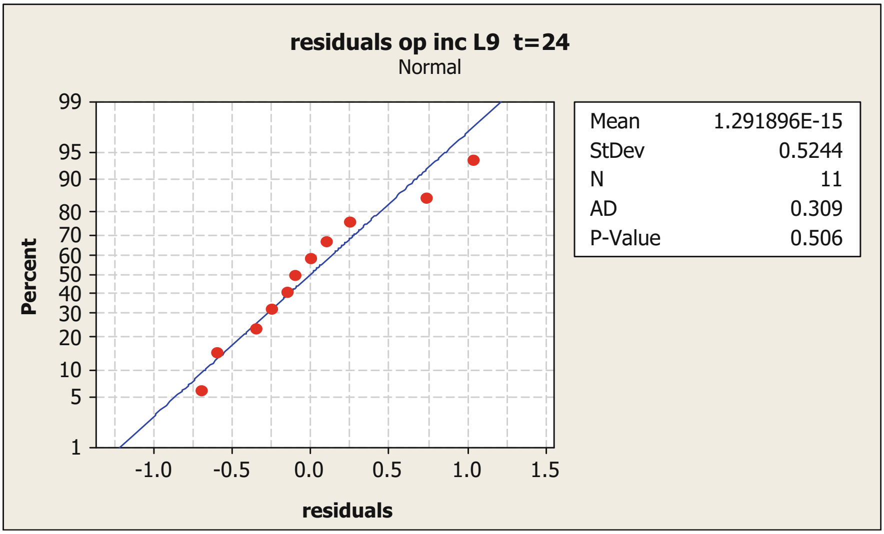


Appendix 6.9.3 ANOVA Table and Residuals t = 24

Analysis of Variance. AOI $L_9(3^{4-2},2^3+1)$ t = 24

Source	DF	Seq SS	Adj SS	Adj MS	F	P
r&d	2	42.195	44.634	22.317	16.23	0.058
yield	2	19.899	23.648	11.824	8.60	0.104
cogs	2	37.780	45.394	22.697	16.51	0.057
price	2	73.048	73.048	36.524	26.56	0.036
Error	2	2.750	2.750	1.375		
Total	10	175.672				

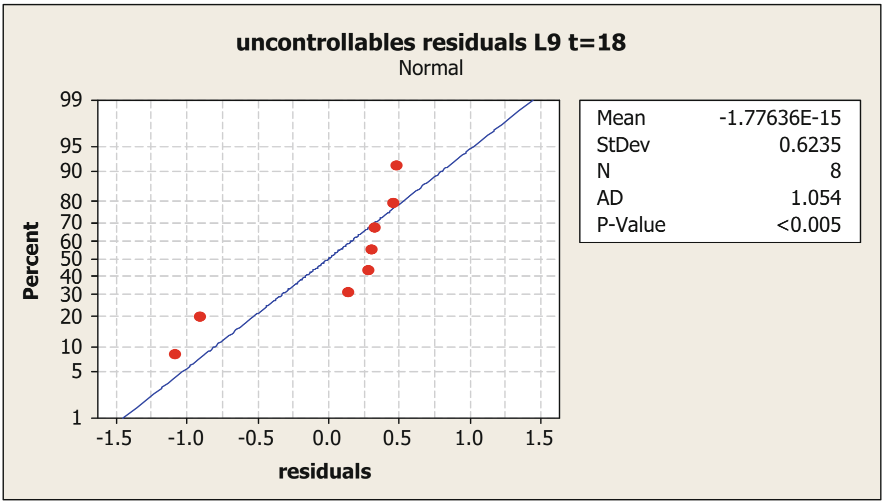
S = 1.17266, R-Sq = 98.43%, R-Sq(adj) = 92.17%



Appendix 6.10 ANOVA AOI($L_9(3^{4-2},2^3$+1)) Uncontrollable Variables Statistics

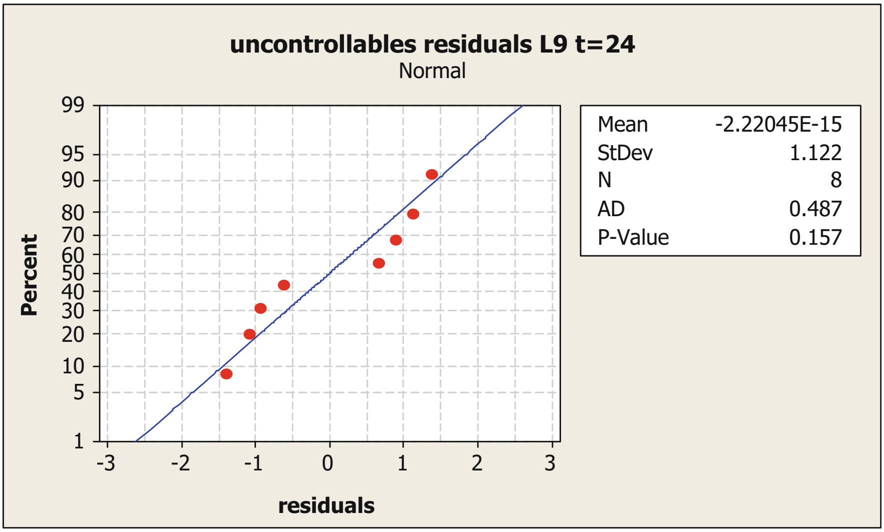
Appendix 6.10.1 ANOVA Table and Residuals t = 18

Analysis of Variance. AOI L9(3^{4-2},2^3+1) t = 18, uncontrollable variables						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
LT growth	1	43.30	43.30	43.30	63.64	0.001
ADI orders	1	599.85	599.85	599.85	881.69	0.000
Competitor	1	214.59	214.59	214.59	315.41	0.000
Error	4	2.72	2.72	0.68		
Total	7	860.46				
S = 0.824829, R-Sq = 99.68%, R-Sq(adj) = 99.45%						



Appendix 6.10.2 ANOVA Table and Residuals t = 24

Analysis of Variance. AOI L9(3^{4-2},2^3+1) t = 24						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
LT growth	1	125.72	125.72	125.72	57.02	0.002
ADI orders	1	647.40	647.40	647.40	293.66	0.000
Competitor	1	271.60	271.60	271.60	123.20	0.000
Error	4	8.82	8.82	2.20		
Total	7	1053.54				
S = 1.48480, R-Sq = 99.16%, R-Sq(adj) = 98.54%						



Appendix 6.11 AOI Response Tables $L_9(3^{4-2},2^3+1)$

Appendix 6.11.1 AOI Response Tables $L_9(3^{4-2},2^3+1)$ t = 18

Response Table for Means t = 18

Level	r&d	yield	*cogs*	price
1	51.88	48.28	52.54	46.14
2	49.92	49.96	51.15	50.55
3	49.27	52.83	47.38	54.38
Delta	2.61	4.55	5.16	8.24
Rank	4	3	2	1

Response Table for Standard Deviations t = 18

Level	r&d	yield	*cogs*	price
1	11.02	10.72	10.54	10.62
2	10.55	10.50	10.71	10.45
3	10.25	10.59	10.56	10.74
Delta	0.77	0.22	0.17	0.28
Rank	1	3	4	2

Appendix 6.11.2 AOI Response Tables $L_9(3^{4-2},2^3+1)$ t = 12, 18, 24

Response Table for Means t = 24

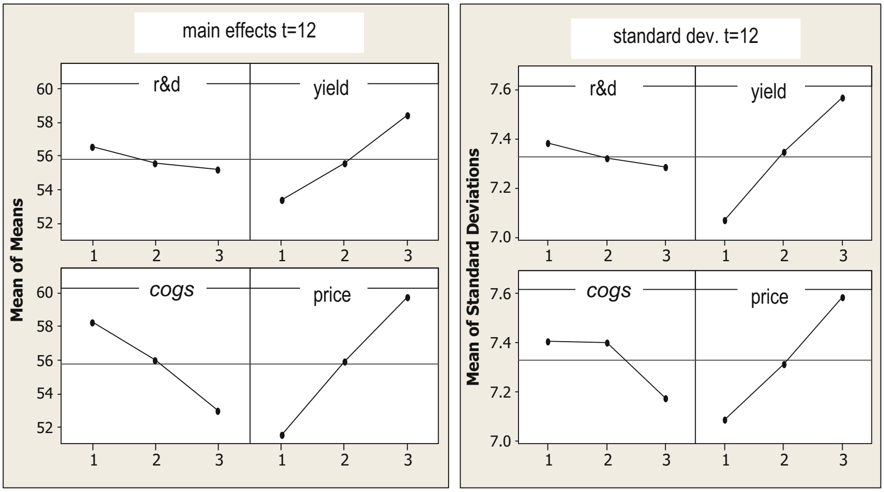
Level	r&d	yield	*cogs*	price
1	46.03	42.19	44.31	39.98
2	42.92	42.10	45.29	43.70
3	41.10	45.76	40.45	46.37
Delta	4.92	3.67	4.83	6.39
Rank	2	4	3	1

Response Table for Standard Deviations t = 24

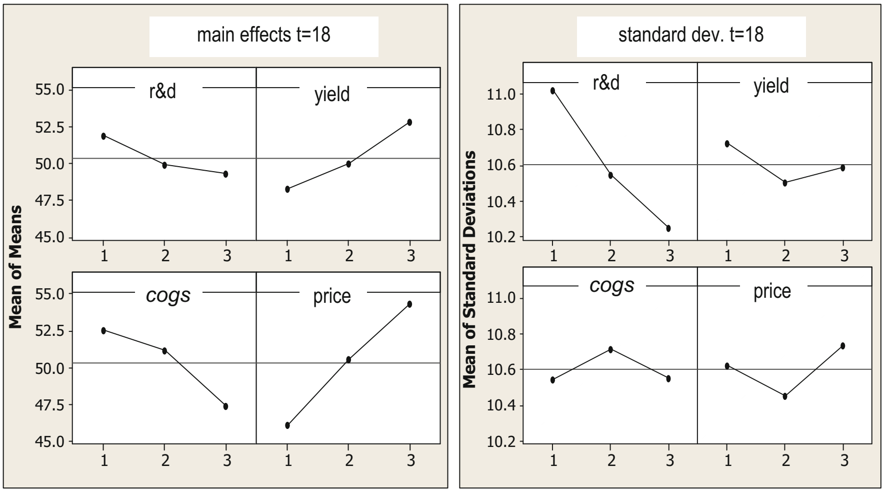
Level	r&d	yield	*cogs*	price
1	12.40	12.23	12.97	12.24
2	11.63	13.18	11.56	11.56
3	12.64	11.26	12.14	12.88
Delta	1.02	1.92	1.41	1.32
Rank	4	1	2	3

Appendix 6.12 Plots of Response AOI($L_9(3^{4-2},2^3+1)$) for t = 12, 18, 24

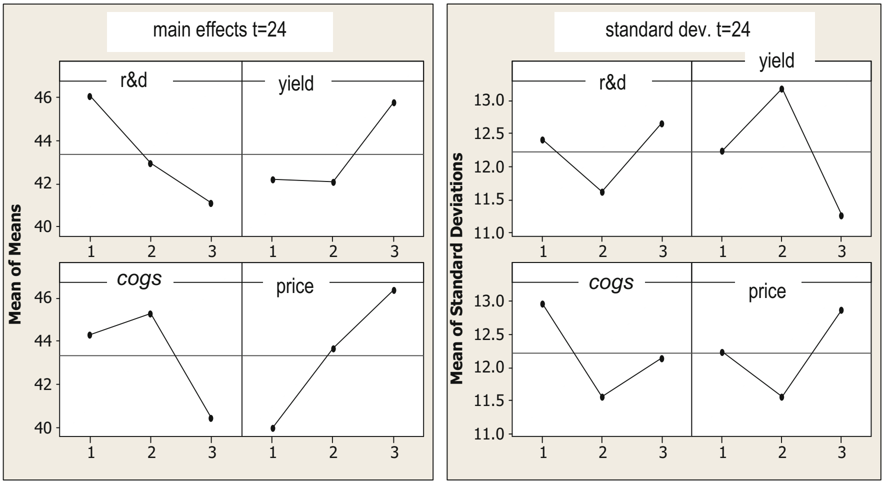
Appendix 6.12.1 Plots of Response AOI($L_9(3^{4-2},2^3+1)$) for t = 12



Appendix 6.12.2 AOI Plots of Response AOI($L_9(3^{4-2},2^3+1)$) for t = 18



Appendix 6.12.3 AOI Plots of Response $AOI(L_9(3^{4-2},2^3+1))$ for $t = 24$



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Part III
Verifying Efficacy: *In Situ* Case Studies

The goal of Part III is to illustrate the *efficacy* of our prescriptive paradigm, by going to the field and testing with customers in the real world. Our assertion is that our prescriptive methodology *works* if and only if both its *functionality* and *efficacy* can be verified. Functionality is verified by us as developers of the paradigm and its prescriptions. Efficacy is verified by executives who want to use our prescriptive methodology to address their complex and messy decision situations.

In Part II we addressed the issues of functionality. We demonstrated support for functionality with simulations using a system dynamics surrogate of a real firm.

The goal of Part III is to demonstrate the efficacy of our prescriptive methodology with *in situ* applications with real organizations. This material is presented in three chapters.

	Chapter 7	Chapter 8	Chapter 9
Case	HiTEM Inc.	Yokozuna project	US Navy
Domain	Electronics manufacturer	e-business services	National Defense
Scope	Global business	Global business	US and global security
Decision situation	• survival of the firm • 3 years of no profits • severe cash flow problem	• risky high tech project • unstable requirements • customer satisfaction at risk • managerial uncertainty	• geopolitical uncertainties • constant global problems • severe budget constraints • US hegemony
Goals Objectives	• turn around in 6 months and show profit	• stabilize requirements • meet schedule commitments • drive customer satisfaction	A US fleet for 2037 that can: • protect the US homeland • build global security • project power • win decisively
Challenges	• president's job at risk • bankers getting nervous • key skills may walk	• new technology for provider and customer • senior execs "helping"	• emerging new regional crises • new administration

Chapter 7
Verifying Efficacy: HiTEM Inc.

Abstract This chapter is an introduction to Part III, the third step in our presentation of our paradigm and prescriptive methodology. This first chapter of Part III is our first real business-enterprise case study executed in the field. Whereas in Part II, we used the ADI system dynamics model as a surrogate to verify *functionality*, we now go to field in the real word to verify *efficacy*. Functionality and efficacy demonstrate that our methodology *works*.

7.1 Introduction

In Part I, we showed the conceptual and technical rigor, as well as, the distinctive and practical nature of our methodology. Following and extending the work of scholars, we distilled multi-disciplinary first-principles and framed the executive-decision life-cycle as a sociotechnical complex of five spaces. Our methodology is grounded on engineering-design thinking, systems-development methods and proven sociotechnical practices. We showed how to systematically design decisions that are robust even under noisy operating environments. To design such decisions, we specified a systematic process to identify the key managerially controllable and uncontrollable variables. Using these variables, we prescribed how to construct alternative decision-specifications, predict their outputs and standard deviations. To mitigate the impact of uncertainty, we use robust engineering-design methods to exploit the interactions between controllable and uncontrollable variables. We presented a new and innovative way to measure and analyze the quality of the socio-technical system by using the manufacturing-engineering methods of gage repeatability and reproducibility (Gage R&R). Putting all this together, we have characterized and represented, in detail, the technical and social subsystems of our executive-decision methodology.

In Part II, we raised the question of whether our paradigm and its methods "**work**". We discussed how to systematically determine and measure the extent to which a complex artefact like our executive-decision paradigm and its methods "work", not "work"; why and how to make it "work" better. We argued that our methodology ***works***, if and only if, it simultaneously satisfies two necessary and sufficient conditions, *viz.* it is ready-**to**-work *for users* ***and*** ready-**for**-work *by a user*

V. Tang et al., *Executive Decision Synthesis*, Contributions to Management Science,
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for a specific class of decision situations. Ready-to-work needs to be demonstrated by us as creators of the methodology. In Part II, we demonstrated that our methodology, as an intellectual artefact works. It is functional and ***works*** as intended by us, as engineers of our methodology. We used the ADI surrogate as a test object to demonstrate our methodology is *ready-**to**-work*. By a large measure, our methodology satisfied the X-RL conditions (Tables 4.3 and 7.1).

Now in Part III, we show how users satisfy themselves the methodology *works* for them. Namely, that it is ready-**for**-work with evidence of the ***efficacy*** of our methodology. So, in this chapter we concentrate on the right hand side of Fig. 7.1.

In this chapter, we will verify efficacy with a real customer. Because the company wishes to remain anonymous, we will call it HiTEM Inc., for High Tech Electronics Manufacturing. The firm is a contract manufacturing company of electronics components. It has over a dozen manufacturing plants in the US, Asia and South America. We will demonstrate that our methodology will meet the X-RL

Table 7.1 Readiness level specifications for executive decisions

Readiness Level	Our systematic process	Strategy
X-RL1	Characterize the problem space	Sense making, frame goals and objectives
X-RL2	Engineer the solution space	Engineer experiments/alternatives
X-RL3	Explore the operations space	Explore entire solution and uncertainty spaces
X-RL4	Evaluate the performance space	Measure robustness, repeatability, reproducibility
X-RL5	Enact the commitment space	Commit plan with approved resources

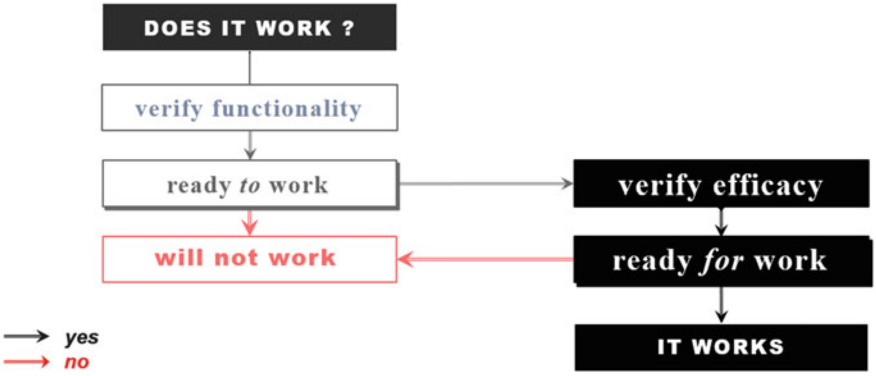

Fig. 7.1 Efficacy is a necessary condition to demonstrate methodology is *ready-for-work*

specifications for *efficacy* (Fig. 7.2). The goal is to prove that the new president can lead the firm out of a disaster, make it profitable and prove he can lead the company and reverse its fortunes. The objective is produce a profit, however small, in 6 months.

In this chapter, we devote a section to each of the five spaces of the executive decision life-cycle, i.e. the Problem, Solution, Operations, Performance, and Commitment Spaces (Fig. 7.3). The objective is to systematically determine the X-RL readiness at each phase of our methodology during the executive-decision life-cycle. We will verify the efficacy of our methodology, against the requirements stipulated for each X-RL. The overall findings will be shown in Chapter Summary.

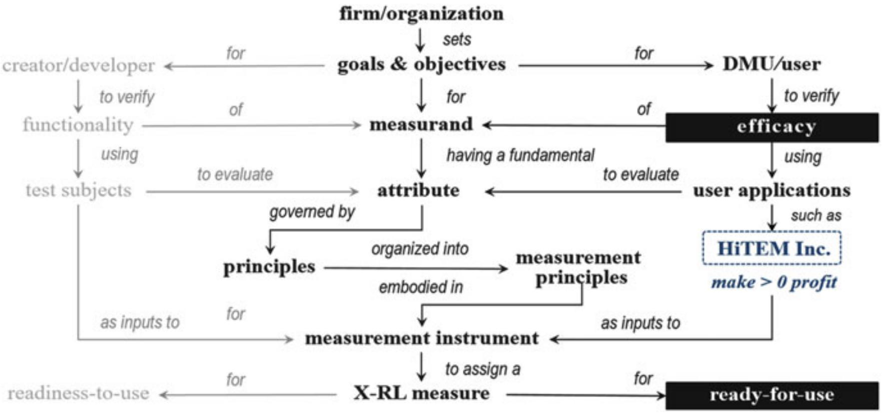

Fig. 7.2 Functionality is a necessary condition to demonstrate methodology *works*

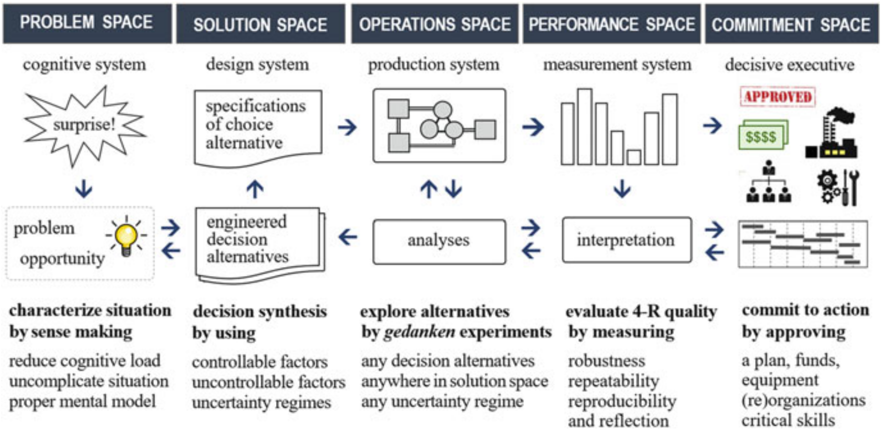

Fig. 7.3 Five spaces of the executive-decision life-cycle

Section 2 covers Characterizing the Problem Space. We apply our methodology to characterize the decision situation adhering to our principles of *abstraction* and *uncomplication* to develop an uncomplicated, but accurate narrative of the executive-decision situation. In Sect. 3, Engineering the Solution Space, we identify the essential decision variables, the problem solving constructs for the solution space and the representations of the spectrum of the uncertainty conditions. We discretize the uncertainty space into a discrete set of *uncertainty regimes*. These are used to establish the base-line for our quantitative work that will follow. In Sect. 4, Exploring the Operations Space, we use an array of experiments under our set of uncertainty regimes that spans the entire uncertainty space. We use representations, of the many and varied decision alternatives, to fully explore the Solution Space. We show a procedure for constructing and exploring any "what if" hypothetical decision alternative and for which we can determine a risk profile by means of its standard deviation. To these ends, we collect data for the evaluations we undertake in the Performance Space, Sect. 5. The Analysis of the Performance Space is fully investigated. We concentrate on the 4-R's of Robustness, Repeatability, Reproducibility and Reflection of key operational performance measurements of our decision methodology. We use the Gage R&R methods from the engineering discipline of Measurement System Analysis (AIAG 2002) to analyze the performance of the sociotechnical system as a production system. This a new and novel application of Gage R&R. We argue that it is a new research area worthy of investigation. In Sect. 6, the Commitment Space, we demonstrate efficacy by reporting what actually happened. Section 7 closes this chapter with a summary of the key learning of this exercise.

7.2 Characterizing the Problem Space

We begin with a brief sketch of HiTEM, follow with a description of the decision situation, and continue with the details of our experiment. This step includes the discovery process for the decision situation and the framing of the decision in DOE form. Forming the DMU and creating a management system to review progress of the work are also part of this process.

7.2.1 Sense-Making and Framing

To preserve the company's anonymity, we will call it High Tech Electronics Manufacturing Inc., HiTEM. The company is a start-up that has been in business less than 10 years. It was formed by a group of young but experienced savvy functional and technology executives. Its business is contract manufacturing for firms that outsource this function. HiTEM is a sizable firm, with ≈$700 M yearly revenues. It has many world class companies as its customers. The majority of them

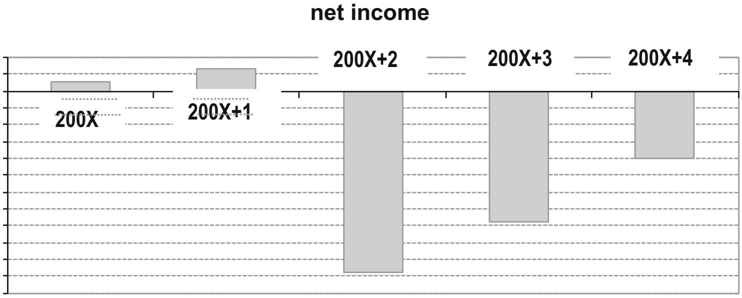

Fig. 7.4 HiTEM net income

are leading companies in the communications, computer, industrial equipment, medical, and defense industries. To work with them, HiTEM has world class technical capabilities; e.g. FDA compliant factories, Class 10,000 clean rooms for development and manufacturing of Class I, II, and III medical products, for classified products for the US military, and so on. It has 15 plants in the US, Asia, and Europe. HiTEM also provides services for product design, automation and test, and manufacturing fulfillment functions. HiTEM's recent financial performance is dismal, no profits for three consecutive years. Though the trend was improving, there were no signs that profits would move to positive territory. There was no end in sight to the problem (Fig. 7.4). Patience exhausted, the board of directors fired its president and replaced him with the VP of manufacturing. To keep his job, the new president has been directed to produce a profit, however modest, in 6 months. He was been empowered to take strong measures to turn around HiTEM.

The new president joined the firm as a founding member. He has a very strong sense of obligation to its employees and major stockholders. He was unsure about the results he could produce. He also judged he needed a "complete big picture" of the alternatives he could exercise with what other outcomes he could reasonably expect. He agreed to participate in this study because he wanted the following:

- A critique of the turnaround initiatives he had just launched,
- More insight into his strategy, its implications, and "new and different alternatives",
- A more rigorous analyses beyond the superficial advice he was getting,
- A deeper and clearer understanding of the effects of uncertainty.

7.2.2 The DMU: Decision Making Unit

HiTEM's president formed the DMU immediately upon our arrival on site at the company's headquarters. He appointed his business strategy executive to administer the DMU's day to day operations. DMU members were the chief financial officer, senior executives from corporate operations, marketing and sales, and

Fig. 7.5 Schematic of the problem space

manufacturing. The president appointed himself *ex officio* sponsoring executive for the project with us as his special advisors. He requested periodic briefings on the progress of the DMU (Fig. 7.5). We used annual reports, SEC filings, board of directors' and confidential internal reports, and company confidential models from manufacturing, finance, marketing, and key geographies. Team members by virtue of their position in the firm had access to line managers and other staff to obtain detailed and specific information on-demand. Data and information that did not exist in the firm, the DMU was empowered to buy or mandate studies.

7.2.3 Goal and Objectives of the Experiment

The objective was simple and direct: Produce a profit in 6 months. The board of directors had been very adamant to the president about this goal. It was the condition for his continued employment. As a founding member of the firm, he was sincerely and highly motivated to succeed. He felt an obligation to the people that had followed him to start this firm. After a number of planning meetings with the DMU, we set the following objectives for our experiment.

- Identify levers that can directly influence corporate profitability within 6 months.
  - Identify those within the control of the executive team
  - Identify those outside the control of the executive team
- Enable orderly and sustainable future profitability.
- Construct alternative solutions to estimate and contrast their effect on profitability against the business-as-usual (BAU) case under a variety of external uncertainty conditions.
- Ensure the analyses and recommendations will be convincing to HiTEM's board of directors.
- Evaluate the overall process.

7.2.4 The Essential Variables

The essential variables are the factors that directly influence the outcomes and attainment of goals. They are either managerially controllable or uncontrollable. The uncontrollable variables are the ones that form the uncertainties that are most important to the achievement of intended outcomes. The DMU specified ten variables, six controllable and four uncontrollable.

7.2.4.1 Managerially Controllable Variables

The controllable variables were identified as follows.

1. *sg&a.* These are the well-known financial variables of Selling, General and Administrative Expense. It is the sum of the eponymous items identified. These are not production or product related expenditures. For example, taking a customer to an expensive lunch is an expense, which has nothing to do with production of the materials of a product. A frugally managed company will watch *sg&a* very carefully to ensure these finds are not wasteful.
2. *cogs (Cost of Goods Sold).* This is another accounting entry in a company's financial statement. It reports the accumulated expenditures attributable to the production of goods sold by a company. It includes the cost of materials, labor and overhead expenditures used to produce products. It also includes warranty expenditures. ***cogs*** **i**s a good indicator of the engineering capability of a company. Given two companies in the same industry making products that compete against each other, with similar technologies; *ceteris paribus* the one with lower *cogs* is likely to be the superior engineering company.
3. *Capacity Utilization.* HiTEM has 15 manufacturing plants around the world. They represent enormous assets and financial expenses to maintain, and operate. Ideally they should be working, at full capacity all the time, making products that will produce profit. For example, airlines keep their planes flying nearly 100% of time. They are not in the air only for maintenance and repairs. A visit to one of HiTEM's flagship plants did not look like a bee-hive of activity.
4. *Customer Portfolio Mix.* It is a truism that not all customers are equally profitable to serve. Some customers produce high profits and many others much less. Identifying the mix of these customers would enable HiTEM to pay more attention to those that were more profitable. A portfolio-analysis of the customer base showed that their profit contribution varied by the kind of services HiTEM performed for them. A new strategy considered shedding customers that did not meet a designated level of profit contribution; e.g. product-design customers contributing <10%, assembly and test (A&T) <6%, and manufacturing <4% level of profit contribution.
5. *Sales.* This variable is more tactical relative to the other variables, which are more strategic in nature. Sales can be ramped up more readily than the other variables. Increased Sales can produce some immediate effect on profit. This is an initiative that hard work and "wearing out shoe leather" can make a difference.

Table 7.2 Controllable variables and levels

Controllable variables	Level 1	Level 2	Level 3	Characteristic
sg&a	\$54 M + 10%	\$54 M (BAU)	\$54 M – 10%	Less is better
cogs	\$651 M + 2%	\$651 M (BAU)	\$651 M – 2%	Less is better
Plant capacity	40% utilization	60% utilization (BAU)	80% utilization	More is better
Customer portfolio mix	Current mix (BAU)	• Development < 10% • A&T < 6% • Manufacturing < 4%	• Development < 20% • A&T < 12% • Manufacturing < 8%	More profitable customers is better
Sales	\$690 M – 5%	\$690 M (BAU)	\$690 M + 5%	More is better
Financing	Annual cash shortfall of \$10 M (BAU)	Divest Mexico plant yields \$12 M annualized	Divest China plant yields \$25 M annualized	More cash is better

6. *Financing*. This variable deals with cash flow and cash availability, both of which are under pressure for HiTEM. It draws management attention to a variety of initiatives that can lessen this cash deficiency.

Through DMU work-sessions and iterative reviews with the president, we arrived at a three-level specification that bracketed the limits of controllability for each of the decision variables (Table 7.2). Operations at "level 3" were deemed doable, albeit with maximum strong effort, but not impossible and "level 1" judged as most unacceptable. DMU members were free to consult with their staffs or develop models to help them determine these limits. The entries marked (BAU) reflect the condition of the variables of Business-As-Usual, i.e. the current business operational condition. The most aggressive actions are shown in column "level 3". The plants in Mexico and China were consistently unprofitable and unlikely to improve. Losses and local business practices in China made that factory a very serious problem. Divestiture was the strategy for these two plants, which would yield one-time cash flows.

These variables reflect our principle of "no free lunch" (Sect. 3.3.2.2). The economic sacrifice of exercising the controllable variables are considered in the financing controllable variable. It serves as a regulator for arbitrarily taking all the variables to their best condition without considering the pecuniary sacrifices that need to be incurred.

7.2.4.2 Managerially Uncontrollable Variables

In a similar fashion, working with the DMU and the president, we were able to elicit and specify the uncontrollable variables (Table 7.3). The four uncontrollable variables are:

1. *Customer/demand Base Change*. HiTEM, as a publicly traded company, is required by law to report its financial performance. The fact that it has been unprofitable, over several years, is not a secret. This is known to its customers, its

Table 7.3 Uncontrollable factors and levels

Uncontrollable factors	Level 1	Level 2	Level 3
	Worst uncertainty regime	Current regime	Better uncertainty regime
Customer/ demand base change	**Lose** customer/ demand and lose >5% gross profit	No change (current)	**Gain** customer/demand and gain >5% gross profit
Senior executive interactions	Senior executives rarely confront or deal openly with differences of opinion; rarely request, get, or give honest feedback. End-runs are routine and disruptive. Weak management unity (current)		Senior executives deal openly with differences; routinely request, get and give honest feedback. Work style is win-win. There's solid management unity
Bankers' actions	US banks terminate business with HiTEM	No change (current)	US banks cooperate with HiTEM and relax terms
Change in critical skills	Lose $\geq$3 in critical skills list	No change (current)	Gain 1 or 2 highly qualified skills

stockholders and banks that hold HiTEM's debts. Some customers were expressing concern about doing business with HiTEM. A few were deciding to take their business elsewhere. This situation created uncertainty in HiTEM's executive ranks; hence, this uncontrollable variable. A change in *customer/ demand* of a loss >5% in gross profit was set as level 1, the worse. On the other hand, the opposite was set at level 3, the most favorable.

2. *Senior executive interactions.* The president judged that the interactions among his senior executives were not acceptable and could not be tolerated. Executives were not as open and direct about business problems. And he considered them excessively reticent about their honest, if unpopular, but constructive opinions. End runs and petty bureaucratic games were routine and disruptive. The president's goal was to have a cohesive executive team. He communicated these problems, led by example and was alert for improvements or backsliding. If required, he was prepared to take disciplinary action.
3. *Bankers' actions.* As in the case of the customer/demand base change, HiTEM's precarious financial position was very visible to its bankers. HiTEM's needs liquidity to service current debt and keep the company running. HiTEM's relationship with its banks were good, but, long term, their risky relationship was not sustainable
4. *Change in critical skills.* HiTEM's situation was also clearly visible to its work force. As in any high technology company, HiTEM is dependent on its key technical contributors. They too were aware of the uncertain future of the company. Highly qualified engineers would have no difficulty finding new employment. The DMU identified three professionals by name currently holding key positions. The DMU judged that if they left, HiTEM would be severely impacted. The best condition would be if they could hire one or two new critical skills.

Table 7.4 HiTEM's BAU situation

Controllable variable	Level	Value	Uncontrollable variable	Level	Value
sg&a	2	\$54 M	Customer/ demand change	2	No change
cogs	2	\$651 M			
Plant capacity	2	60%	Senior executive interactions	2	Low management unity—unacceptable
Customer portfolio mix	1	Current state			
Sales	2	\$690 M	Bankers' actions	2	No change
Financing	1	−\$10 M	Critical skills	2	No change

Table 7.3 organizes the uncontrollable variables by level and uncertainty regime.

For HiTEM's current decision situation, BAU, with the uncontrollable variables at their current condition under BAU is specified as [(2,2,2,1,2,1);(2,2,2,2)] (Table 7.4).

7.2.5 *Summary Discussion*

We have demonstrated that our methodology meets the criteria for X-RL1 (Table 7.5). The opportunity is framed as a strategic goal to turn around the firm in six months and the core objective is to produce a profit. The controllable variables are the functional levers the senior executes manage. The uncontrollable variables are determined by the uncertainties of demand and competition, senior executives team work, and bankers' tolerance for further risk.

Table 7.5 X-RL1 readiness level specifications for executive-management decisions

Readiness level	Our systematic process for the problem space	Efficacy
X-RL1 Characterize problem space	Sense making—uncomplicate cognitive load	☑
	Framing problem/opportunity–clarify boundary conditions	☑
	Specify goals and objectives	☑
	Specify essential variables	
	Managerially controllable variables	☑
	Managerially uncontrollable variables	☑

☑ indicates support is demonstrated

7.3 Engineering the Solution Space

7.3.1 Introduction

We now understand the business situation, the goals and objectives of the stakeholders and the president of the firm. The DMU has been formed (Fig. 7.6). The fundamental variables for the decision process have been identified and specified. The uncontrollable variables have also been identified and specified. We now will demonstrate that the efficacy conditions stipulated for X-RL2 are met.

7.3.2 The Controllable Space and the Uncontrollable Space

We have six controllable factors of three levels. The number of experiments in the full factorial Controllable Space is $3^6 = 729$. We use an L_{18} orthogonal array of 18 experiments (Table 7.6). L_{18} data are sufficient to derive the outcomes of *any* treatment from the *entire full-factorial* set of $3^6 = 729$. The sampling efficiency of the L_{18} array is $(1 - 18/729) = 97.5\%$. To the 18 experiments, we add five additional ones. They are: BAU (2,2,2,1,2,1) and four "test experiments" of (3,1,3,1,1,3), (1,3,1,3,3,3), (1,3,3,1,1,3), and (3,2,3,3,1,1). These four are *high-leverage* treatments obtained using the Hat matrix (Montgomery 2001; Hoaglin and Welsch 1978). Test experiments will be used to check the accuracy of the forecasts from the DMU. These 23 experiments in Table 7.6 form the sample space we will use to forecast and investigate the performance and results of our methodology.

For the uncertainty conditions, the DMU members decided that they were most concerned with changes from the current uncertainty condition. They elected to consider a "worst" and a "best" condition relative to the current condition. They are as shown in Table 7.6. The three *uncertainty regimes* are shown as: current $(2,2,2,2)^T$, worst $(1,2,1,1)^T$, and best $(3,3,3,3)^T$.

The first column, in Table 7.6, lists the experiments. Experiments 1 through 18 are our abbreviated L_{18} with columns 1 and 8 deleted from the normally used L_{18} (e.g. Phadke 1989; Taguchi et al. 2000). Experiments 19 through 22 are our

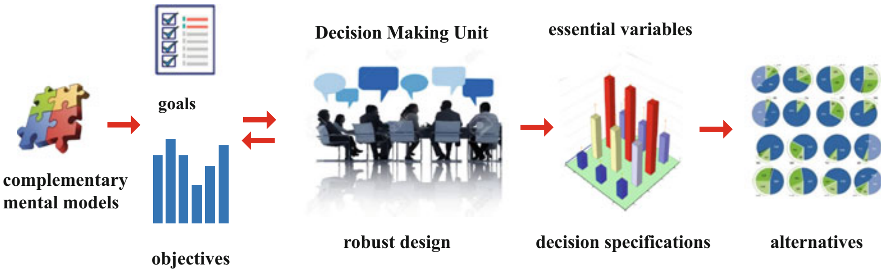

Fig. 7.6 Schematic of the solution space

Table 7.6 Data set structure for the HiTEM experiment. L_{18}, test experiments and three uncertainty regimes "Current, Worst, Best"

	Controllable variables						Uncontrollable variable			
							Level 2	Level 1	Level 3	← *Customer/demand changes*
							Level 2	Level 2	Level 3	← *Senior executive interactions*
							Level 2	Level 1	Level 3	← *Bankers' actions*
							Level 2	Level 1	Level 3	← *Critical skills*
Experiment	*sg&a*	*cogs*	Capacity	Portfolio	Sales	Financing	Current	Worst	Best	← *Uncertainty regime*
BAU	***2***	***2***	***2***	***1***	***2***	***1***	***BAUc***	***BAUw***	***BAUb***	
1	1	1	1	1	1	1				L_{18} experiment 1
2	1	2	2	2	2	2				L_{18} experiment 2
3	1	3	3	3	3	3				L_{18} experiment 3
4	2	1	1	2	2	3				L_{18} experiment 4
5	2	2	2	3	3	1				L_{18} experiment 5
6	2	3	3	1	1	2				L_{18} experiment 6
7	3	1	2	1	3	2				L_{18} experiment 7
8	3	2	3	2	1	3				L_{18} experiment 8
9	3	3	1	3	2	1				L_{18} experiment 9
10	1	1	3	3	2	2				L_{18} experiment 10
11	1	2	1	1	3	3				L_{18} experiment 11
12	1	3	2	2	1	1				L_{18} experiment 12
13	2	1	2	3	1	3				L_{18} experiment 13
14	2	2	3	1	2	1				L_{18} experiment 14
15	2	3	1	2	3	2				L_{18} experiment 15
16	3	1	3	2	3	1				L_{18} experiment 16
17	3	2	1	3	1	2				L_{18} experiment 17
18	3	3	2	1	2	3				L_{18} experiment 18
19	*3*	*1*	*3*	*1*	*1*	*3*				*Test* experiment 1
20	*1*	*3*	*1*	*3*	*3*	*3*				*Test* experiment 2
21	*1*	*3*	*3*	*1*	*1*	*3*				*Test* experiment 3
22	*3*	*2*	*3*	*3*	*1*	*1*				*Test* experiment 4

supplemental test experiments. The test experiments will be used to test the forecasting ability and accuracy of the DMU. Table 7.6 is for the DMU, using their best judgment, to populate the cells in the table. Once that is completed, we will analyze the data, and using the data, we will use to design and predict the outcomes of alternatives for the president and the DMU.

But first, we will establish the base line and use our debiasing procedure. This is the subject of the next section.

7.3.3 Establishing the Base-Line and Dispelling Bias

Don't fall in love with your first estimate.[1] (Tetlock and Gardner)

The first line in Table 7.6 is the **base line**. It is the BAU configuration of the controllable variables under the three uncertainty regimes of current, worst and best. The task for the DMU is to forecast profit 6-month out for the BAU case, in all these three uncertainty regimes. This process is also a learning step. Included is a procedure designed to diminish information-asymmetry within the group. And to avoid specious anchoring (e.g. Baron 2000) and false convergence, forecasting figures are held private and disclosure is prohibited. A record of their forecasting confidence is made for subsequent analysis. In addition, we include counter-argumentation procedures to reduce systematic biases by insisting on explicit, ***but*** anonymous, articulation of the reasons why a forecast might be correct ***and*** why it might not be correct (Fischhoff 1999; Russo and Schoemaker 1992; Arkes 2001; Koriat et al. 1980). Counter-argumentation also improves the DMU's problem solving effectiveness by enriching and complementing team members' individual mental models (Mohammed et al. 2010; Mohammed and Dumville 2001; Kray and Galinsky 2003; Lerner and Tetlock 2003). Winquist and Larson (1998) show that information pooling of shared fresh information improves decision quality and conceptualizing alternatives (See Sects. 3.3.5 and 3.3.6). The HiTEM implementation of the procedure follows next.

Establishing the base line is done in two rounds. In the first round, we obtain an initial forecast of the base line from the DMU. This is to prepare the DMU for the work of populating the entire data set Table 7.6. We begin by asking each DMU member to ***independently*** forecast profit for BAU, the (2,2,2,1,2,1) line, 6 months out for the three uncertainty regimes. The DMU is reminded that a forecast is an informed estimate, a professional judgement (March 1997), based on data, explicit modeling, and mental models. The data are placed in cells *BAUc, BAUw, BAUb* in Table 7.6 (see Appendix 7.3 also). The DMU members were reminded of two rules. **No disclosure of the forecast figures and no discussion among DMU members.** We wanted to avoid peer pressure that could lead to false convergence in the forecasts (Mest and Plummer 2003; Hanson 1998; Boje and Mirninghan 1982). This also mitigates the so-called "herd effect", social pressure that drive forecasts to

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[1] http://www.theworldin.com/article/11813/keeping-score

cluster together (Hanson 1998; Sterman 2000). Each DMU member was then asked to record their confidence-level on a confidential form we provided.

The second round concentrates on debiasing and developing an updated baseline. This is a process of counter-argumentation and accountability. We request each DMU member to write three reasons why their forecast is accurate, and three other reasons why their forecast is not accurate. The DMU members were reminded of two more rules. **All inputs are anonymous, no names on the inputs, and no discussion.** We had their input printed so that handwriting would not be used to recognize the authors. This gave us a total of 15 reasons why the forecasts were considered to be accurate and 15 opposing reasons. We asked the DMU members to read all 30 reasons and then to discuss them. This is a form of accountability, to explain the reasons behind judgments and actions (Lerner and Tetlock 2003). Accountability generates feedback, which improves performance, particularly in groups (Hastie 1986; Hastie and Kameda 2005).

The following are some examples of the input from the DMU about their forecasts. For example, reasons for why the data are accurate:

- "We are at the end of the quarter, so I have confidence in the BAU number."
- "A good portion of the uncontrollable factors can be estimated with level of reason or rationale."
- "Current financial data . . . fairly consistent range with current sites and customer mix. Large percentage of costs is purely variable will follow sales numbers."

And examples for reasons why the data are not accurate:

- "Difficult to quantify increasing impact underutilization from customer loss."
- "Interdependency between controllable and uncontrollable factors."
- "Continued cash shortfall may deteriorate supplier and cost base faster than can be projected."

At the end of this discussion, the DMU is requested to again forecast the BAU treatment and to record their confidence level once more. Table 7.7 summarizes the results of the *ex post* discussion results. Consider the BAU profit forecast 6 months out, under the current regime. The average remains the same between rounds, but the standard deviation declines. For the worst uncertainty regime, the forecast is not as pessimistic after the first round, *viz.* −10.9 versus −9.75 respectively, but the standard deviations is substantially less, 2.7 versus 0.5, respectively. For the best uncertainty regime, the forecast is not as optimistic, but the standard deviation tightens significantly from 2.5 to 1.0. These data suggest that learning took place.

Table 7.7 BAU forecasts' standard deviations decline between round 1 and round 2

Uncertainty regimes	BAU profit forecast 6 months out					Confidence level		
	Avg. profit $M		Standard deviation					
	Round 1	Round 2	Round 1	Round 2	Trend	Round 1	Round 2	Trend
Current	−5.5	−5.5	1.3	1.2	↓	Conf = 3.3 Stdev = 0.84	Conf = 3.9 Stdev = 0.89	↑ ↓
Worst	−10.9	−9.75	2.7	0.5	↓			
Best	−4.28	−5.13	2.5	1.0	↓			

Table 7.8 Confidence rises between round 1 and round 2

Confidence of BAU profit forecast 6 months out					
Current uncertainty regime	Average of team' confidence		Standard deviation		
	Round 1	Round 2	Round 1	Round 2	↓
	3.3	3.9	0.84	0.55	

Table 7.7 summarizes the results of the *ex post* discussion results on confidence. The average of the team member's confidence rises between round 1 and round 2, from 3.3 to 3.9. A "3" is specified as a "toss-up", and a "4" is specified as "confident." And the stdev of the scores between round 1 and round 2 declines (Details are in Appendix 7.2) (Table 7.8).

The goal for this iterative procedure is to promote organizational learning. Simon (1991) summarizes it well:

> What an individual learns in an organization is very much dependent on what is already known to (or believed by) other members and what kinds of information are present in the organizational environment... an important component or organizational learning is internal learning—that is transmission of information from one organizational member or group of members to another.

Findings

Between round 1 and round 2, for the current uncertainty regime, the mean remained unchanged, but the standard deviation narrowed. We interpret this as an improvement in accuracy. For the worse uncertainty regime, in round 2, the mean was not as pessimistic as in round 1 and there was a ×5.4 reduction in the standard deviation. We interpret this as a major improvement in accuracy. For the best uncertainty regime, the mean is not nearly as optimistic, a reduction of 17%, and the standard deviation narrowed by ×4.0. We also interpret this as a major improvement in accuracy. Significantly, the confidence level of the DMU improved by 15% and with a reduction from 0.84 to 0.55. The improvement in confidence supports the belief that the forecasts improved.

7.3.4 Summary Discussion

The objective of this section has been to verify the efficacy of our methodology for the Solution Space. Namely, can a user use our methodology to systematically specify the entire solution space and the spectrum of uncertainty regimes, the base line and finally debias it effectively?

Those familiar with the Delphi Method will find similarities with our base-line and debiasing procedure. *Our process improves on Delphi.* We address the information asymmetry issue of decisions and forecasting, by not starting or concentrating on the numbers, but rather on the issue of incomplete and asymmetric **mental models**.

Delphi is a group forecasting technique for participants to anonymously exchange and modify data, among each other, over several rounds. The data is then aggregated to a number representing the group's consensus. The goal is to improve forecasting accuracy by allowing participants to reflect, about supporting or opposing inputs, and make adjustments. Delphi is intended to stimulate participant's desire for accuracy, while suppressing detrimental social pressures from members of the group. Sniezek and Henry (1989) report on their work that "group judgements were, with few exceptions more accurate than mean or median individual judgments ... Furthermore, 30% of the group's judgement were *more* accurate than the group's *most* accurate individual judgement." Studies show Delphi improves accuracy over other methods (e.g. Rowe et al. 2005; Rowe and Wright 2001). Yousuf (2007) and Hsu and Sanford (2007) present the pros and cons of Delphi. A common failure is ignoring and [not] exploring disagreements, so that an artificial consensus is likely to be generated. We think that the method emphasizes numbers and less on the logic of the numbers. In our approach, we modified key attributes of the Delphi method as follows:

1. The anonymity requirement in our process requires non-disclosure of the participants' forecast figures. We think this has a positive ameliorating effect on anchoring bias, which has an inhibiting effect on forecasting accuracy.
2. The interactions are not based on numbers; but based on *rationale* of member's forecast. The rationale is also anonymous. The input is anonymous, but the discussions about the anonymous input is not. Our procedure requires for the participants to discuss the rationales without being able to attribute their source. This is designed to avoid defensiveness and social pressure.
3. The interactions among members is not anonymous, but recall that the forecast numbers are not disclosed so that no one knows what their peers forecast. The feedback is anonymous, but the discussions are face-to-face in a meeting format.
4. The feedback documented by the participants are not designed to explain adjustment to numbers, but to explicitly give reasons why their forecasts is right and equal number of reasons it is wrong. Our focus is centered on the participants' mental models, make them frame the task of forecasting in a more complete, richer, and with fewer incorrect assumptions and ideas.
5. We use confidence, rather than consensus of forecast figures, as a proxy of forecasting accuracy. There is a body of research that supports this hypothesis. Sniezek and Henry (1989) and Sniezek (1992) report that group confidence is positively correlated with accuracy. Rowe et al. (2005) write "that not only accuracy tend to increase across rounds in Delphi-like conditions, but subjects' confidence assessments also become more appropriate."
6. We address uncertainty very directly and specifically using uncontrollable variables and uncertainty regimes.

We have demonstrated X-RL2 conditions are satisfied, Table 7.9 summarizes the efficacy of this phase of the methodology.

Table 7.9 Readiness level specifications for executive decisions

Readiness level	Systematic process for the solution space	Efficacy
X-RL2 Engineer solution space	Specify subspaces of solution space Alternatives space and uncertainty space	☑
	Specify entire solution space	☑
	Specify base line and uncertainty regimes Do-nothing case and choice-decision Estimate base line and dispel bias	☑

The symbol ☑ indicates support is demonstrated

7.4 Exploring the Operations Space

7.4.1 Introduction

The next step is to be able to develop a series of decision alternatives from which a choice alternative that satisfices intended goals and objectives can be found (Fig. 7.7).

During this step of our methodology, each DMU member is asked to populate the entire data set Table 7.6. Each participant was given a form that was similar to Table 7.6. But the experiments were presented in a different random order to each DMU member. Each DMU member made 23 × 3 = 69 forecasts, for 23 experiments under three uncertainty regimes. We reminded them **not** to disclose their forecast figures to each other. **But** they were free to consult and discuss with their staffs or people in their managerial and personal networks. The task was done with dispatch and without any grumblings about complexity or excessive workload. The completed data set is in Appendix 10.3.

7.4.2 Analyses of Data

In this step, we analyze the summary statistics of the data set and the DMUs forecasting capability. In other words, are the data something we can use and learn from?

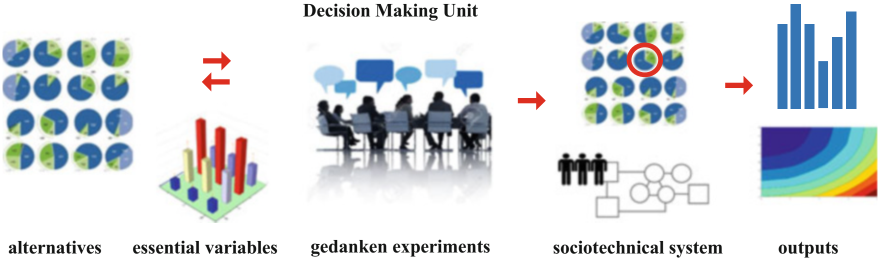


Fig. 7.7 Schematic of the operations space

7.4.2.1 ANOVA Summary Statistics

Table 7.10 is the ANOVA table for the forecast data for the current uncertainty regime. Four variables have $p < 0.000$, one has $p < 0.01$, and another has $p < 0.02$. Their statistical significance is strong. They are strong predictors of the outcomes. *Capacity* makes a contribution to the overall outcome with $p = 0.059$. The managerial controllable variables are strong predictors of the outcome, albeit some stronger than others. R^2 values are good under all the uncertainty regimes (Table 7.10, Appendix 7.6). Residuals do not carry information, they distribute themselves as N(0,1.466) with $p > 0.05$ (Fig. 7.8).

A summary of the ANOVA statistics for the three uncertainty regimes are shown in Table 7.11. The R^2 values are good, and the p values also indicate that the residuals are not carriers of information.

cogs is the dominant controllable variable under every uncertainty regime. HiTEM's 2004 income statement shows that gross profit is 5% and *cogs* is 95% of the revenue line. That *cogs* is dominant is not surprising and consistent for a contract manufacturer. In the best uncertainty regime, *capacity* and *financing* have $p > 0.05$; they are not good predictors of the outcome. Having been in a downward spiral for 3 years, this is possibly an indication of the DMU's difficulties to forecast in the best uncertainty regime. To the DMU, the current and the worst uncertainty regimes were of most concern. The p values for the residuals are good. They all pass the Anderson-Darling test for normality.

We now turn our attention to interactions between the controllable variables. The array L_{18} has a unique property. The interactions between all pairs of columns, except 1 and 2, are confounded partially with the remaining columns (e.g. Phadke 1989). We resort to using Table 7.6, which although an unbalanced array, it gives us the additional dof's to find interactions (Table 7.12). The data show that the interactions are small. Only *customer portfolio*sales* at $t = 18$ and *customer portfolio*capacity* at $t = 24$ are statistically significant with $p < 0.05$. This makes sense, a favorably or unfavorably structured customer portfolio will have an impact on sales. By the same token, the customer portfolio will have an effect on

Table 7.10 ANOVA Table for team forecasts for current uncertainty regime

Source	DF	Seq SS	Adj SS	Adj MS	F	P
sg&a	2	56.902	56.902	28.451	11.14	0.000
cogs	2	569.289	569.289	284.644	111.44	0.000
capacity	2	15.132	15.132	7.566	2.96	0.059
portfolio	1	71.297	71.297	71.297	27.91	0.000
sales	2	51.545	51.545	25.773	10.09	0.000
financing	1	26.850	26.850	26.850	10.51	0.002
Error	61	155.802	155.802	2.554		
Total	71	946.817				
R-sq(adj SS) = 83.8%						

Fig. 7.8 Half Normal plot of residual of forecasts in current environment

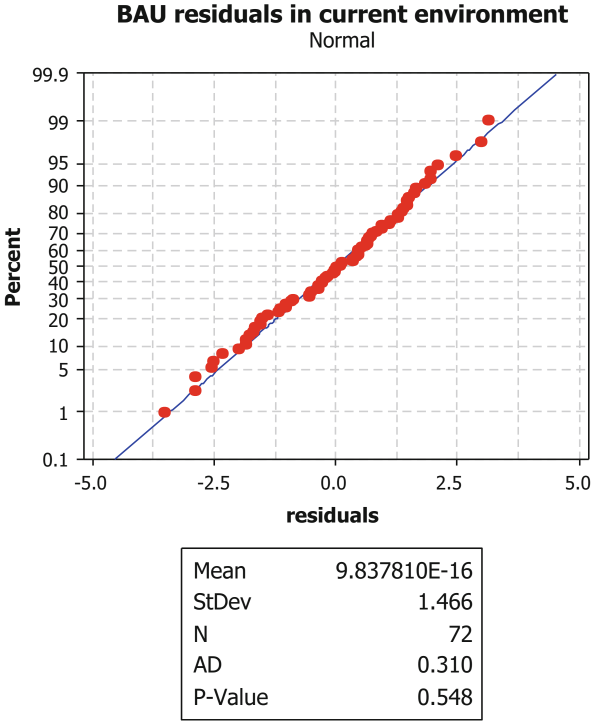


Table 7.11 ANOVA for team forecasts for current, worst, and best uncertainty conditions

	ANOVA for profit forecasts								
	Current uncertainty regime			Worst uncertainty regime			Best uncertainty regime		
	Adj SS	%	p	Adj SS	%	p	Adj SS	%	p
sg&a	56.902	0.06	0.000	73.8	9.1	0.000	56.6	8.3	0.001
cogs	569.289	0.60	0.000	622.8	76.6	0.000	532.0	7.8	0.000
Capacity	15.132	0.02	0.006	36.9	4.5	0.001	8.33	1.2	**0.204**
Portfolio	74.297	0.08	0.000	26.6	3.3	0.000	36.4	5.3	0.002
Sales	51.545	0.05	0.000	28.2	3.5	0.003	37.3	5.5	0.009
Financing	26.850	0.03	0.002	21.7	2.7	0.001	6.5	1.0	**0.283**
Error	155.802	0.016	–	3.0	0.4	–	5.1	0.7	–
Total	949.817	1.00	–	813.1	100%	–	682.2	100%	–
	$R^2 = 83.8\%$			$R^2 = 81.9\%$			$R^2 = 69.3\%$		
	Residuals $p > 0.05$			Residuals $p = 0.338$			Residuals $p = 0.243$		

Table 7.12 Interactions

	Current uncertainty regime		Worst uncertainty regime		Best uncertainty regime	
Two factor interactions	% MS adj	p	% MS adj	p	% MS adj	p
*cogs**sales	1.97%	0.079	–	–	–	–
*cogs**capacity utilization	–	–	1.16%	0.08	–	–
Customer portfolio*sales	–	–	0.9%	0.05	–	–
Customer portfolio*capacity	–	–	–	–	1.31%	0.008
	$R^2 = 90.16\%$ $R^2_{adj} = 88.91\%$		$R^2 = 97.61\%$ $R^2_{adj} = 97.21\%$		$R^2 = 89.24\%$ $R^2_{adj} = 87.64\%$	

Table 7.13 Response tables for Means and Stdev in the current uncertainty regime

Response Table—Means for current environment						
Level	*sg&a*	*cogs*	capacity	portfolio	sales	financing
1	−4.50000	−6.87083	−4.05417	−4.80417	−4.45417	−4.15417
2	−3.50417	−3.47500	−3.32500	−3.15833	−3.49167	−3.51667
3	−2.32500	0.01667	−2.95000	−2.36667	−2.38333	−2.65833
Delta	2.17500	6.88750	1.10417	2.43750	2.07083	1.49583
Rank	3	1	6	2	4	5

Response Table—Standard Deviations for current environment						
Level	*sg&a*	*cogs*	capacity	portfolio	sales	financing
1	1.593	1.834	1.262	1.572	1.307	1.379
2	1.531	1.648	1.613	1.349	1.430	1.612
3	1.605	1.247	1.854	1.808	1.992	1.738
Delta	0.073	0.586	0.593	0.459	0.685	0.358
Rank	6	3	2	4	1	5

HiTEM's plant utilization. The other variable interaction of *cogs*sales* is only marginally significant with $p = 0.079$ and $p = 0.08$, respectively.

7.4.2.2 Response Tables and Graphs

In the upper panel of Table 7.13 is the response table for the controllable variables. In the bottom panel is the table for the standard deviations for these variables. Figure 7.9 presents the same Table 7.13 information in graphical form.

Some of the advantages of a three-level specification for the forecasts are apparent from Fig. 7.9. At three levels the non-linear response of HiTEM output are revealed for both profit and the standard deviation. Notably some of the standard deviations exhibit V-shaped curves. Should we have assumed two levels standard deviations, this non-linear behavior would not be visible for analysis. These data will become particularly useful in Sect. 7.4.3 where we discuss the design of alternative decision specifications and predict their standard deviations.

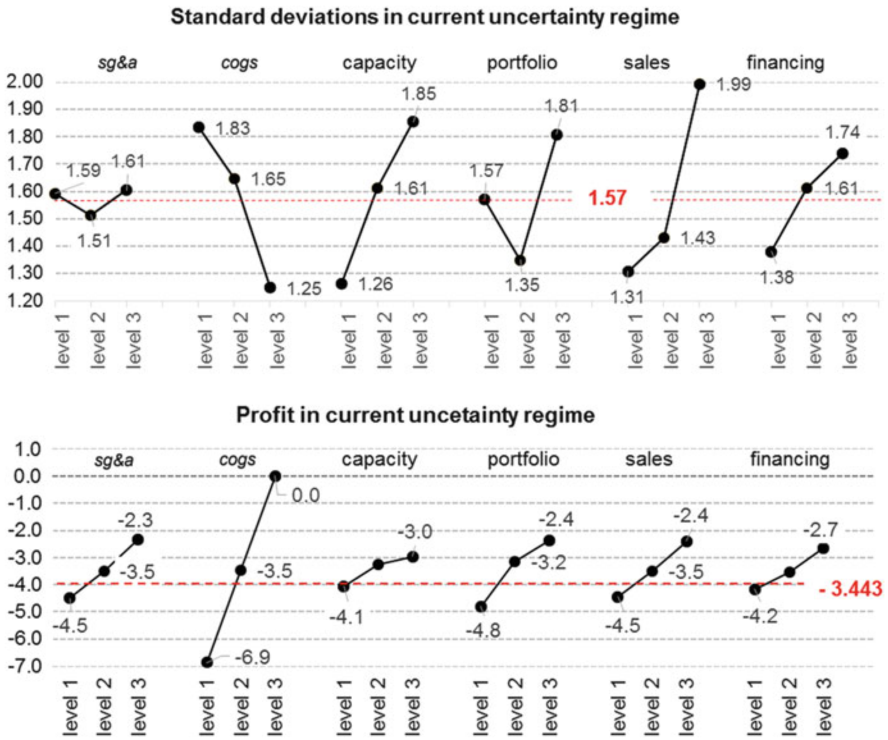


Fig. 7.9 *Panel 1* Response plots of HiTEM standard deviations in current environment. *Panel 2* Response plots of HiTEM profit in current environment

7.4.3 Synthesis: Construction and Analysis of Alternatives

Using the controllable and uncontrollable variables, we can engineer forecasts for any what-if alternative. One simply specifies an experiment using the decision specification for that alternative. We present four examples for constructing alternatives:

- First is the construction of the what-if alternatives from the Board of Directors. He was obligated to develop a reasoned evaluation of their suggestions. This was a priority concern of HiTEM's president.
- Second is our algorithm to construct any alternative desired, with no constraints.
- Third is a variation of the traditional DOE approach to constructing a robust alternative.

7.4.3.1 Board of Directors' Alternatives

The president was being pressured by the board of directors to improve the BAU, in the current uncertainty regime, by "concentrating on one thing and doing it well".

Table 7.14 Profit for one-factor improvement beyond the BAU alternatives

		Profit $M under uncertainty regimes		
One-factor improvement alternatives versus BAU		Current	Worst	Best
2,2,2,1,2,1	BAU	−5.486	−9.347	−2.896
3,2,2,1,2,1	BAU ⊕ *sg&a*+	−4.281	−8.231	−1.679
2,**3**,2,1,2,1	BAU ⊕ *cogs*+	−1.995	−5.855	0.433
2,2,**3**,1,2,1	BAU ⊕ capacity+	−5.186	−8.380	−2.717
2,2,2,**2**,2,1	BAU ⊕ portfolio+	−3.844	−7.827	−1.150
2,2,2,1,**3**,1	BAU ⊕ sales+	−4.378	−8.222	−1.896
2,2,2,1,2,**2**	BAU ⊕ financing+	−4.849	−8.118	−2.413

⊕ means the factor identified by [factor+] is set at next higher level in the BAU 6-tuple

What they meant was to improve one variable and make sure that it is done, avoid the distractions of doing too many things, and do not fritter away the limited time and energies of the firm. They were confident that this kind of concentrated focus would improve the prospect for profits. Those alternatives are shown in Table 7.14. Note that the shorthand of $BAU \oplus sg\&a+$ is used to indicate that *sg&a* has been improved to the next higher level in the BAU 6-tuple. The table shows that the *concentrate-on-one-thing* strategy will not produce the desired outcome of profit. All alternatives, except one, in the table are negative in every uncertainty regime. These data demonstrate that the "concentrate on one thing" strategy will not work.

These results were obtained using the procedure described in Sect. 5.4.3.2 and the response tables in Table 7.13 and Appendix 7.5. For example, we can predict the value for BAU in the worst environment, as follows:

First, calculate the grand average m of responses,

$$\begin{aligned} \mathrm{m} &= \mathrm{average}(sg\&a \text{ responses}) \\ &= \tfrac{1}{3}[(-8.267) + (-6.904) + (-5.788)] = -6.986, \text{and} \\ &= \mathrm{average}(sg\&a \text{ responses}) = \mathrm{average}(cogs \text{ responses}) \\ &= \mathrm{average}(capacity \text{ responses}) = \mathrm{average}(portfolio \text{ responses}) \\ &= \mathrm{average}(sales \text{ responses}) = \mathrm{average}(financing \text{ responses}) \end{aligned}$$

Then to get the predicted response for BAU(2.2.2,1,2,1) in the worst uncertainty regime,

$$\begin{aligned} &= -6.986 + (sg\&a2 - \mathrm{m}) + (cogs2 - \mathrm{m}) + (\mathrm{capacity2} - \mathrm{m}) \\ &\quad + (\mathrm{portfolio1} - \mathrm{m}) + (\mathrm{sales2} - \mathrm{m}) + (\mathrm{financing1} - \mathrm{m}) = -9.35\,\$\mathrm{M}. \end{aligned}$$

Note that *sg&a*2 means the value of the variable *sg&a* at level 2, which can be obtained from Table 7.13 or Fig. 7.9. The same convention applies to the other controllable variables.

If the concentrate-on-one-thing strategy will not work. Will a "concentrate-on-**two**-things" strategy work? We explored all those possible alternatives. Table 7.15 shows seven representative examples. For example (2,3,2,2,2,2,1) is the BAU

Table 7.15 Profit for one-factor improvement beyond the BAU alternatives

Two-factor improvement alternatives versus **BAU**		Profit $M under uncertainty regimes		
		Current	Worst	Best
2,2,2,1,2,1	**BAU**	**−5.54**	**−9.40**	**−2.89**
2,**3**,2,**2**,2,1	BAU ⊕ (*cogs*+) ⊕ portfolio+	−0.40	−4.24	*2.18*
3,**3**,2,1,2,1	BAU ⊕ (*cogs*+) ⊕ *sg&a*+	−0.86	−4.79	*1.65*
2,**3**,3,1,2,**2**	BAU ⊕ (*cogs*+) ⊕ sales+	−0.93	−4.78	*1.43*
2,**3**,3,1,**3**,1	BAU ⊕ (*cogs*+) ⊕ financing+	−1.40	−4.67	*1.82*
3,2,2,**2**,2,1	BAU ⊕ (portfolio+) ⊕ sga+	−2.71	−6.61	*0.07*
2,2,2,**2**,**3**,1	BAU ⊕ (portfolio+) ⊕ sales+	−2.78	−6.60	0.15
3,2,2,1,2,**2**	BAU ⊕ (sales+) ⊕ *sg&a*+	−3.25	−7.15	−0.68

⊕ means the factor identified by [factor+] is set at next higher level in the BAU 6-tuple

configuration with *cogs* and *portfolio mix* upgraded to the next higher levels, under the *best uncertainty regime*. This is shown as BAU ⊕ [*cogs*+] ⊕ [portfolio+]. The calculation is,

$$\begin{aligned} &= -6.986 + (sg\&a2 - \text{m}) + (cogs2 - \text{m}) + (\text{capacity}2 - \text{m}) \\ &\quad + (\text{portfolio}1 - \text{m}) + (\text{sales}2 - \text{m}) + (\text{financing}1 - \text{m}) = 2.18\ \$\text{M}, \\ &\text{where m} = 1.004. \end{aligned}$$

BAU⊕[*cogs*+]⊕[portfolio+] under the *current* uncertainty regime the predicted profit it produces is a loss of −$0.40 M and in the worst uncertainty regime a bigger loss of −$4.24 M. And in the *best* uncertainty regime it could produce a profit of $2.18 M. But this occurs under the condition that ***all*** the uncontrollable variables "line-up" in the right direction. The best uncertainty regime assumes a *gain* customer/demand and *gain* >5% gross profit, a dramatic *change* the way they work with other such that senior executives deal openly with differences of opinion; routinely request, get and give honest feedback. Work style is win-win and there is strong management unity. US banks cooperate with HiTEM and *relax* terms, and 1 or 2 professionals with *critical skills join* HiTEM. Given the 6-month window to turn around the firm into a profitable enterprise and simultaneously expect that the workstyle among executives improves did not seem like a feasible strategy.

7.4.3.2 President's Realistic Alterative

The one-factor and even the two-factor improvement strategy do not prove themselves effective or convincing. The president discussed what he judged was realistically all he could do to produce a profit. He discussed his operational experience in HiTEM, his first-hand and personal business relationships with HiTEM's external business constituencies. He concluded that (3,2½,2,2,1½,1½) was the "realistic alternative". The juxtaposition of the two are shown in Table 7.16.

This is a variation on the BAU strategy of (2,2,2,1,2,1), i.e.

Table 7.16 President's realistic strategy

	BAU (2,2,2,1,2,1)		Realistic (3,2½,2,2,1½,1½)		Prospects
sg&a	Level 2	$54 M	Level 3	$53.46	Save $5.4 M
cogs	Level 2	$651 M	Level 2½	$594.9	Save $6.51 M
Plant capacity	Level 2	60%	Level 2	60%	60% no change
Customer portfolio	Level 1	Current mix	Level 2	Drop customers of profit contributions: • In development <10% • In assembly and test <6% • In manufacturing <4%	Reduce losses
Sales	Level 2	$690 M	Level 1½	$672.75	Add $3.45 M
Financing	Level 1	−$10 M	Level 1½	−$10 M Sell Mexico/China factory	Generate ≥$10 M

Table 7.17 Responses for strategy alternatives from the president and its DMU

		Worst uncertainty		Current uncertainty		Best uncertainty	
Decision alternatives		Profit $M	Stdev	Profit $M	Stdev	Profit $M	Stdev
(2,2,2,1,2,1)	BAU	−$9.40 M	1.06	−$5.49 M	1.29	−$2.89 M	1.38
(3,2½,2,2,1½,1½)	Realistic	−$4.46 M	1.11	−$1.13 M	1.00	$1.59 M	0.44
(3,2½,2,2,1½,3)	Realistic⊕ China-divestiture	−$3.20 M	0.83	−$0.05 M	1.24	$2.38 M	0.74

1. Downsize the sales force to *reduce sg&a*,
2. Expect a decline in *sales*,
3. Reduce manufacturing labor to lower *cogs*.
4. President was less sanguine that he could increase *plant capacity* sufficiently to influence profitability. Having been VP of manufacturing, on the subject of plant utilization, the president was most knowledgeable.
5. He also judged that with a reduced sales force he could not take effective action on the *customer-mix* issue.
6. Finally for the anticipated *cash shortfall* of $10 M, he was prepared to unload the Chinese or Mexican plants. Table 7.17 shows the calculations for this case.

The realistic strategy will outperform BAU in all three uncertainty regimes. What makes this possible are *sg&a, cogs, customer portfolio, and financing*. *cogs* moves from level 2 to level 2½. *sg&a* and *cogs* make dominant contributions to the profit outcome, but they cannot turn around the company except in the best uncertainty regime. But, divestiture of the Mexico or China plant can make HiTEM break even. HiTEM's exploratory actions to sell the plants, which had begun, moved into high gear. In the current uncertainty regime, **the president's realistic strategy chosen has a lower standard deviation than BAU. It produces more profit and it does so with less risk.** We decided to engage in further analyses to explore a wider range of alternatives.

7.4.3.3 Design of a Robust Alternative

This is a key section—designing robust decision specification that is insensitive to uncontrollable variables even when they are not removed, for the current and the worst uncertainty regimes. It is more important for the HiTEM decision to cover downside risks than capture potential upside opportunities. The construction is as follows (Taguchi et al. 2000; Otto and Wood 2001):

Improve the mean, and then tighten the distribution by reducing the standard deviation.

1. Identify the uncontrollable variables that have the largest influence on the controllable variables.
2. Identify the controllable variables that have the largest influence on the response.
3. Use steps 1 and 2 to construct a solution that has a high response and a low standard deviation.

We apply this algorithm to construct an alternative that will satisfice the HiTEM DMU. Consider Fig. 7.9, which shows the plots for the main effects and the standard deviation for the current environment. The maximum response alternative is (3,3,3,3,3,3). From the same figure, we find that the most robust, i.e. the one with the lowest standard deviation, is (2,3,1,2,1,1). Now from the response Table 7.13, we know the ranking of each variable with respect to output and standard deviation. We put all this information together in the first five columns of Table 7.18. The two columns on the RHS are explained the paragraphs that follow.

To construct the robust decision alternative, we consider each variable in the order of their rank in the response table in Table 7.13. Therefore, we begin with *cogs*.

Table 7.18 Optimum alternative by selective maximizing profit and stdev

	Profit		Stdev		BAU level change: from to	Recommended setting and rationale
	Rank	Max. level	Rank	Min. level		
sg&a	3	**3**	6	**2**	2 → 3	*sg&a* can improve, stdev barely changes
cogs	1	**3**	3	**3**	2 → 3	Optimum change for both. Profit ↑ and stdev ↓
Capacity	6	**3**	2	**1**	2 → 2	Keep BAU level
Portfolio	2	**3**	4	**2**	1 → 2	Optimum change for both. Profit ↑ and stdev ↓
Sales	4	**3**	1	**1**	2 → 2	Keep BAU level
Finance	5	**3**	5	**1**	1 → 3	Profit ↑ China plant unaffordable hole, accept stdev ↑
						Result is (3,3,2,2,2,3) with a derived profit \$2.32 M

1. *cogs*. This has the highest ranking factor for profit. Its maximum is at level 3. The minimum standard deviation for *cogs* is also at level 3. The maximum response level is also the minimum standard deviation level. So, for our alternative, we keep *cogs* level at 3.
2. *Customer-portfolio mix*. This is the second ranking factor for profit. Its maximum is attained at level 3. The minimum standard deviation is attained at level 2. From discussions with the operations executive, we know that to move this factor from level 1 to level 3 is an arduous undertaking of shedding a large set of customers. It is not realistic to move two levels. Although changing from level 1 to level 2 is challenging, it is doable with effort. More importantly, level 2 is where the minimum stdev is attained. So we set this factor at level 2.
3. *sg&a* is the third ranking factor for profit. Set this level at its maximum level, 3. *sg&a* is the lowest ranking factor, 6, for standard deviation, so the level for profit trumps the setting for standard deviation.
4. *Sales* is the fourth ranking factor for profit. BAU is set at level 2. We don't want to reduce sales, so we keep it at level 2. Although this level is not optimal for standard deviation, it is second best, an acceptable compromise for a fourth ranking factor.
5. *Financing* is the penultimate ranking factor. Its maximum is at level 3, Minimum stdev is at level 1. It is unaffordable to have either the Mexico or the China plant. The China plant is a bigger problem, so we set at level 3.
6. *Capacity* is lowest ranking factor for profit. Its highest level for profit is 3. For standard deviation, minimum level is 1. BAU is level 2. We keep it at BAU level 2.

We know from discussions with the president that *cogs* level 3 is not realistic. We change that to the realistic level of 2½, we get then the treatment (3,2½,2,2,2,3). *We have rediscovered the realistic strategy+China divestiture+sales+* described in Table 7.17 (3,2½,2,2,1½,1½). **We summarize the results of various constructions in** Table 7.19. Figure 7.10 **presents the same information in graphical form.**

7.4.4 Discussion

Figure 7.10 is comprised of three panels. The first panel maps the alternatives of Table 7.19 as points in a 2-space of profit $M versus stdev. Clearly the most desirable region is the northwest quadrant. There standard deviation is lower and profits is higher. And the least desirable region is the southeast quadrant of the figure. The ***black*** point is the BAU, the ***green*** ring point is the realistic cum China divestiture, and the ***blue*** point is the robust alternative.

Findings

By inspection of all three panels, we find the following:

1. **BAU** (*black* points) are consistently the ***worst*** decision specification for profit, under *every* uncertainty regime. It is inferior to the other alternatives by a large margin. For HiTEM, staying the course and doing nothing different, is clearly

Table 7.19 Responses for strategy alternatives from the president and its DMU

Decision alternatives			Worst		Current		Best	
			Profit $M	Stdev	Profit $M	Stdev	Profit $M	Stdev
(2,2,2,1,2,1)	BAU	⚫	$9.40 M	1.06	−$5.49 M	1.29	−$2.89 M	1.38
(3,2½,2,2,1½,1½)	Realistic	🟢	−$4.46 M	***1.11***	−***$1.13 M***	1.00	***$1.59 M***	0.44
(3,2½,2,2,1½,3)	Realistic⨁China-divest	○	−$3.20 M	0.83	−$0.05 M	1.24	$2.38 M	0.74
(3,3,1,2,1,3)	Robust OFAT	🔵	−$2.54 M	1.22	$0.56 M	0.63	$3.02 M	0.640
(3,3,2,2,2,3)	Robust alternative	🔴	−$1.34 M	0.12	$2.32 M	1.11	$4.44 M	0.644
(3,2½,2,2,2,3)	Modified robust-alter	⭕	−$3.09 M	1.80	$0.56 M	1.30	$2.77 M	0.79

The colored circles are to identify key point in Fig. 7.10

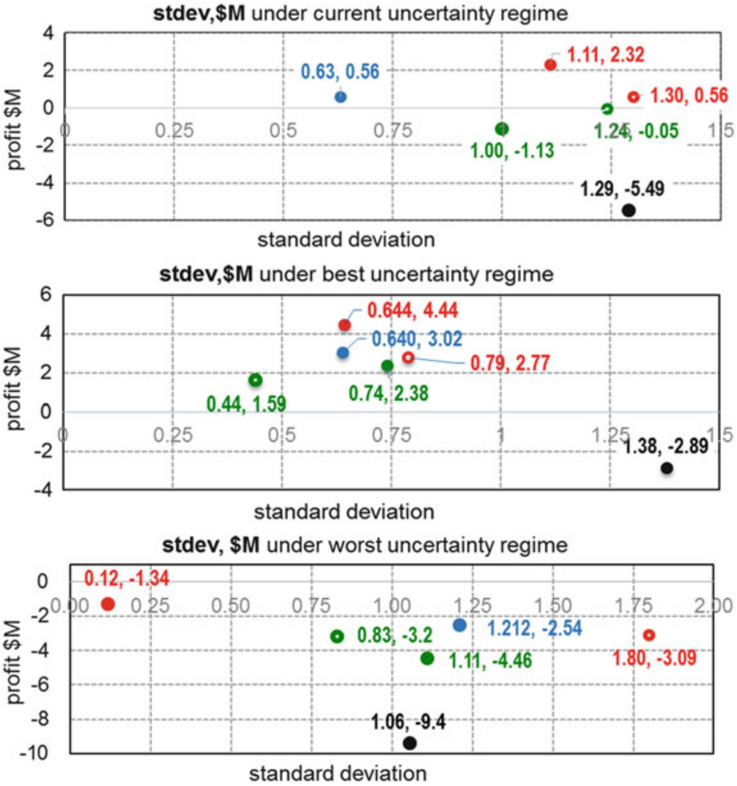


Fig. 7.10 *Panel 1* Profit $M versus stdev for the alternatives, current uncertainty regime. *Panel 2* Profit $M versus stdev for the alternatives, best uncertainty regime. *Panel 3* Profit $M versus stdev for the alternatives, worst uncertainty regime

not a meaningful alternative. The track record of losses, for three consecutive years, has made this apparent.

2. The **constructed robust-alternative** (*solid red* points) predicts the ***highest profit***, under *every* uncertainty regime. Except under the worst uncertainty regime the standard deviation is noticeably low. The DMU has a clear view of the scenario under the worst uncertainty regime.
3. The **robust OFAT** (*blue* point) is the second highest performing design. However, the design is not realistic from the president's point of view. It drives *cogs* to its lowest level, which is not realistic, makes plant capacity to an even lower acceptable level, and lowers sales, and to a large extent depends on the sale of the China factory to produce a profit. The logic of this action is akin to burning your furniture to keep your house warm.
4. The **realistic** decision specification (*solid green* points) outperforms BAU by a wide margin, also under every uncertainty regime. The prescience and accuracy of the president's mental model for HiTEM and his keen judgement about it operational capabilities are impressive.

Table 7.20 Readiness level specifications for executive decisions

Readiness Level	Systematic process for the operations space	Efficacy
X-RL3 Explore operations space	Specify	
	Sample orthogonal array	☑
	Do-nothing case and choice decision-alternative	☑
	Predict outcomes	☑
	Design and implement robust alternative	☑
	Design and implement any what-if alternative	☑

The symbol ☑ indicates support is demonstrated

5. The **modified realistic** decision specification (*green* point with a *white* center) which includes the sales of the China factory is predicted to have better results than the realistic decision design. Higher profit and less standard deviation.
6. The **modified constructed** robust-alternative (*red* point with a *white* center) outperforms the *realistic* design and the *modified realistic,* in terms of *both* output and standard deviation. Close inspection of this *modified constructed robust-alternative* reveals that it is a close cousin of the *modified realistic* design. The notable difference is the sales controllable variable, in which the *modified realistic* design is specified at level 2 instead of level 1½.
7. In the *worst uncertainty regime*, the **modified** realistic-alternative (*red* point with a *white* center) the standard deviation is lower in the *worst uncertainty* regime than the *current* uncertainty regime. The *worst* uncertainty regime was of most serious concern to the president. That, in fact, it performs better in both output and standard deviation than in the *best* uncertainty regime was very persuasive to the president.

The analyses and syntheses, of the observations 5, 6 and 7, convinced the president and the DMU that the *modified* realistic-design was the appropriate strategic objective for HiTEM. This design became the president's commitment and he directed the DMU to enact this decision.

We conclude that XRL-3 conditions for efficacy are met (Table 7.20).

7.5 Evaluating the Performance Space as a Production System

7.5.1 Introduction

The discussions have concentrated on our methods to construct decision alternatives using DOE experiments to predict their performance. Experiments depend on data, but how do we know the data are "good enough"? What is good enough? How do we know the quality of those performing the experiments or function mechanisms? These are the questions we explore and discuss (Fig. 7.11). We consider the

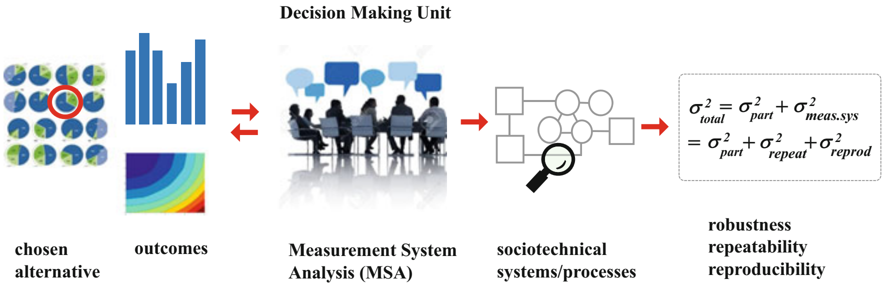


Fig. 7.11 Schematic of the outcomes space

sociotechnical system that implements a decision specification as a **production system**. We evaluate performance with two methods. One simple and the other more involved. The first is a simple test of consistency. And the second is using the Gage R&R method of Measurement System Analysis (MSA) (IAG 2002).

7.5.2 *Test of Consistency*

It is a common practice, in surveys, to ask a participant the question posed in two different ways to determine whether the respondent will answer them in a consistent manner. Are the respondent's inferences to the question the logically consistent. We apply, on the DMU as a group, the spirit of this test of consistency. For this test, we use the Hat matrix (Sect. 3.2) to find four experiments that were most different from the L_{18} experiments. They are the high-leverage test-experiments of (3,1,3,1,1,3), (1,3,1,3,3,3), (1,3,3,1,1,3), (3,2,3,3,1,1). We know that data from the L_{18} orthogonal array are sufficient to derive the outcome of profit for any configurable experiments. Thus, we can compare the values forecast for the test experiments by the DMU against the L_{18} derived values to obtain a measure of forecasting consistency. Results of this tests are shown in Table 7.21. **This is an important test of the DMU's ability to make consistent forecasts**. The forecasts from the DMU as a group, as well as, its individual members when compared against the derived forecasts are close, then the DMU forecasting ability is accurate. This is a form of data triangulation (Thurmond 2001). Triangulation is the use of multiple sources, approaches to confirm, negate, data in order to take corrective action or improve the ability to analyze or to interpret the findings (Thurmond 2001). The strong form of triangulation, which is used to confirm theory (Benzin 2006). This process is analogous to parity checking (Christensson 2011) and checksum error-checking (Christensson 2009) in digital transmission and computer technology. We use this test and Gage R&R to confirm forecasts and as a strong form of triangulation of our executive decision methodology.

Table 7.21 Comparison of DMU's forecasts versus derived forecasts

	Profit $M						|%| Δ		
	Average of DMU forecasts			Average derived from L_{18} data			Forecast versus derived		
	Uncertainty regimes			Uncertainty regimes			Uncertainty regimes		
Test experiments	Current	Worst	Best	Current	Worst	Best	Current	Worst	Best
2,2,2,1,2,1	−5.20	−9.80	−4.10	−5.23	−9.08	−4.30	1	8	5
3,1,3,1,1,3	−5.76	−9.76	−3.20	−5.74	−9.59	−3.10	0	2	3
1,3,1,3,3,3	1.94	−2.28	4.06	2.47	−2.17	4.85	22	5	17
1,3,3,1,1,3	−1.14	−5.16	1.70	−1.16	−5.04	1.30	2	2	31
3,2,3,3,1,1	−0.14	−4.34	2.60	0.0	−3.64	2.90	–	20	10
					Average		6%	7%	13%

Finding

We find support for the claim that DMU's ability to make consistent forecasts is good. For most cases, |%Δ| between the team forecast and the derived forecast is reasonably small. We can infer that the forecasts are "consistent." Some treatments exhibit a large % difference, e.g. 31% for the (1,3,3,1,1,3) in the best uncertainty regime. This appears to be a case of over optimism. In this uncertainty regime, *Cost of Goods Sold* is low, *plant capacity* is high, the China plant has been divested (which releases new funds) and the customer mix has not changed. All of this assumes the best of good news. Although *sg&a* is high, and s*ales* are sluggish, the high forecast suggests that best uncertainty condition is probably casting a positive glow to this forecast. We will explain in Sect. 7.5.3 why Table 7.21 data is actually better than it looks. A bias from a DMU member that is skewing the distributions.

7.5.3 Production Gage R&R

7.5.3.1 Introduction

Table 7.21 data indicate that the DMU's forecasts are consistent for the *four* test experiments. But how can we determine whether the set of $18 \times 3 = 64$ forecasts for the L_{18} are equally "good enough?" As discussed in Sect. 3.5.4, we apply the engineering method of Measurement System Analysis (MSA). MSA is a way to analyze the sources of variation in a measurement system (Fig. 7.12). *To that end, we consider the DMU members who are forecasting, their knowledge, data bases, formal and informal procedures, and their network of contacts as a* ***measurement system***. MSA uses the terminology of "operator" to designate the person making the measurement. We will use the term "DMU member" or "DMU participant". Instead of measuring a manufactured part, each DMU member is making a forecast, i.e. "measuring" a decision alternative. We use "DMU" to identify the collective body. We use "DMU 4", for example to identify DMU member number four. The parts of this measurement system are decision alternatives. Instead of "measuring parts", we have forecasts outcomes of decision alternatives. Since we want to

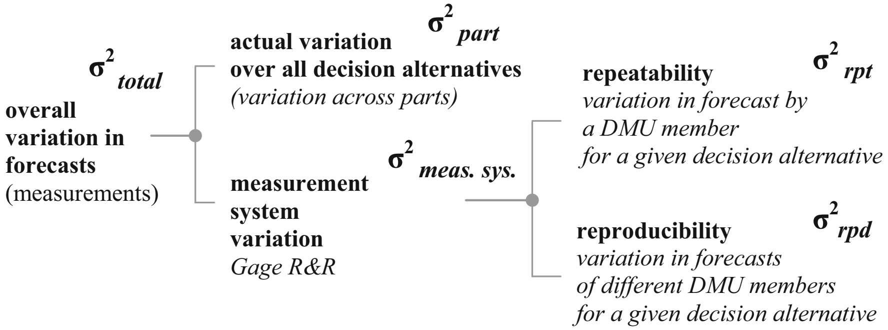


Fig. 7.12 Sources of variability of forecasts for decision alternative

measure the quality of the measurement system, as defined above, the Gage R&R Eq. (3.9) of Sect. 3.5.4 becomes Eq. (7.1) in this chapter. In the graphical form of the equation (Fig. 7.12), we show the MSA nomenclature inside the parentheses.

$$\sigma^2{}_{\text{total}} = \sigma^2{}_{\text{forecasts}} + \sigma^2{}_{\text{meas.sys.}} = \sigma^2{}_{\text{forecasts}} + \sigma^2{}_{\text{repeability}} + \sigma^2{}_{\text{reprodicibility}} \tag{7.1}$$

7.5.3.2 Reproducibility

Reproducibility is a quantity that indicates the precision of a measurement system. Reproducibility is the ability of a DMU member to replicate a forecasting result of a decision specification, by a ***different*** DMU member. The individual forecasts for a given experiment by different DMU members give us an indication of *reproducibility* across DMU members. That is to say, for a given experiment, are different DMU members able to reproduce a given forecast?

Figure 7.13 shows the forecasts for five test experiments (in the current and best uncertainty regimes) from our five DMU members. The graphical representation for the worst uncertainty-regime is similar and omitted in the interest of space. The five test experiments are specified as 6-tuples on the x-axis. The forecasts of each DMU member are shown as a line connecting their forecasts. An anomaly is apparent. DMU 4's forecasts (red line) are consistently higher than the others that cluster close together. It is apparent that DMU 4's forecasts show a positive bias. For this reason DMU 4 data is omitted in the Gage R&R analysis. A more complete rationale is presented in Appendix 7.4. Forecasts from the other DMU members are "closer," they show more *reproducibility*.

Figure 7.13 shows the data for each test experiment from each individual DMU member. What about the reproducibility of the DMU, as an ensemble, with and without DMU 4, not just for the test experiments, but for the whole array L_{18}? Table 7.22 shows the data, for each of these cases, in three uncertainty regimes. The consistent bias of DMU 4 is self-evident in Fig. 7.14. The red points represent DMU 4 data.

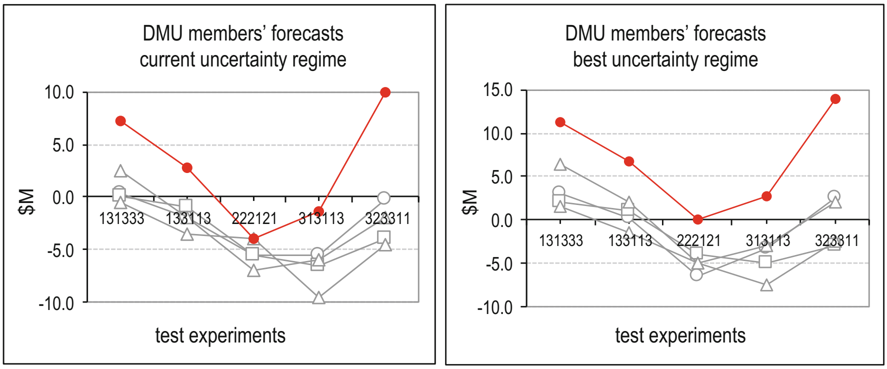


Fig. 7.13 Sources of variability for forecasts for test experiments

Table 7.22 Forecasts variability for L_{18} experiments, with and without DMU4

	DMU profit forecast $M uncertainty regimes			Forecasts' standard deviation uncertainty regimes		
	Worst	Current	Best	Worst	Current	Best
DMU **with** DMU 4	−6.3	−2.0	0.4	14.9	19.4	28.1
DMU **without** DMU 4	−7.1	−3.3	−1.3	6.3	9.1	14.0

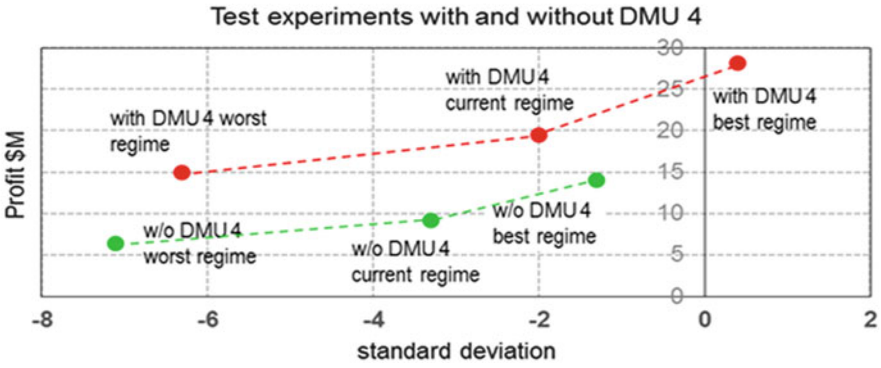


Fig. 7.14 Graphical representation of Table 7.22

7.5.3.3 Repeatability

Repeatability is another quantity that is used to indicate the quality of a measurement system. Repeatability is the ability of a DMU member to replicate its own forecast result of a ***same*** decision specification, under the same conditions. The individual forecasts for a given experiment by the same DMU member give us an indication of *repeatability* of a DMU member. That is to say, for a given experiment, are DMU members able to reproduce their own forecasts?

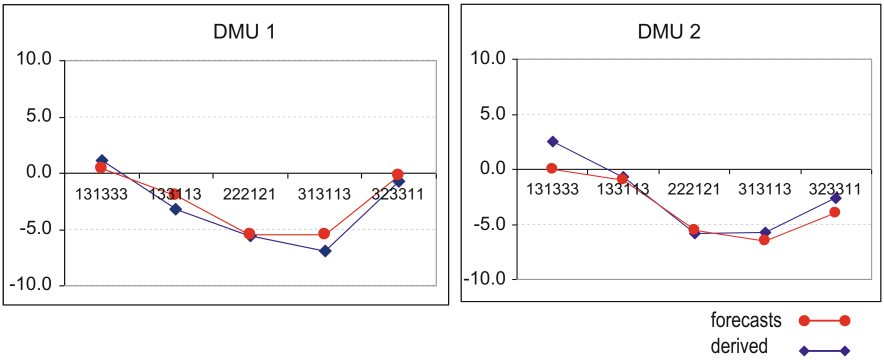


Fig. 7.15 Repeatability of forecasts: forecast versus derived

Figure 7.15 shows the forecasts for five test experiments (in the current and best uncertainty regimes) from DMU 1 and DMU 2 under the current uncertainty regime. We plot the forecast data by the individual DMU member from the L_{18} array and what our method predicts what that forecast ***ought to*** be. If they are "close" then there is good repeatability; otherwise, there is not. The forecast data and the predicted are indeed very close. We show these two as illustrative examples, the entire statistical data and analyses, of the entire DMU, are the subjects of the next section.

7.5.3.4 New Research Findings

We get the following ANOVA table for our Gage R&R statistics, without DMU 4 (Table 7.23).

The two-way ANOVA table shows the p values for "treatment" (experiment), "operator" (DMU member), "treatment*operator" (DMU-member * experiment), and repeatability are all statistically significant. The Garge R&R statistics show that of the total variation, 7.07% is from repeatability, 11.00% from reproducibility, and 81.92% from part-part variation (i.e. experiment-experiment). A graphic of the total variation and its elemental components are shown in Fig. 7.16.

The column on the LHS depicts the variations from the measurements without DMU 4. The column on the RHS depicts the variations from the measurements including DMU 4's measurements. The impact of bias from DMU 4 on the Gage R&R statistics is not trivial. We discuss the bias of DMU #4 in more detail in Appendix 10.4. For these and other reasons, data from DMU 4 has been omitted from this analyses.

AIAG has guidelines for measurement system statistics (AIAG 2002). Table 7.23 statistics fall "short" of AIAG benchmarks. The well-known AIAG guidelines stipulate that the Gage R&R variation should be <10%, whereas in our case it is 18.08%. The part-part should be >90%, whereas in our case, it 81.92%. The ASQC and AIAG guidelines specify a 10:90 split, which indicates in a

Table 7.23 ANOVA for measurement variances

Gage R&R study—ANOVA method

Two-way ANOVA table with interaction

Source	DF	SS	MS	F	P
treatment	4	299.099	74.7746	38.2558	0.000
operator	3	25.009	8.3363	4.2650	0.029
treatment * operator	12	23.455	1.9546	2.4870	0.035
Repeatability	20	15.719	0.7859		
Total	39	363.281			

Gage R&R

Source	VarComp	(of VarComp)	
Total Gage R&R	2.0084	18.08	
Repeatability	0.7859	7.07	←
Reproducibility	1.2225	11.00	
Operator	0.6382	5.74	
Operator*treatment	0.5843	5.26	
Part-To-Part	9.1025	81.92	
Total Variation	11.1109	100.00	

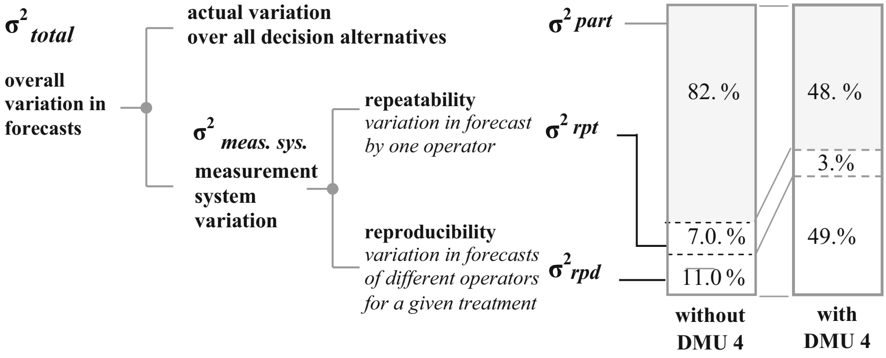


Fig. 7.16 Sources of variability for forecasts

discriminatory capability or four for the measurement system. The *discriminatory capability* measurement number also called the *discrimination ratio*. It is obtained by:

$$(\text{discrimination ratio}) = \surd[\text{Var}(\text{part-to-part})/\text{Var}(\text{total gage R\&R})]^{*}\surd 2 \tag{7.2}$$

This is the number of distinct groups the measurement system can discriminate within the total observed product or process variation. It is a measure of the sensitivity of the process. For a discrimination ratio of two, the measurement system has the capability of only being able to discriminate between high and low results within the observed variation. With a discrimination ratio of 3 you can use your measurement system to categorize three discrete levels within the observed product or process variation, such as high, medium and low. The ASQC and AIAG recommended number is >4.

Our system can distinguish three categories ($\sqrt{9.1025}/\sqrt{2.0084}) \times \sqrt{2} = 3.01$). But with DMU 4 data, the number of categories is much smaller. In a team oriented forecasting effort of this kind, all data from all the DMU members would have been considered in the analysis. By excluding DMU 4, we are able to more accurately determine the discriminatory power of our forecasting system, and of the DMU and our DOE methodology.

To our knowledge, *this is the first example* of the use of Gage R&R for a sociotechnical system. This is a new and worthy subject for further research.

It is significant that the Gage R&R specifications and standards were co-developed by the AIAG, Ford, GM, and DaimlerChrysler, at the cradle of mass production. It is safe to estimate that many of person-centuries of manufacturing expertise and historical data went into this effort. It is also safe to say that data from the manufacturing measurements of millions of parts went to the development of the Gage R&R method. We have not found any literature to tell us whether the manufacturing measurement standards apply in equal measure to sociotechnical processes; such as forecasting. This is an open area for further investigation. We invite the US National Institute of Technology and Standards (NIST), scientists, engineers and metrologists to tackle this subject. This research is important. The world's economy is being transformed into a service economy.

Gage R&R, in the context of sociotechnical systems, raises many challenging and unanswered questions about the quality of such complex systems. Nevertheless, the Gage R&R method has shown to be useful, given us new insights, which are consistent with findings obtained by other means. The method has given us an analytic approach to determine the capabilities of a forecasting group, individually and as a "composite". The "composite" is a sociotechnical ensemble, their knowledge of the DMU (individually and collectively), organizational data bases, formal as well as informal procedures, and DMU members' network of contacts. This is consistent with our engineering approach of our work. We now have rigorous metrics derived from Gage Theory to evaluate important properties of the forecasts and of the sociotechnical composite. We have concentrated on the properties of repeatability, reproducibility, and Gage R&R metrics. We were able to obtain a measure of the discriminatory power of the composite, the sources of forecasting variations, and pinpoint the individuals contributing the most bias to the measuring system. The use of Gage theory and MSA in forecasting for exploring related management issues is an important, new and useful area for research.

7.5.4 Feedback from the DMU

We had preprinted forms for the DMU to write in anonymous feedback about the process. The following were typical comments from the DMU.

- “Excellent and rational process. . .understand risk with factors cannot control.”
- “Value of this process is in the process not the conclusions.”
- “The company executives need to do this exercise.”
- “It is not clear how the math arrives at the results. Explanations of the calculations would help understand the process.”

We were gratified for the general positive tone of the feedback. That the mathematics of the process was something that was not clearly explained is a valid criticism. One which needs to addressed. This is one challenge that we have tried to tackle with this book.

7.5.5 General Discussion

A decision is a specification, of an intellectual artefact, designed and intended for implementation and execution. It is not an artefact to merely satisfy a curiosity. A decision specification is intended to enable purposeful action. To act, we view the composite, of people and sociotechnical systems, that executes the decision specification as a production system, like a factory. This chapter shows that the engineering method of Gage R&R from Measuring System Analysis (MSA) is effective to measure and evaluate the quality of the sociotechnical systems. The evaluation measures are reproducibility, repeatability of the Gage R&R method. The measures demonstrate their usefulness for our tests of efficacy for it gives detailed and nuanced insight into the operational elements and system behavior. The Gage R&R method and its guidelines were formulated with the assistance and data from the major US automobile manufacturers. We find no data or information data about sociotechnical systems. Nevertheless, our application of the method is effective. This is a new field that merits research attention.

The application of the Gage RR&R method for sociotechnical production systems is a gap in the research literature. ***This is an entirely new domain of research***. In particular, when manufacturing has ceased to be a dominant component of the economic engine in the world’s most important economies.

We conclude that XRL-4 conditions for efficacy are met (Table 7.24).

Table 7.24 Readiness level specifications for executive decisions

Readiness Level	Systematic process for the performance space	Efficacy
X-RL4 Evaluating performance space	Evaluate performance: analyze 4R	☑
	Robustness, repeatability, reproducibility	☑
	Reflect	☑

The symbol ☑ indicates support is demonstrated

7.6 Enacting the Commitment Space

> Entschluss wird von Entschlossenheit geboren. (Decisions are born from decisiveness.)
> (von Clauswitz)

A *sine qua non* of executive decisions is a decisive executive. The one person empowered to commit to a decision specification, a schedule for its implementation, an allocation of resources that makes enactment possible. These commitments give meaning to decisive decision-making (Fig. 7.17).

HiTEM's president told us at the end of briefing:

- "Let's take this to our board of directors."
- "This approach will make better decisions."

In the next paragraph we present HiTEM president's implementation of his realistic strategy.

7.6.1 *What Actually Happened*

We were on site at HiTEM headquarters on the second quarter of the year 20XX. This was at the end of the 6-month forecast period of our experiment. HiTEM turned a profit and the president retained his position. As required by law for a public company, HiTEM had just reported a net income of $1 M to the Securities and Exchange Commission (SEC). (The SEC is the US government agency missioned to regulate the commerce in stocks, bonds, and other securities.) Table 7.25 summarizes HiTEM's actions that led to these results leading to this profitable report. In the execution of the realistic strategy, they were able to improve on two variables and underperformed in two others. HiTEM improved plant utilization from 60% to 70% and improved the customer portfolio mix by shedding some of the most unprofitable customers. However, instead of generating sales of $690 M, it generated sales of $655 M. And although HiTEM was unable to unload the China or

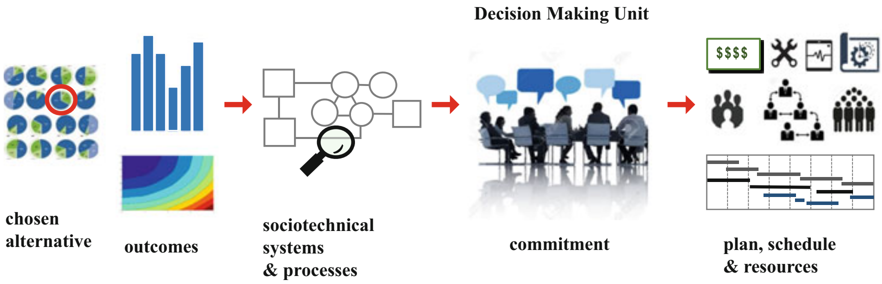


Fig. 7.17 Schematic of the commitment space

Table 7.25 HiTEM's performance: actual versus plan

	BAU	Realistic strategy plan		Actual performance	
Controllable factors	Level	Level	Values at level	Level	Values at level
sg&a	2	3	\$54 M – 10%	3	\$54 M – 10%
cogs	2	2½	\$651 M – 1%	2½	\$651 M – 1%
Plant utilization	2	2	60%	2½	70%
Portfolio actions	1	2	No change	2½	Improved mix
Sales	2	1½	\$690 M –2.5%	1	\$690 M – 5%
Financing	1	1½	Shortfall ~\$5 M	1	Shortfall ~\$5 M
		Derived results: \$−1.13 M		Derived results: \$0.41 M	
				Results reported to SEC: \$1 M	

the Mexico factory, it did manage to sell some real estate. All this allowed HiTEM to have a profit of \$1 M. Our method predicted \$0.41 M without the sale of real estate or China plant divestiture.

7.6.2 Summary Discussion

Findings

1. The method is useful. HiTEM's president was enthusiastic about the work. Most useful to him were the abilities to:
    - Construct any hypothetical what-if decision alternative,
    - Predict their outcomes under the uncertainty regimes,
    - Know the % contribution; and therefore the relative weight, of each controllable variable to the outcomes,
    - Use of the standard deviation of the outcomes of each controllable variable as an indicator of the risk associated with the variables at those levels.

      The president took our analyses, data and our findings to his board of directors, who readily approved his actions.

2. The decision protocol is effective. The protocol was an effective blueprint for our experiment. We found that the DMU had no difficulty making forecasting the experiments' outputs for all three uncertainty regimes. This suggests that the team learned how to forecast complex scenarios, even under pressure. Moreover, our methodology was able to produce all the data expected by the DMU for analyses and discussions.
3. There is support for method validity. To test construct, internal validity, external validity, and reliability, we follow Yin (2013), Hoyle et al. (2002); and for repeatability and reproducibility, we use the Gage R&R methods and MSA metrics.

Construct validity. Can we demonstrate we have a meaningful conceptual framework for our experiment, it can be operationalized. A framework that can be

uncontrollable variables
1. customer base changes
2. senior management interactions
3. banker actions
4. loss of critical skills

controllable variables
1. *sg&a*
2. *cogs*
3. plant capacity utilization
4. customer portfolio mix
5. sales
6. financing

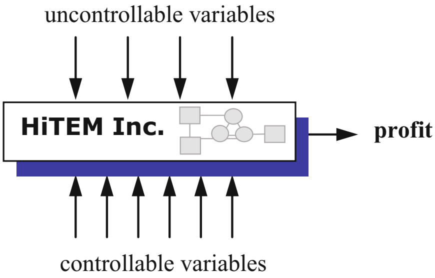


Fig. 7.18 Conceptual construct of our experiment

operationalized with accurately specified independent and dependent variables? The answer is in the affirmative. The p-diagram is our construct (Sect. 3.7) for HiTEM the DOE method (Fig. 7.18).

To determine the interactions between the controllable and uncontrollable variables we have the orthogonal array construct (Table 7.6). ANOVA data support their statistical significance (Tables 7.10 and 7.11). Our protocol makes our constructs operational (Sect. 4) and Gage R&R construct for quality analyses. The ANOVA summary data support their statistical significance.

Internal validity. Can we demonstrate that we can draw conclusions about the causal effects of the independent variables on the dependent variables? Address whether the conclusions that can be drawn are plausible and credible to domain experts? This is also known as face validity?

The answer is: Yes. The president and the DMU judged the effects of the controllable variables of the outcome variables to be consistently credible with their domain knowledge and with experience with HiTEM.

External validity. Can we demonstrate that we can generalize from this experiment to a larger and more general population and/or broader settings? Yes, we will do so in the next chapters with more examples. Results support that our method is sufficiently general to other complex management decisions in the sociotechnical domain.

Reliability Use of Gage R&R. Tests of reliability are used to determine whether the procedures can be repeated to produce consistent results by people and instruments. Earlier in Sect. 3.3 we used two rounds of forecasts for the BAU outcomes data. The consistency of the results is high. The Gage R&R data support, as valid, the quantitative metrics for repeatability, reproducibility, and experiment-to-experiment variations. ***These are two new and novel findings in our use of Gage R&R quality heuristics in our domain of executive decisions***. The literature is very silent on this regard.

We conclude that XRL-5 conditions for efficacy are met (Table 7.26).

Table 7.26 Readiness level specifications for executive decisions

Readiness level	Systematic process for the commitment space	Efficacy
X-RL5 Enacting commitment space	Decisive executive	☑
	Approval of plan	☑
	Commit funds, equipment, organizations	☑

The symbol ☑ indicates support is demonstrated

7.7 Chapter Summary

Our goal for this chapter has been to report on the **efficacy** of our methodology with a real world company, HiTEM. We stipulated that our methodology *works*, if and only if, two conditions are simultaneously satisfied, *viz*. it is ready-*to*-work for users in general, as well as, ready-*for*-work by a user to satisfy a specific set of application needs. We set out to demonstrate that our methodology is *ready-for-work* by users. We exercised our methodology to cover all five spaces of HiTEM's decision life cycle. The new president engaged us to help reverse, in 6 months, a downward spiral.

Using our DOE-based method, we explored a wide range of diverse hypothetical "what-if" questions posed by the president and his key executives. Significantly, the questions were posed without imposing constraints on the range or scope of hypothetical questions. Our DOE based methodology enabled us to explore the entire solution space over a wide space of environmental uncertainty. The decision specifications for the alternatives for this exploration were readily constructed using the controllable and uncontrollable variables. We introduced DOE and Gage R&R to this new domain.

The results in this chapter show that:

- **Use of DOE and Gage R&R for executive-management decisions is meaningful**. This approach yields useful and statistically meaningful results. We can explore the entire solution space over the entire uncertainty space; thus, vacating any constraints to the range of "what if" questions that can be explored.
- **There is support for the validity of our method**. Validity is inferred from executive feedback, statistical analyses of HiTEM's experiments, validation criteria for tests of construct, internal, and external validity.
- **Engineering approach to analyze data quality using Gage theory is meaningful**. We can consider the executives who are forecasting outcomes, their knowledge, data bases, formal and informal procedures as a measurement system. We can use Gage R&R to evaluate its repeatability and reproducibility. This is new ground in executive-management decision analysis. We plan to study and explore this further with more experiments in other business environments in the next two chapters.
- **The senior executives are able to identify the controllable variables that provide a meaningful representation of the organizational systems**.

Tables 7.10 and 7.11 data show that the chosen variables of *sg&a, cogs, plant utilization, portfolio actions, sales,* and *financing* explain >90% of the behavior of the system as measured by MS_{adj} data. Moreover, the interactions among the controllable variables are very small. The complex systems behavior is "near decomposable" (Simon 1997, Simon 2001). The system behavior exhibits "the robust beauty of linear models" (Dawes (1979) that perform well for complex decisions (Dawes 1979; Camerer 1981).

We stepped through every step of our systematic process to demonstrate the *efficacy* of our method and its readiness, from X-RL1 to X-RL5 (Table 7.1). Our work with HiTEM demonstrated there is support for the following:

Readiness level	Our systematic process	Strategy
X-RL1	Characterize the problem space	Sense making
X-RL2	Engineer the solution space	Design and engineer experiments/alternatives
X-RL3	Explore the operations space	Explore entire solution and uncertainty spaces
X-RL4	Evaluate the performance space	Measure Robustness, Repeatability, Reproducibility
X-RL5	Enact the commitment space	Commit plan with approved resources

X-RL1 In the *Problem Space* the decision situation is very clearly framed as the firm's and personal mandatory necessity to produce a profit in 6 months. The problem is represented by six controllable variables, four uncontrollable variables, and three uncertainty regimes spanning the uncertainty space. All variables are specified at three levels.

X-RL2 The specifications for *Solution Space* is thoroughly specified using an $\mathbf{L_{18}}$ orthogonal array and four test experiments. The base line is established with our debiasing procedure. The data demonstrates it reduces bias and improves confidence.

X-RL3 Exploration of the *Operations Space* is exhaustively executed and analyzed. The ANOVA statistics show that all the variables are statistically significant. The confirmatory test experiments show that the forecasting capabilities of the DMU, as well as, its members are consistent with the independently predicted values. We explored the construction of a wide variety of alternative decision specifications under a spanning set of uncertainty regimes. Alternatives that are predicted to produce both superior outputs and lower risk.

X-RL4 Evaluation of the *Performance Space* is performed to determine robustness, repeatability, reproducibility. We use Gage R&R and the response tables for output and standard deviations for the controllable variable. 3-R data supports the application of our sociotechnical methodology for HiTEM.

Regrettably the literature is silent the use of Gage R&R for sociotechnical production systems. The research and applications are dominated by traditional thinking that focus on physical products and production. ***Our use of Gage R&R and***

the 3-R metrics in our domain of executive decision engineering and production is a first and a novel application in a new domain. This is a new and useful area of research.

X-RL5 Enacting the Commitment Space is demonstrated by the actions taken by the president and the results obtained. The results, which were officially reported to the US government, satisfied the goals and objectives originally specified by HiTEM's president and the DMU. There is support for the predictive capabilities of our methodology.

The results reported in this chapter demonstrate strong support for the efficacy of our methodology.

Readiness level specifications for executive decisions		
Readiness level	Our systematic process	Efficacy
X-RL1 Characterize Problem space	Sense making—uncomplicate cognitive load	☑
	Frame problem/opportunity and clarify boundary conditions	☑
	Specify goals and objectives	☑
	Specify essential variables Managerially controllable variables Managerially uncontrollable variables	☑
X-RL2 Engineer solution space	Specify subspaces of solution space Alternatives space and uncertainty space	☑
	Specify entire solution space	☑
	Specify base line and uncertainty regimes Do-nothing case and choice-decision Estimate base line and dispel bias	☑
X-RL3 Explore operations space	Specify	
	Sample orthogonal array	☑
	Do-nothing case and choice decision-alternative	☑
	Predict outcomes	☑
	Design and implement robust alternative	☑
	Design and implement any what-if alternative	☑
X-RL4 Evaluate performance space	Evaluate performance: analyze 4R	☑
	Robustness, repeatability, reproducibility, reflect	☑
X-RL5 Enact commitment space	Decisive executive	☑
	Approval of plan	☑
	Commit funds, equipment, organizations	☑

☑ indicates support is demonstrated

Appendix 7.1 DMU Forecasting BAU Round 1 and Round 2

	BAU forecasts														
	Current uncertainty regime					Worst uncertainty regime					Best uncertainty regime				
DMU #	#1	#2	#3	#4	#5	#1	#2	#3	#4	#5	#1	#2	#3	#4	#4
Round 1	−6.0	−5.0	−7.0	−7.5	−4.0	−8.0	−10	−11	−14.5	−10	−4.0	−1.0	−5.0	−7.1	−0.0
Round 2	−4.0	−5.5	−7.0	−5.0	−5.5	−8.0	−10	−10	−9.0	−9.0	−0.0	−4.0	−5.0	−3.0	−3.0

Appendix 7.2 DMU Forecasting Confidence, BAU Round 1 and 2

	Confidence						
	DMU 1	DMU 2	DMU 3	DMU 4	DMU 5	Average	Stdev
Round 1	4	2	4	3	3.5	3.3	0.84
Round 2	4	4	3	4.0	4.5	3.9	0.55

Appendix 7.3 Complete Forecast Data Set

	Controllable variables						Current uncertainty-regime						
							Level 2, current state					Cust. base change	
							Level 2, current state					Sr. exec xactions	
							Level 2, current state					Banker actions	
							Level 2, current state					Critical skills	
Experiment	*sg&a*	*cogs*	Capacity utilization	Portfolio	Sales	Financing	DMU1	DMU2	DMU3	DMU4	DMU5	Mean	Stdev
BAU	2	2	2	1	2	2	−5.97	−6.01	−5.99	−4.00	−7.00	−5.80	1.09
1	1	1	1	1	1	1	−10.90	−11.5	−12.50	−12.80	−11.0	−11.74	0.87
2	1	2	2	2	2	2	−3.70	−3.5	−6.00	0.80	−4.50	−3.38	2.54
3	1	3	3	3	3	3	2.40	4.0	−0.50	14.30	3.50	4.74	5.62
4	2	1	1	2	2	3	−6.80	−5.0	−8.00	−3.80	−7.00	−6.12	1.69
5	2	2	2	3	3	1	−1.50	−2.5	−4.50	6.80	0.50	−0.24	4.33
6	2	3	3	1	1	2	−4.30	−1.5	−2.00	3.00	−1.50	−1.26	2.65
7	3	1	2	1	3	2	−7.00	−6.0	−8.00	−4.30	−3.00	−5.66	2.02
8	3	2	3	2	1	3	−0.50	−0.5	−3.50	7.00	−2.00	0.10	4.05
9	3	3	1	3	2	1	1.80	0.5	0.00	7.00	0.50	1.96	2.90
10	1	1	3	3	2	2	−5.70	−4.5	−10.00	6.00	−5.00	−3.84	5.92
11	1	2	1	1	3	3	−6.20	−5.0	−6.50	−6.00	−1.50	−5.04	2.06
12	1	3	2	2	1	1	−1.90	−2.5	−1.50	2.30	−3.50	−1.42	2.21
13	2	1	2	3	1	3	−4.80	−4.0	−8.50	4.00	−6.50	−3.96	4.77
14	2	2	3	1	2	1	−4.50	−5.0	−7.00	−0.50	−3.50	−4.10	2.38
15	2	3	1	2	3	2	1.30	2.0	−0.50	2.50	1.00	1.26	1.15
16	3	1	3	2	3	1	−3.20	−6.0	−7.50	3.30	−2.50	−3.18	4.16
17	3	2	1	3	1	2	−2.00	−1.5	−4.50	4.00	−4.00	−1.60	3.38
18	3	3	2	1	2	3	0.60	2.5	−1.00	2.50	1.00	1.12	1.47
19	*3*	*1*	*3*	*1*	*1*	*3*	*−5.50*	*−6.5*	*−9.50*	*−1.30*	*−6.00*	*−5.76*	*2.94*
20	*1*	*3*	*1*	*3*	*3*	*3*	*0.40*	*0.0*	*−0.50*	*7.30*	*2.50*	*1.94*	*3.21*
21	*1*	*3*	*3*	*1*	*1*	*3*	*−2.00*	*−1.0*	*−3.50*	*2.80*	*−2.00*	*−1.14*	*2.38*
22	*3*	*2*	*3*	*3*	*1*	*1*	*−0.20*	*−4.0*	*−4.50*	*10.00*	*−2.00*	*−0.14*	*5.92*

	Controllable variables						Worst uncertainty-regime						
							Level 1					Cust. base change	
							Level 2					Sr. exec xactions	
							Level 1					Banker actions	
							Level 1					Critical skills	
Experiment	*sg&a*	*cogs*	Capacity utilization	Portfolio	Sales	Financing	DMU1	DMU2	DMU3	DMU4	DMU5	Mean	Stdev
BAU	2	2	2	1	2	2	−9.00	−10.00	−10.00	−10.00	−10.00	−9.80	0.45
1	1	1	1	1	1	1	−16.00	−16.0	−15.50	−18.80	−15.0	−16.26	1.48
2	1	2	2	2	2	2	−7.70	−8.0	−8.00	−5.30	−8.50	−7.50	1.26
3	1	3	3	3	3	3	−1.70	−0.5	−2.50	8.30	−1.50	0.42	4.46
4	2	1	1	2	2	3	−10.80	−10.0	−10.00	−9.80	−11.0	−10.32	0.54
5	2	2	2	3	3	1	−5.50	−7.0	−7.50	0.80	−3.50	−4.54	3.37
6	2	3	3	1	1	2	−7.80	−6.0	4.00	−3.00	−5.50	−3.66	4.61
7	3	1	2	1	3	2	−10.50	−10.5	−10.00	−11.30	−7.00	−9.86	1.67
8	3	2	3	2	1	3	−4.50	0.5	−5.50	1.00	−6.00	−2.90	3.38
9	3	3	1	3	2	1	−2.20	−4.0	−3.00	1.00	−3.50	−2.34	1.98
10	1	1	3	3	2	2	−9.70	−9.0	−12.00	0.00	−9.00	−7.94	4.61
11	1	2	1	1	3	3	−9.70	−9.5	−8.50	−12.00	−5.50	−9.04	2.36
12	1	3	2	2	1	1	−5.60	−7.0	−4.50	−3.80	−7.50	−5.68	1.58
13	2	1	2	3	1	3	−8.80	−9.0	−10.50	−2.00	−10.5	−8.16	3.54
14	2	2	3	1	2	1	−8.00	−9.5	−10.00	−6.50	−7.50	−8.30	1.44
15	2	3	1	2	3	2	−2.80	−3.0	−2.50	−3.50	−3.00	−2.96	0.36
16	3	1	3	2	3	1	−6.70	−10.5	−10.50	−2.80	−6.50	−7.40	3.23
17	3	2	1	3	1	2	−6.00	−6.0	−6.50	−2.00	−8.00	−5.70	2.22
18	3	3	2	1	2	3	−3.00	−3.0	−3.00	−3.50	−3.00	−3.10	0.22
19	*3*	*1*	*3*	*1*	*1*	*3*	*−9.00*	*−11.0*	*−11.50*	*−7.30*	*−10.0*	*−9.76*	*1.68*
20	*1*	*3*	*1*	*3*	*3*	*3*	*−3.70*	*−4.0*	*−2.50*	*1.30*	*−2.50*	*−2.28*	*2.11*
21	*1*	*3*	*3*	*1*	*1*	*3*	*−5.50*	*−5.5*	*−5.50*	*−3.30*	*−6.00*	*−5.16*	*1.06*
22	*3*	*2*	*3*	*3*	*1*	*1*	*−4.20*	*−8.0*	*−7.50*	*4.00*	*−6.00*	*−4.34*	*4.89*

	Controllable variables						Best uncertainty-regime						
							Level 3					Cust. base change	
							Level 3					Sr. exec xactions	
							Level 3					Banker actions	
							Level 3					Critical skills	
Experiment	*sg&a*	*cogs*	Capacity utilization	Portfolio	Sales	Financing	DMU1	DMU2	DMU3	DMU4	DMU5	Mean	Stdev
BAU	2	2	2	1	2	2	−6.50	−4.00	−5.00	0.00	−5.00	−4.10	2.46
1	1	1	1	1	1	1	−8.70	−10.0	−10.50	−8.80	−4.00	−8.40	2.58
2	1	2	2	2	2	2	−1.00	−2.00	−4.00	4.80	−0.50	−0.54	3.27
3	1	3	3	3	3	3	5.10	5.50	−2.50	18.30	7.50	6.78	7.48
4	2	1	1	2	2	3	−4.00	−4.00	−6.00	0.30	−3.00	−3.34	2.31
5	2	2	2	3	3	1	1.20	0.00	−2.50	10.80	4.50	2.80	5.13
6	2	3	3	1	1	2	−2.10	0.00	0.00	7.00	2.50	1.48	3.49
7	3	1	2	1	3	2	−4.80	−4.50	−6.00	−0.30	1.00	−2.92	3.07
8	3	2	3	2	1	3	2.30	1.00	−1.50	11.00	2.00	2.96	4.74
9	3	3	1	3	2	1	4.50	2.00	2.00	11.00	4.50	4.80	3.68
10	1	1	3	3	2	2	−3.00	−3.00	−8.00	10.00	−1.00	−1.00	6.67
11	1	2	1	1	3	3	−4.00	−4.50	−4.50	−2.00	2.50	−2.50	2.98
12	1	3	2	2	1	1	0.50	0.00	0.50	6.30	0.50	1.56	2.66
13	2	1	2	3	1	3	−2.00	−3.00	−6.50	8.00	−3.50	−1.40	5.52
14	2	2	3	1	2	1	−2.30	−3.50	−5.00	3.50	−0.50	−1.56	3.27
15	2	3	1	2	3	2	4.00	3.00	1.50	6.50	5.00	4.00	1.90
16	3	1	3	2	3	1	−1.00	−4.50	−5.50	7.30	1.50	−0.44	5.15
17	3	2	1	3	1	2	0.70	0.00	−2.50	8.00	0.00	1.24	3.97
18	3	3	2	1	2	3	2.80	3.00	1.00	6.50	5.00	3.66	2.13
19	*3*	*1*	*3*	*1*	*1*	*3*	*−3.30*	*−5.00*	*−7.50*	*2.80*	*−3.00*	*−3.20*	*3.80*
20	*1*	*3*	*1*	*3*	*3*	*3*	*3.00*	*2.00*	*1.50*	*11.30*	*6.50*	*4.86*	*4.10*
21	*1*	*3*	*3*	*1*	*1*	*3*	*0.20*	*1.00*	*−1.50*	*6.80*	*2.00*	*1.70*	*3.13*
22	*3*	*2*	*3*	*3*	*1*	*1*	*2.50*	*−3.00*	*−2.50*	*14.00*	*2.00*	*2.60*	*6.85*

Appendix 7.4 DMU-4 Forecasts

The bar chart in this appendix shows forecasts of each DMU team member for each of the three uncertainty regimes. Data from DMU-4 are out of step with respect to other DMU members. DMU-4's forecasts are in the opposite direction of all the remaining participants in the current and the best uncertainty regimes. And DMU-4 is more optimistic in the best environment. DMU-4 appears to be overconfident in his forecasts.

Is DMU-4 the only one that is right and all the others are wrong? Ashton (1985) writes: "... there is the possibility that an oddball genius, who does not agree with anyone else, could be proved correct by subsequent events". Notably, Ashton (1985) credits Einhorn (1974) for the insight "that the identification of the oddball as a genius requires that some criterion other than consensus become available." Such criterion was not evident to the DMU.

DMU-4 is HiTEM's finance executive. His organization had missed deadlines for filing SEC's required financial reports on time. Moreover, they were inaccurate. It required HiTEM to restate financial reports, which had been released officially and to the press. For these reasons we judge that it is appropriate to exclude operator #4's data from the analyses.

More specifically, DMU-4's forecasts bias the results. The Table 7.27 show statistics for the forecasts of all the treatments with and without DMU-4.

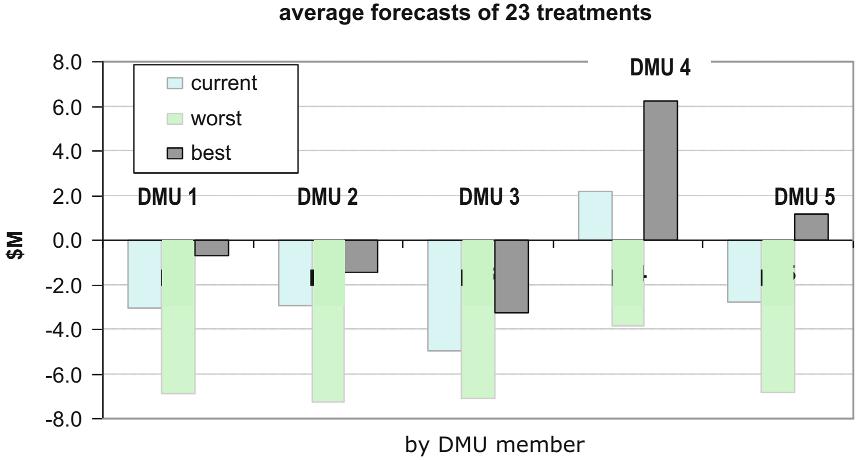


Table 7.27 Profit forecast statistics with and without DMU-4 in all uncertainty regimes

Forecasts for current uncertainty regime							
DMU-1	DMU-2	DMU-3	DMU-4	DMU-5	DMU average	Stdev	
−3.03	−2.91	−4.96	–	−2.76	−3.4	1.0	Without op #4
−3.03	−2.91	−4.96	2.21	−2.76	−2.5	2.7	With op #4
					36%	**63%**	|% delta|: with and without DMU-4

Forecasts for worst uncertainty regime							
DMU-1	DMU-2	DMU-3	DMU-4	DMU-5	DMU average	Stdev	
−6.89	−7.24	−7.09	–	−6.8	−7.0	0.2	Without op #4
−6.89	−7.24	−7.09	−3.85	−6.8	−6.4	1.4	With op #4
					9%	**9%**	|% delta|: with and without DMU-4

Forecasts for best uncertainty regime							
DMU-1	DMU-2	DMU-3	DMU-4	DMU-5	DMU average	Stdev	
−0.69	−1.46	−3.26	–	1.15	1.6	3.5	Without op #4
−0.69	−1.46	−3.26	6.22	1.15	0.2	3.7	With op #4
					700%	**5%**	|% delta|: with and without DMU-4

Appendix 7.5 Response Tables for Worst and Best Uncertainty Regimes

Response Table—Means for worst uncertainty regime

Level	*sg&a*	*cogs*	Capacity	Portfolio	Sales	Financing
1	−8.267	−10.625	−7.833	−8.167	−7.633	−8.021
2	−6.904	−6.913	−7.046	−6.650	−7.225	−6.792
3	−5.788	−3.421	−6.079	−6.142	−6.100	−6.146
Delta	2.479	7.204	1.754	2.025	1.533	1.875
Rank	2	1	5	3	6	4

Response Table—Standard deviations for worst uncertainty

Level	*sg&a*	*cogs*	Capacity	Portfolio	Sales	Financing
1	1.0595	1.2151	0.8157	1.7668	2.0012	1.3082
2	1.6644	1.5312	1.0170	1.2820	0.7063	1.6549
3	1.4388	1.4164	2.3300	1.1139	1.4552	1.1996
Delta	0.6049	0.3161	1.5143	0.6529	1.2949	0.4553
Rank	4	6	1	3	2	5

Response Table—Means for best uncertainty regime

Level	*sg&a*	*cogs*	capacity	portfolio	sales	financing
1	−2.04583	−4.33333	−1.50000	−2.37917	−1.84583	−1.51250
2	−1.09167	−1.00417	−0.84583	−0.63333	−1.08333	−1.02917
3	0.12500	2.32500	−0.66667	−0.00000	−0.08333	−0.47083
Delta	2.17083	6.65833	0.83333	2.37917	1.76250	1.04167
Rank	3	1	6	2	4	5

Response Table—Standard deviations for best uncertainty

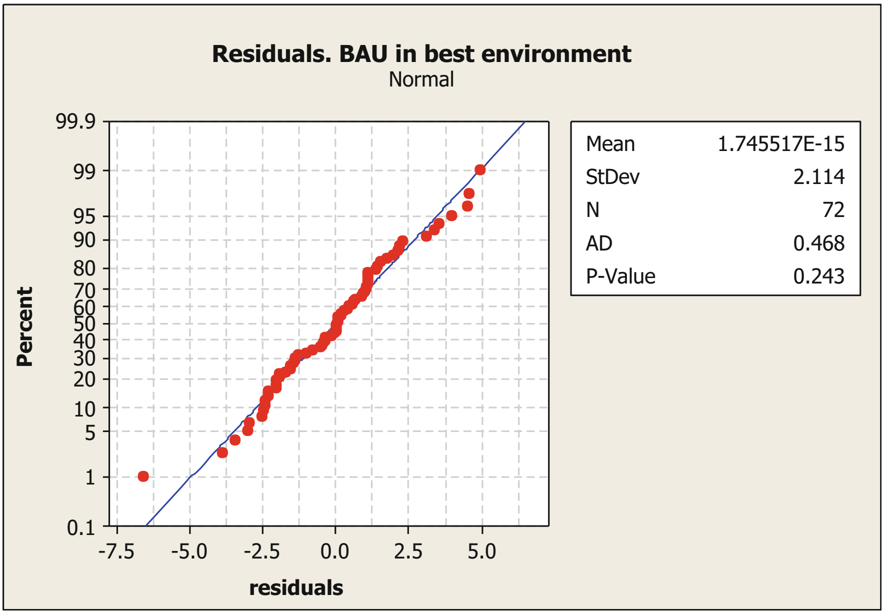
Level	*sg&a*	*cogs*	capacity	portfolio	sales	financing
1	2.595	2.581	1.998	2.488	1.694	2.116
2	1.897	2.153	1.900	1.583	1.796	2.072
3	2.092	1.850	2.686	2.512	3.094	2.396
Delta	0.698	0.732	0.786	0.929	1.400	0.324
Rank	5	4	3	2	1	6

Appendix 7.6 ANOVA of BAU in Best and Worst Uncertainty Regimes

Analysis of Variance BAU in best uncertainty regime

Source	DF	Seq SS	Adj SS	Adj MS	F	P
sg&a	2	56.826	56.826	28.413	5.29	0.008
cogs	2	532.001	532.001	266.000	49.48	0.000
Capacity	2	9.236	9.236	4.618	0.86	0.429
Portfolio	2	72.876	72.876	36.438	6.78	0.002
Sales	2	37.502	37.502	18.751	3.49	0.037
Financing	2	13.043	13.043	6.522	1.21	0.305
Error	59	317.165	317.165	5.376		
Total	71	1038.649				

S = 2.31855, R-Sq = 69.46%, R-Sq(adj) = 63.25%

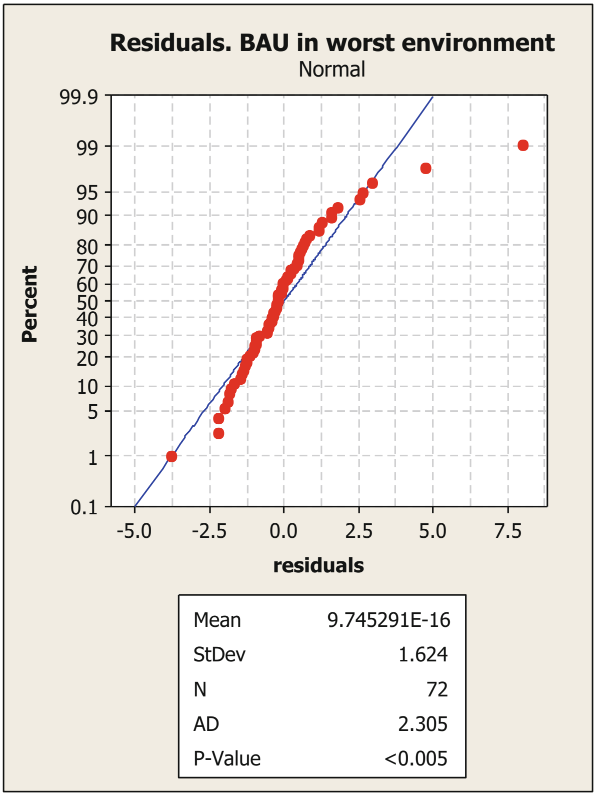


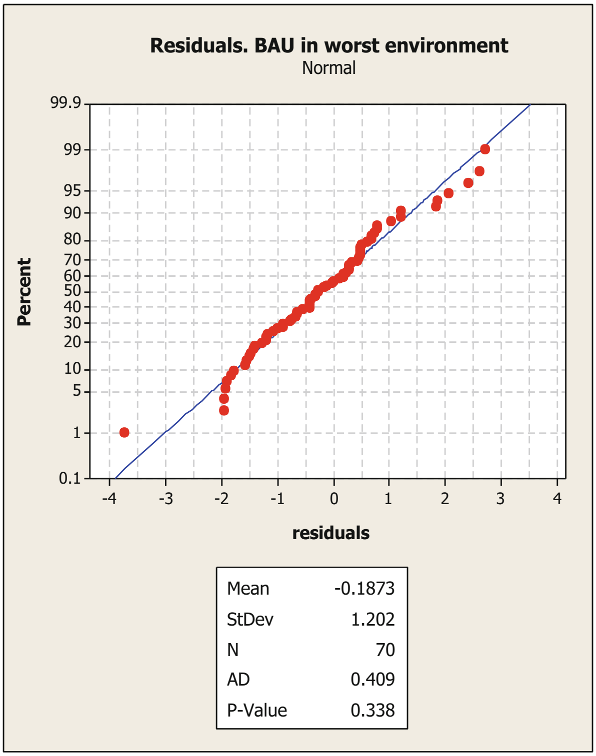
Analysis of variance for BAU in worst uncertainty regime

Source	DF	Seq SS	Adj SS	Adj MS	F	P
sg&a	1	73.76	73.76	73.76	24.46	0.000
cogs	1	622.80	622.80	622.80	206.58	0.000
capacity	1	36.93	36.93	36.93	12.25	0.001
portfolio	2	53.27	53.27	26.64	8.84	0.000
sales	1	28.21	28.21	28.21	9.36	0.003
financing	2	43.55	43.55	21.77	7.22	0.001
Error	63	189.93	189.93	3.01		
Total	71	1048.45				

S = 1.73630, R-Sq = 81.88%, R-Sq(adj) = 79.58%

The residuals are plotted below.





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Chapter 8
Verifying Efficacy: Yokozuna Project

Abstract This is the second chapter of Part **III.** We engage with a real world customer to verify the efficacy of our methodology. In the previous chapter, we worked with HiTEM, a high- technology contract manufacturer of electronics components. In this chapter, we report our work with a world-class e-business service company, eSvcs Japan, eSvcsJ for short. This chapter documents an evaluation of an eSvcsJ decision that was under implementation with a world-class Japanese manufacturer. The client of eSvcs, we name Yokozuna. Yokozuna is a title given to grand champions Sumo wrestlers. Yokozuna is a gigantic enterprise, intensely competitive, and remarkably nimble for its size. The firm has a demanding no-nonsense CEO and an authoritarian command and control system that emphasizes execution. The appellation, Yokozuna, is appropriate.

8.1 Introduction

In the previous chapter, we worked with HiTEM. Whereas HiTEM was a product company, this time we wanted to work with a service company. We wanted to test the *efficac*y of our methodology with a company that concentrates in technology-intensive and non-manufacturing business. Services are especially important because, in virtually every country in the world, services have become a dominant contributor to the generation of economic wealth (Fig. 8.1). The 2016 UN International Labor Organization reports that for the first time in history, worldwide employment in services (54.33%) exceeds that of agriculture and manufacturing combined (World Bank 2016, 2017). Many national economies are undergoing a "servicization" transformation, physical products and services are bundled as an integral offering to meet customer needs (Tang 2009). These bundles are called Product-Service-Systems (PSS) (e.g. Müller and Blessing 2007; Helo et al. 2017). This chapter is about a high technology PSS application of our methodology.

In **Part I**, we showed the conceptual and technical rigor, as well as, the distinctive and practical nature of our methodology. Our methodology is grounded on engineering-design thinking, systems-development methods and proven sociotechnical practices. In previous chapters, we presented prescriptions for the

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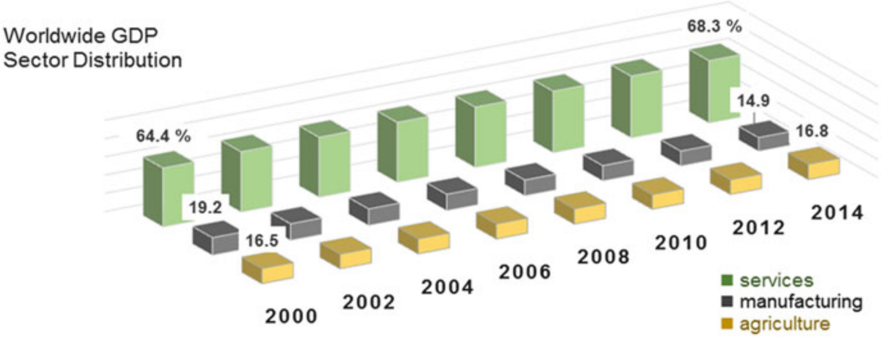


Fig. 8.1 Services plays a dominant role in the world economy

systematic design of decision specifications that are robust even under uncontrollable uncertainty conditions. We showed a systematic process to identify key managerially controllable and uncontrollable variables. Using these variables, we presented our methodology for the design of desired robust decision-specifications. To mitigate the impact of uncertainty, we use robust engineering-design methods to exploit the interactions between controllable and uncontrollable variables. We presented a new and innovative way to measure and analyze the quality of the socio-technical system by using the manufacturing-engineering methods of gage repeatability and reproducibility (Gage R&R). We have characterized and represented, in detail, the technical and social subsystems of our executive-decision methodology.

In **Part II,** we deconstructed the meaning and pragmatics about whether our paradigm and its methods "**work**". We argued that whether a complex artefact, like our executive-decision paradigm and its methods, "work", not "work", or how to make it "work" better, cannot be resolved as if discussing a light bulb. We argued that our methodology ***works***, if and only if, it simultaneously satisfies two necessary and sufficient conditions, *viz.* it is ready-**to**-work *for users **and*** ready-**for**-work *by a user* for a its specific class of decision situations. Ready-to-work needs to be demonstrated by us as creators of the methodology. We need to show that our methodology (Fig. 8.3), as an intellectual artefact, is ***functional*** and ***works*** as intended by us, as creators of our methodology. We used extensive simulations using an ADI system dynamics modelas a test object to demonstrate our methodology is *ready-**to**-work*. Due to inherent limitations of simulations, XRL-5 was deferred to Part III. However, by a large measure, our methodology satisfied the X-RL conditions (Table 8.1) for ready-to-work.

Now in Part **III**, we show how three non-trivial organizations satisfy themselves that the methodology *works* for them. Namely, that it is ready-**for**-work with evidence of the ***efficacy*** of our methodology (Figs. 8.2 and 8.4).

In this chapter, we will verify **efficacy** with a world-class e-business services company, eSvcs working with a client Yokozuna. We will demonstrate that our

Table 8.1 Readiness level specifications for executive decisions

Readiness Level	Our systematic process		Strategy
X-RL1	Characterize	Problem Space	Sense making
X-RL2	Engineer	Solution Space	Engineer experiments/alternatives
X-RL3	Explore	Operations Space	Explore entire solution and uncertainty spaces
X-RL4	Evaluate	Performance Space	Measure robustness, repeatability, reproducibility
X-RL5	Enact	Commitment Space	Commit plan with approved resources

methodology will meet the X-RL specifications for *efficacy* (Table 8.1) in use by Yokozuna. The goal was to evaluate the effectiveness project executive's decisions and actions to obtain the highest level of customer satisfaction (CSAT) for this project with Yokozuna in order to obtain a very large follow on project.

As in the previous chapter, we devote a section to each of the five spaces of the executive decision life-cycle, i.e. the *Problem, Solution, Operations, Performance*, and *Commitment* spaces (Figs. 8.2 and 8.4).

The objective is to systematically determine the X-RL readiness at each phase of our decision life-cycle. We will verify the efficacy of our methodology, against the requirements stipulated for each X-RL. The overall findings will be shown in the Chapter Summary. Section 8.2 covers *Characterizing the Problem Space*. We apply our methodology to characterize the decision situation adhering to our principles of *abstraction* and *uncomplication* to develop an uncomplicated, but accurate narrative of the decision situation.

In Sect. 8.3, *Engineering the Solution Space*, we identify the essential decision variables, the problem solving constructs used for the solution space, and the representations of the spectrum of the uncertainty conditions represented by

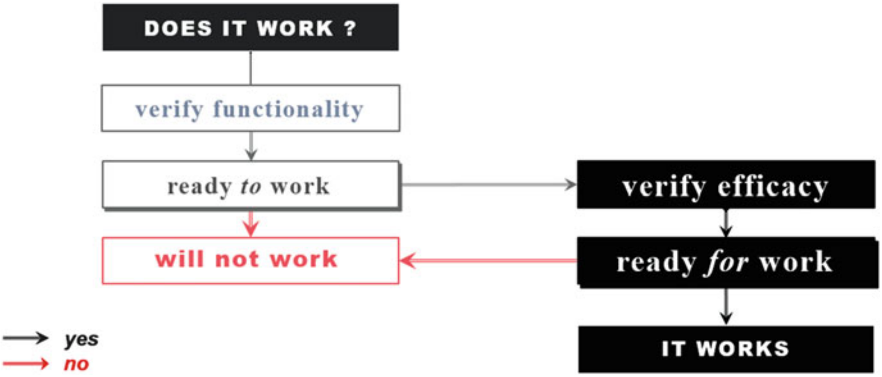


Fig. 8.2 Efficacy is a necessary condition to demonstrate methodology is *ready-for-work*

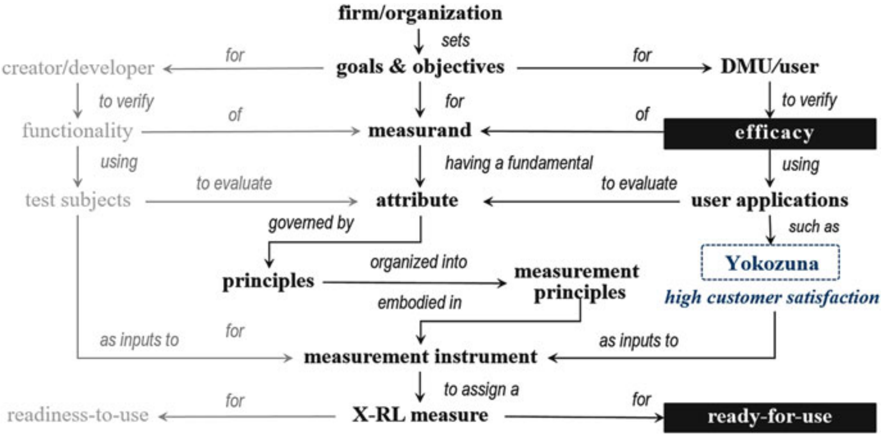


Fig. 8.3 Functionality is a necessary condition to demonstrate methodology *works*

uncertainty regimes. We discretize the entire uncertainty space into a discrete set of *uncertainty regimes*. These are used to establish the base-line and uncertainty conditions for our quantitative work. In Sect. 8.4, *Exploring the Operations Space*, we use an array of experiments under our set of uncertainty regimes that span the entire uncertainty space. We use representations, of the many and varied decision alternatives to fully explore the Solution Space. We show a procedure for constructing and exploring any hypothetical decision alternative for which we can determine a risk profile by means of its standard deviation. In this way, we collect data for the evaluations needed in the *Performance Space*, Sect. 8.5. The Performance Space is fully analyzed and investigated. We concentrate on the 4-R's of

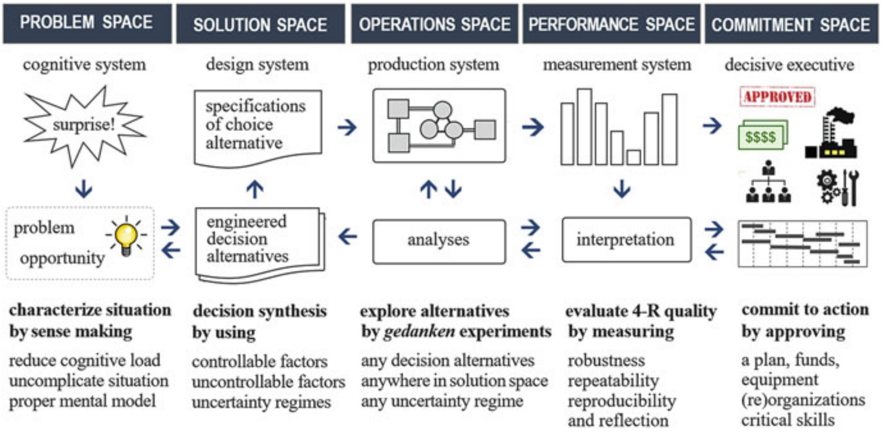


Fig. 8.4 Schematic of the five spaces in the executive-decision life cycle

Robustness, Repeatability and Reproducibility of the operational performance of our decision methodology and Reflect on the results and the sociotechnical systems that produced them. We use the Gage R&R methods from the engineering discipline of Measurement System Analysis, (AIAG 2002) to analyze the performance of the sociotechnical system as a **production** system. This is a new, novel, and *unprecedented* application of Gage R&R. It is also new territory for research. In Sect. 8.6, the *Commitment Space*, we demonstrate efficacy by reporting what actually happened. Section 8.7 closes this chapter with a summary of the key learning of this exercise with Yokozuna.

8.2 Characterizing the Problem Space

We begin with a brief sketch of the company, follow with a description of the decision situation, and continue with the details of our experiment. This step includes the discovery process for the decision situation and the framing of the decision in DOE form. Forming the DMU and creating a management system to review progress of the work are also part of this process.

8.2.1 Sense-Making and Framing

eSvcs is a prestigious Japanese provider of high technology services. It specializes in business management and IT services to address a broad spectrum of business problems—from business strategy, business transformation, IT strategy, design, implementation, installation, to repair and maintenance. e-business is eSvcs' strong suit. e-business is the use of the technologies of the Internet and World-Wide-Web to transform legacy management sociotechnical ecosystems or create new business models, processes, redefine major business functions, or an entire firm's strategy. Yokozuna, a $70 B global manufacturer, has contracted eSvcs to design and install an e-business technical platform from which it can build and deliver all its key internal and external services; such as, HR information, scheduling services, inventory, supply chain logistics, finance, accounting, and so on.

The project's Total-Contract-Value (TCV) was about $40 M, very modest for organizations of eSvcs and Yokozuna's scale and scope. However, eSvcs undertook this engagement as a technology-intensive project with high expectations and Yokozuna's hints of very large, indeed massive (~$1 B), follow-on repeat business. Although the dollar volume of the contract is modest, the most senior officers from eSvcs and Yokozuna actively review the progress of this project. Moreover, the CEO's of eSvcs and Yokozuna sit on each other's board and they both consider this product development (PD) effort to be very technically significant and prestigious for market presence.

This chapter, on the Yokozuna project, examines the period during which a new Japanese Project-Manager (JPM) was recently appointed to lead the project. The chapter concentrates specifically on decisions, actions taken and contemplated new actions by the JPM. The JPM wants us to critique key decisions, new and potential actions to be committed. He wants to know whether those decisions will improve client satisfaction (CSAT) at the end of the project, whether he has focused on the right issues and managerial levers, and what level of CSAT he can expect after customer acceptance upon completion of the project. In eSvcs, it is an article of faith that CSAT is a strong predictor of follow-on business. This is a belief nurtured by institutional memory and supported by decades of hard data from hundreds of projects. Managing CSAT is both a necessary skill and a necessary condition for career advancement. Consequently in eSvcs, CSAT measurement is a disciplined and enforced business process. The eSvcs CSAT instrument was the key document on which we anchored our experiment. Because it is a confidential document, we can only attach a few sample questions in Appendix 8.1. The JPM clearly was strongly motivated to obtain a high CSAT score from Yokozuna.

eSvcs organizational structure for this project is a matrix of geographic region, country, and functional organizations. Typical regions are, for example, Asia Pacific, Central America, Middle East and so on. Executives and senior managers are responsible and accountable for target setting and execution excellence. However, execution is delegated to line executives and managers in this complicated matrix. For the Yokozuna project, there are four key players.

- One is the Japanese eScvs Project-Manager, the JPM. He leads a skilled team of planners, software and system engineers, consultants and a small administrative staff. A senior Project Leader (PL) leads smaller groups who are responsible for all major deliverables to a client: the system (platform and middleware), the Information Architecture, the Content Management subsystem, Development, Integration and Test Plans, and final customer acceptance.
- The JPM reports to an Executive Project-Manager (EPM), a mid-level executive who is also responsible for many projects. EPMs are responsible for meeting targets set by their superior executives by planning and execution a portfolio of projects like the eScvs-Yokozuna project. They have line responsibility of these projects, but execution is highly delegated. EPMs are typically from the local country.
- At the geographic regional level there is an important function. Geographic Regions by virtue of their size have many projects, which are considered strategic. Strategic is a loose label to identify projects that are either very large in Total Contract Value, or First-In-Kind risky projects that become landmarks in the industry. First-in-Kind projects become templates and role models for business and market development. Regional-Project Management-Executives are experienced senior executives with deep technical expertise in specific functional domains. Their job is to monitor selected strategic projects to ensure they succeed and also to recommend culling, if required.

- The CEO's of eSvcs and Yokozuna sit on each other's board. The eSvscs CEO considers the Yokozuna project important. To manage this global matrix and the sensitivities of the eSvcs and Yokozuna's board members who have backchannel visibility of this project, eSvcs Japan created a project management structure as a mirror image of eSvcs. eSvcsJ has appointed equivalent counterparts in the worldwide eSvcs organizational structure. eSvcsJ's goal was, in equal parts, successful project acceptance by Yokozuna and landing the massive follow-on business. eSvcs is not famous as a lean organization. Ability to matrix manage is an indispensable skill in eSvcs.

Difficulties in communicating across the geographies and functional groups resulted in creeping and unstable project scope and conflicting requirements among the geographic regions. This was exacerbated by unexpected swings in sales in regional markets. This has created unexpected volatility and disagreements in the project's scope, strategy and priorities. The cumulative effect was a sense that project's risks were mounting and not well controlled. eSvcs' project management system also had its share of problems. A technical project leader (PL) was viewed as inexperienced to lead the design and development of this major system plat form. The PL lacked deep multi-geographic project-management experience, e-business expertise, and business knowledge to negotiate requirements and to bring the project under control. Leadership had limitations that was considered to making the project vulnerable. But why was he appointed to that position? The modest TCV biased the decision in the appointment.

8.2.2 The DMU: Decision Making Unit

The project's status and risk is visible at the highest levels in eSvcs. It has come to the attention of the Asia Region System Assurance Executive in eSvcs. By virtue of his position he is the *ex officio* sponsoring executive for the project. We will call him SAE for Asia-Region System-Assurance Executive. As Asia Region System Assurance Executive, he supervises about $6.0 B worth of Total Contract Value of selected strategic projects a year. He has a reserve of $300 M to help projects get out of trouble. We were asked to serve as his advisors for this project. He wanted to avoid having a high visibility project and its potential follow-on business go badly during his watch. His support was pivotal to get the buy-in of the JPM and the support for our participation.

We ran this experiment as a task force with the JPM as its operational leader. Collectively, the team had about 75 person-years of technical experience in IT, systems engineering, PD, and consulting. One team member was less expert with <5 years of working experience. This was to be a learning and grooming experience, for he was viewed as future management material. The others have all been engaged from the beginning of this project. Morale and team spirit is high and the JPM has their respect and trust. The DMU members by virtue of their position in the firm had access to line managers and other staff to obtain detailed and specific information on-demand (Fig. 8.5).

Fig. 8.5 Schematic of the problem space

8.2.3 Goal and Objectives of the Experiment

The JPM and the AP executive wanted to participate on this project because:

- an evaluation and critique of the decisions made to turnaround the project,
- a reasoned prognosis of what CSAT score was reasonable to anticipate,
- a fresh approach the above tasks,
- a deeper and clearer understanding of the effects and risks of uncertainty,
- to learn about the DOE methodology for new insights to their situation.

We held a number of planning meetings with the Project Management Executive (PME) and the JPM. We set the following objectives:

- identify levers that can guide and drive managerial action that will lead to an acceptable CSAT at project completion time,
- determine the influence of these variables on CSAT,
- explore alternative decisions to estimate and contrast CSAT values,
- summarize our findings and lessons to guide actions and commitments.

These goals and objectives are summarized in Table 8.2.

Table 8.2 Yokozuna Project decision situation

Problem	• Management of high visibility project that needs to be improved • Project and massive follow-on business opportunity at risk • Fear negative feedback from CEO's on project progress.
Goal and opportunity	• Make the project's e-platform a success and market model • Gain the confidence of Yokozuna executives on eSvcs e-business ability • Secure the massive follow-on project
Objectives	• Get the best possible CSAT for current project

8.2.4 The Essential Variables

The essential variables are the factors that directly influence the outcomes and attainment of goals. They are either managerially controllable or they are uncontrollable. They are consistent and meaningful given the scale and level of abstraction of the problem (Sect. 3.3.2). The uncontrollable variables are those that form the uncertainties that are most important for the intended outcomes. The DMU specified four controllable and three uncontrollable variables.

8.2.4.1 Managerially Controllable Variables

The controllable variables of this case are particularly challenging. Controllable variables in services tend to have a higher share of qualitative controllable variables than for physical products (e.g. Hoyle et al. 2002). We eschew the term *soft* variable, an expression that has undeserved negative connotations. Engineers and scientists naturally prefer *hard* variables endowed with ratio scale measures tied to physical properties (e.g. Khurshid and Hardeo 1993). Executives also take pride in making “data driven” and “facts based” decisions. A key advantage of our DOE-based method is that it readily and appropriately accommodates soft variable and use of even categorical variables as well (e.g. Phadke 1989; Taguchi et al. 2000). For example, a categorical controllable variable is the choice of using or not using a cleaning method, or use tool 1 or tool 2, for an experiment. Or, as in the previous chapter, to sell or not sell a factory.

The controllable factors were identified as follows:

1. *Project Leader*. There are many skills that an effective leader must possess. Key among them are conceptual, social, technical, and institutional political skills (Yukl 2010; Northouse 2010). Given the political sensitivity from regional and corporate executives who were based on different continents and the expectations of a massive follow-on project, it is was clear that the project should be led by one with proven technical, business and organizational skills, in order to work with the Yokozuna technical and managerial staffs. Key personnel changes needed to be made. None too soon, the JPM took action. The technically weak and inexperienced project leader (PL) was replaced in order to bring more managerial proficiency and tougher technical control to the work. The PM made himself JPM and had himself appointed as a new country representative in the Regional office. This forceful action brought an equivalent response from Yokozuna. These joint actions by the two firms brought new stability to the work and extra confidence from the senior executives in eSVcs and Yokozuna.
2. *Project Approach*. The instability of the requirements raised many questions at the highest levels of eSvcs and Yokozuna, as well as, unwelcome second-guessing and “offers to help” from headquarters. On the ground, in Japan, the conundrum was how to adopt an approach that is meaningful in technical content, will generate a high CSAT rating, keep senior executives and their

offers "to help" at bay, and that will enhace everyone's career prospects by obtaining the follow-on big project.

The JPM was in the hot seat and the most vulnerable. In addition to the personnel changes he took additional action to bring the project under better control. He astutely observed that the first users of the e-services platform and the initial applications were going to be US and Japanese nationals, not the Europeans. So he decided to deemphasize European requirements and rebalanced resources in favor of US and Japan. The JPM did not expect strong opposition because sales in Europe were relatively stagnant and they had reduced their manpower commitments to the project. The JPM had access to this information because he had backchannel information from his personal network. To meet the new requirements, the JPM considered delivering in three waves instead of a one-shot "Big-Bang" delivery. This would entail more resources, changes in delivery date, and more risk. He chose to explore renegotiating the terms for delivery. Grudgingly, the Yokozuna agreed to discuss modifying their agreement on vague hints from eScvs for additional functional "goodies". Since then, Yokozuna has been led through a forced march led by the JPM. But the JPM is unsure that his decisions will produce the CSAT index that will make the client want to engage eSvcsJ for its follow-on projects. The magnitude of the follow-on project encouraged eSvcs senior executives to support the JPM. This project because of its risky nature was also reviewed and approved by the Asia Region System Assurance Executive (SAE) who also felt that the prospect potential for follow-on business was worth the risk. As one very experienced in risky and failed projects, his support carried weight.

The JPM was faced with three competing choices for a project approach.

Level 1 was the worst for CSAT, i.e. deliver all the functionality at once (Big-Bang, BB) and satisfy the latest strident geographic requirements, of the moment, from all geographies, US, Japan and Europe. These requirements did not accurately represent Yokozuna's original agreements. But were the results of functional "creep". In this case, eSvcJ has to put equal weight on Europe's requirements, which the development team considered a blow to their ability to deliver a high quality product.

Level 2 was: release in three waves. First wave consisted of a very lean and frugal functional platform (bare bones, but working) to satisfy a tightly selected set of key US and Japan applications. Second wave included incremental functional platform enhancements for US and Japan only. Third wave was to expand the repertoire of applications, again for US and Japan only.

Level 3 the best CSAT choice was to meet their original contractual agreements, one-shot delivery of a fully functional platform, the originally agreed to a complete repertoire of canned representative applications, so-called "out of the box" (OTB), for the US, Japan and Europe. All in a Big Bang.

3. *Contingency*. eSvcs encourages its project executives to take on risky projects that are strategically significant. Projects, which are FIK (First in Kind) and never been done before, or have such visibility that they attract others to do the same, qualify as strategic. Yokozuna was judged to be strategic. For those projects, the SAE was empowered to commit funds to ameliorate financially weak but strategic projects, by providing funds to cover cost overruns. These funds are called *contingency funds*. Contingency funds are a two-edged sword. Executives who have a track record of taking on risky projects, without using any contingency, expect to be rewarded with rapid promotions. Generally, to demonstrate their managerial prowess, project managers prefer not to use contingency funds. The JPM's predicaments were—use contingency funds, not use, or if using contingency funds, how much to use, and whether the cost to his career prospects was worth it.
4. *Delivery date*. This was a choice between Scylla and Charybdis. It is the bane of every project manager to miss a committed checkpoint. Slipping schedules is visible to everyone and impossible to hide. No project manager needs to be told that missing deadlines is not considered a sign of managerial competency. The JPM was once more on the horns of a dilemma. Slip schedule and deliver a better product, or not slip schedule?

This was followed with team work sessions. We arrived at a three-level specification that bracketed the limits of controllability for each of the decision variables (Table 8.3). "Level 3" was deemed doable, albeit with effort, and "level 1" judged unacceptable. Team members were free to consult with their staffs or run models to help them determine these limits.

Table 8.3 Controllable variables and levels

Controllable factors	Level 1	Level 2	Level 3	Characteristic
Project leader	Do nothing	Change 1 project leader (PL)	Change PL, add PM geography, technical & business skills	More change is better
Project approach	BB, current WW requirements, *du jour*. Respecify original reqmts	Three waves for Japan & US only. Slight expansion scope & function.	Meet original agreement—BB, OTB, for US, Japan, Europe	More geography coverage, stronger platform, complete applications OTB.
Use of contingency	Use contingency to cover all cost overruns	Use contingency to cover all cost overruns	Do not use contingency	Less use is better
Delivery date	Slip 3–6 months	Slip 2–3 months	Meet delivery date	Less slip of contract delivery is better

8.2.4.2 Managerially Uncontrollable Variables

In a similar fashion, working with the DMU and the JPM, we were able to elicit and specify the uncontrollable variables (Table 8.4).

The four uncontrollable variables are:

1. *Stakeholder requirements consensus.* Yokozuna, clearly the most important stakeholder, was perturbating the process requirements and their content. And additional disruptions were coming from the eSvcs business units in US, Japan and Europe. Volatility and instability were originating from all these stakeholders. The prognosis for stability were dim. Moreover, there was a history of no sense of direction from eSvcs on how stabilize the situation.
2. *Yokozuna willingness for cost overruns.* The use of contingency was one of the controllable variables in the toolkit of the JPM. The unknown was whether Yokozuna would be willing to help eSvcs cover cost overruns. Yokozuna could refuse on many grounds, for which the JPM had no knowledge. Yokozuna could stand on legal grounds—terms and conditions were negotiated and agreed. Yokozuna costs could be out of control. Or it could entertain the idea, understand the particulars and negotiate. The only negotiating lever available to eSvcs was the case that Yokozuna project team was also sensitive to "offers to help" from their own executives and their perceptions on the progress of the project.

Table 8.4 Uncontrollable variables and levels

Uncontrollable factors	Level 1	Level 2	Level 3	Characteristic
Stakeholder requirements consensus	Stakeholders' instability and inconsistencies persist. Requirements environment unstable.level 1 and level 2 are identical.		Requirements environment is stabilized.	More stable is better.
Yokozuna willingness to cover cost overruns	Not known whether Yokozuna willing/funded for overruns	Yokozuna will pay for a reasonable % of PD cost overruns.	Willing and has flexibility to pay for all PD cost overruns	More Yokozuna overruns funds is better
Parallel project with Yokozuna	Parallel project in serious trouble, impacts CSAT for this project.	Parallel project, looks OK, but outcome unknown. Potential impact to this project's CSAT is unknown.	Parallel project points to OK results. Potentially positive impact, but not certain.	Positive impact is better.

3. *Parallel project with Yokozzuna.* Yokozuna had engaged eSvcs in the US for another high visibility PD project. That project was technically and managerially completely independent from the Yokozuna project in Japan. Unfortunately, the US project was experiencing many problems. This tainted perceptions of the eSvcs capabilities. Yokozuna corporate executives were beginning to question the competency of the entire eSvcs company. The JPM and eSvcsJ were very concerned of potential negative spillover to their Yokozuna project in Japan with the effect of lowering CSAT.

8.2.5 Summary Discussion

The current situation with Yokozuna is summarized in Table 8.5.

We have demonstrated that our methodology meets the criteria for X-RL1 (Table 8.6).

Table 8.5 eSvcs' current situation

Controllable factor	Current	
Project leadership	2	Change 1 project leader (PL)
Project approach	1	BB, *du jour* WW requirements. Renegotiate requirements.
Use of contingency	2	Use contingency to cover some cost overrun
Delivery date	2	Slip 2–3 months.

Uncontrollable factor	Current	
Stakeholder requirements consensus	1	• Stakeholders' instability and inconsistencies persist. • Requirements environment unstable.
Client willingness for cost overruns	1	• Unwilling or has room in their budget for overruns.
Parallel project with client	2	• Parallel project under control. • Potential impact to this project's CSAT is unknown.

BAU

Table 8.6 X-RL1 Readiness level specifications for executive-management decisions

Readiness Level	Our systematic process for the Problem Space	Efficacy
X-RL1 Characterize Problem Space	• Sense making—uncomplicate cognitive load	☑
	• Framing problem/opportunity–clarify boundary conditions	☑
	• Specify goals and objectives	☑
	• Specify essential variables	
	Managerially controllable variables Managerially uncontrollable variables	☑ ☑

☑ indicates support is demonstrated

8.3 Engineering the Solution Space

8.3.1 Introduction

We now understand the business situation, the goals and objectives of the JPM, the visibility to the most senior executives, and the massive opportunity of a follow on project should this one complete satisfactorily. Significantly, the JPM has a "life buoy" in the form of contingency funds he can use. The DMU has been formed (Fig. 8.6). The fundamental variables for the decision process have been identified and specified. The uncontrollable variables have also been identified and specified.

Next, we will demonstrate that the efficacy conditions stipulated for X-RL2 are met by Yokozuna.

8.3.2 The Controllable Space and the Uncontrollable Space

We have four controllable factors of three levels. Thus, the number of experiments in the full factorial Controllable Space is $3^4 = 81$. We use an L_9 orthogonal array of nine experiments (Table 8.7). L_9 data are sufficient to derive the outcomes of *any* treatment from the *entire full-factorial* set. The sampling efficiency of the L_9 array is $(1-9/81) = 89\%$. We add five additional experiments: BAU (2,1,2,2) and three "test experiments" of (1,3,1,3), (3,3,1,1), and (3,1,3,1).. These four are *high-leverage* treatments obtained using the Hat matrix (Montgomery 2001; Hoaglin and Welsch 1978). These 12 experiments form the sample space we will use to forecast and assess the results of our methodology. The test experiments will be used to check the accuracy of the forecasts from the DMU.

For the uncertainty regimes, the DMU members decided that they were most concerned with changes from the current uncertainty condition. They elected to define a "worst" and a "best" uncertainty regimes relative to the current condition. They are as shown in Table 8.7. The three *uncertainty regimes* are shown as: current $(1,1,2)^T$, worst $(1,1,1)^T$, and best $(3,3,3)^T$.

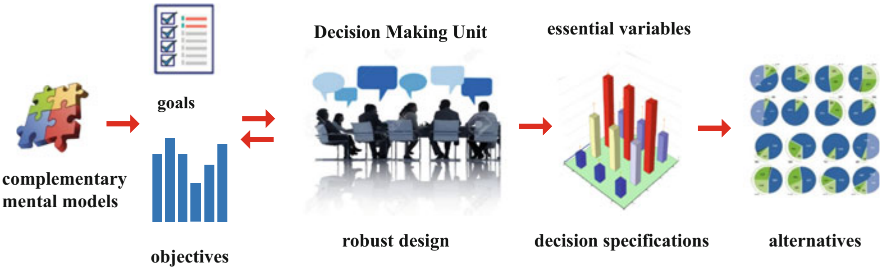


Fig. 8.6 Schematic of the solution space

Table 8.7 Data set structure for the experiment

Experiments	Controllable variables				Uncertainty regimes			Uncontrollable variables
	Project leadership	Project approach	Use of contingency	Delivery date	level 1	level 1	level 3	← *stakeholder requirements*
					level 1	level 1	level 3	← *Yokozuna budget flexibility*
					level 2	level 1	level 3	← *parallel project*
					current	worst	best	← uncertainty regimes
BAU	***2***	***1***	***2***	***2***	***BAUc***	***BAUw***	***BAUb***	
1	1	1	1	1				L_9 experiment 1
2	1	2	2	2				L_9 experiment 2
3	1	3	3	3				L_8 experiment 3
4	2	1	2	3				L_9 experiment 4
5	2	2	3	1				L_9 experiment 5
6	2	3	1	2				L_9 experiment 6
7	3	1	3	2				L_9 experiment 7
8	3	2	1	3				L_9 experiment 8
9	3	3	2	1				L_9 experiment 9
10	*1*	*3*	*1*	*3*				*test* experiment 1
11	*3*	*3*	*1*	*1*				*test* experiment 2
12	*3*	*1*	*3*	*1*				*test* experiment 3

The first column, in Table 8.7, lists the experiments—experiments 1 through 9. The BAU is the current situational settings of the controllable variables. It will be used to establish the-line, on which we will apply our debiasing procedure. The experiments 10, 11, and 12 are our supplemental test experiments obtained from the Hat matrix. They are the most different experiments from the L_9 (Montgomery 2001; Hoaglin and Welsch 1978). They will be used to evaluate the forecasting ability and accuracy of the DMU. Table 8.7 is for the DMU to populate the cells in the table, using their best judgment. Once that task is completed, we will analyze the data, and from the data, we will design and predict the outcomes of alternatives for the president and the DMU.

But first, we establish the base line and use our debiasing procedure. During this step of our protocol, the team will forecast CSAT for the BAU case in all three uncertainty regimes—current, worst, and best.

8.3.3 Establishing the Base-Line and Dispelling Bias

The most reliable way to forecast the future is to understand the present. (J. Naisbit)

The first line in Table 8.7 is the **base line**. It is the BAU configuration of the controllable variables under the three uncertainty regimes of current, worst and best. The task for the DMU is to forecast CSAT for the BAU case in all these three uncertainty regimes (e.g. Einhorn and Hogarth 1988). This process is also a learning step. Included is a procedure designed to mitigate information-asymmetry within the DMU. The procedure is also designed to avoid false anchoring (e.g. Baron 2000). And to avoid false convergence, forecasting figures are held private and disclosure is prohibited. A record of their forecasting confidence is made for subsequent analysis. In addition, we include counter-argumentation procedures to reduce systematic biases by insisting on explicit, ***but*** anonymous, articulation of the reasons why a forecast might be correct ***and*** why it might not be correct (Fischhoff 1999; Russo and Schoemaker 1992; Arkes 2001; Koriat et al. 1980). Counter-argumentation also improves the DMU's effectiveness in problem solving by enriching and complementing team members' individual mental models (Mohammed et al. 2010; Mohammed and Dumville 2001; Kray and Galinsky 2003; Lerner and Tetlock 2003). Winquist and Larson (1998) show that information pooling of shared fresh information improves decision quality and conceptualizing alternatives. We explained this process and its principles in Sects. 3.3.5 and 3.3.6. The Yokozuna implementation of the procedure follows next.

Establishing the base line is done in two rounds. In the first round, we obtain an initial forecast of the base line from the DMU. This is to prepare the DMU for the work of populating the entire data set Table 8.7. We begin by asking each DMU member to ***independently*** forecast CSAT for BAU, the (2,1,2,2) line at the time of project delivery, assuming the three uncertainty regimes shown. The DMU members are reminded that a forecast is an informed estimate, a professional judgement (March 1997), based on data, explicit modeling, and mental models. The data are placed in cells $BAUc, BAUw, BAUb$ in Table 8.7 (see Appendix 8.3 also). The DMU members were reminded of two rules. **No disclosure of the forecast figures and no discussion among DMU members.** We wanted to avoid peer pressure that could lead to false convergence in the forecasts (Mest and Plummer 2003; Hanson 1998; Boje and Mirninghan 1982). This procedure also ameliorates the social pressure that drive forecasters to herd together (Hanson 1998; Sterman 2000). Each DMU member was then to record their confidence-level on a confidential form we provided.

The second round concentrates on debiasing and developing an updated baseline based on new information, not social pressure, or following the herd. This is a process of counter-argumentation and accountability. We request each DMU member to write three reasons why their forecast is accurate, and three other reasons why their forecast is not accurate. The DMU menders were reminded of two more rules. **All inputs are anonymous, no names, and no discussion.** We had their input printed so that handwriting would not be used to recognize the authors. This gave us a total of 15 reasons why the forecasts were considered to be accurate and 15 opposing reasons. We asked the DMU members to read all 30 reasons and then to discuss them. This is a form of accountability, to explain the reasons behind judgments and actions (Lerner and Tetlock 2003). Accountability generates feedback, which improves performance, particularly in groups (Hastie 1986; Hastie and Kameda 2005).

At the end of this discussion, the DMU is requested to again forecast the BAU treatment and to record their confidence level once more. The goal for this iterative procedure is to promote organizational learning. Nobel laurate Simon (1991) writes:

> What an individual learns in an organization is very much dependent on what is already known to (or believed by) other members and what kinds of information are present in the organizational environment… an important component or organizational learning is internal learning—that is transmission of information from one organizational member or group of members to another.

Table 8.8 is a summary of the data from the above procedure (details are in Appendix 8.7). Note the decline in standard deviations from round 1 to round 2.

Table 8.8 BAU forecasts' standard deviations decline between round 1 and round 2

Uncertainty regimes	BAU profit forecast 6 months out					Confidence level		
	Avg. profit $M		Standard deviation					
	Round 1	Round 2	Round 1	Round 2	Trend	Round 1	Round 2	Trend
Current	2.59	2.84	0.68	0.23	↓	conf = 3.1 stdev = 0.8	conf = 3.9 stdev = 0.6	↑ ↓
Worst	1.88	2.12	0.48	0.40	↓			
Best	3.20	3.34	0.57	0.42	↓			

Confidence rises between round 1 and round 2, from 3.1 to 3.9. A "3" is specified as a "toss-up", and a "4" is specified as "confident" (Table 8.8).

Figure 8.7 is a graphical representation of the data in Table 8.8. We observe from the plots that in the best uncertainty regime, the DMU is not as optimistic as in round 1 and the standard deviation declines, see also Fig. 8.8. Both of these results are significant because recall that the forecast data are not disclosed to the DMU members. The possibility for false anchoring, herding and social pressure to conform to forecasts that are close are vastly diminished. The best uncertainty regime the DMU finds that there is more upside, and notably the standard deviation is lower. In the current uncertainty regime, the DMU judges that there is slight room for optimism, and there is a substantial decline in the standard deviations, from stdev = 0.68 to stdev = 0.23 between round 1 and round 2. We infer there is a

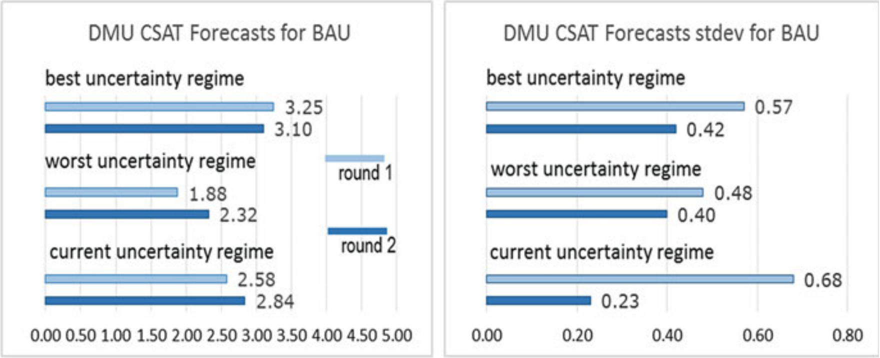
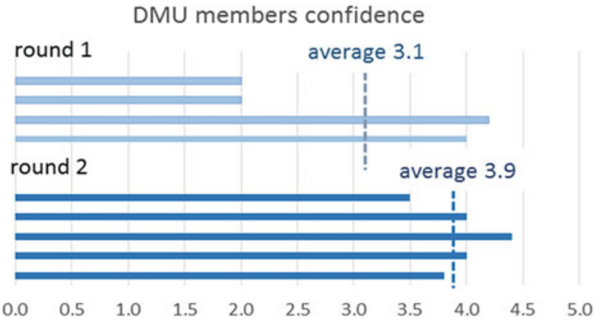


Fig. 8.7 Round 1 and Round 2 DMU CSAT forecasts and standard deviations under three uncertainty regimes. Stdev declines between rounds in all uncertainty regimes, shown by the dark blue and light blue bars

Fig. 8.8 Round 1 and Round 2 DMU CSAT forecasts confidence



reduction in information asymmetry. More complete and accurate mental models have influenced the forecasts in a positive way (e.g. Ashton 1985).

Research supports the hypothesis that there is a positive correlation between confidence and accurate forecasts, Sniezek and Henry (1989) and Sniezek (1992) report that group confidence is positively correlated with accuracy. Rowe et al. (2005) write "that not only accuracy tends to increase across rounds in Delphi-like conditions, but subjects' confidence assessments also become more appropriate."

8.3.4 DMU Forecast Rationale Examples

DMU members were required to state three reasons why their forecasts are accurate and another three reasons why are not accurate. They were required to discuss their rationale, but prohibited from disclosing their forecasting score for CSAT. The strategy is to promote group learning about the **logic** for forecasting CSAT, but not to create group think or herding. The goal is to improve DMU members' mental models, not for identical mental models, but complementary and more accurate representations. Examples of typical reasons why individual members believed their judgments are on-the-mark or off-the-mark. We begin with typical reasons documented by DMU members, e.g. the quotations are exactly as documented.

- "By contrasting the multiple scenarios, I have a better sense of the weight of each factors have on CSAT, thus making the numbers more accurate (the fine tuning process make so you come to realize which factor is more important than the others)".
- "Unless we meet the project schedule, won't be able to satisfy steering committee members".
- "Client had no experience with this kind of project. Therefore, they see bad sides rather than good sides in this challenging project. Client sat would not be high at this moments".
- "Change in PL . . . minimal impact in judgement".

Typical opposite reasons, why the forecasts are off-the-mark, were for example:

- ". . . difficult to explain all the differences between each cases".
- "About stakeholder's requirements consensus (it is not realistic) it is difficult to imagine the situation "requirement is stable" in this global complexed environments".
- "The perception of [provider] based on parallel project with client could bias the CSAT numbers no matter how the actual Yokozuna project did".
- "In the best situation, the client may not be happy even if the requirements are stable if the project is behind. The client may be paying us but may feel that [provider] should be paying".
- "The client in US is not pro-US . . . no matter what we have done differently, the outcome would not have been much different It's hard to quantify this".

These examples focus on the logic of the judgements, not on the numbers. The goals are learning to improve individual's mental models in order to reach more accurate judgments. Figure 8.8 data support the efficacy of debasing.

8.3.5 Summary Discussion

Those familiar with the Delphi Method will find similarities with our base-line and debiasing procedure. However, our process improves the Delphi process. We address the information asymmetry issue of decisions and forecasting, by **not** starting or concentrating on the numbers, but rather on the issues of incomplete and asymmetric **mental models**.

Delphi is a widely used group forecasting technique for participants to anonymously exchange and modify data, among each other, over repeated rounds. The data is then aggregated to a number representing the group's consensus. The goal is to improve forecasting accuracy by allowing participants to reflect, about supporting or opposing inputs, and make mental adjustments. Delphi is intended to stimulate participant's desire for accuracy, while suppressing detrimental social pressures from members of the group. Sniezek and Henry (1989) report "group judgements were, with few exceptions more accurate than mean or median individual judgments … Furthermore, 30% of the group's judgement were *more* accurate than the group's *most* accurate individual judgement." Studies show Delphi improves accuracy over other methods (e.g. Rowe et al. 2005; Rowe and Wright 2001). Yousuf (2007) and Hsu and Sanford (2007) present the pros and cons of Delphi. A common failure is ignoring and exploring disagreements, so that an artificial consensus is likely to be generated. We think that the Delphi method *emphasizes numbers* without *sufficient attention to the logic* of the numbers.

In our approach, we improve key attributes of the Delphi method as follows:

1. The anonymity requirement in our process requires non-disclosure of the participants' forecast figures. We think this has a positive ameliorating effect on anchoring that which has an inhibiting effect on forecasting.
2. Our people interactions are not based on numbers; but on *rationale* of member's forecast. The rationale is also anonymous. The input is anonymous, but the discussions about the anonymous input is not. Our procedure requires for the participants discuss their rationales without being able to attribute their source. This is designed to avoid defensiveness and social pressure.
3. Their people interactions among members are not anonymous. In our approach the forecast numbers are not disclosed so that no one knows what their peers' forecast. The feedback is anonymous, but the discussions on rationale are face-to-face in a meeting format.
4. In our process, the feedback documented by the participants are not designed to explain adjustments to numbers, but to explicitly give reasons why their forecasts is right with an equal number of reasons why it is wrong. Our focus is

Table 8.9 Readiness level specifications for executive decisions

Readiness Level	Systematic process for the Solution Space	Efficacy
X-RL2 Engineer Solution Space	Specify subspaces of solution space Alternatives space and uncertainty space	☑
	Specify entire solution space	☑
	Specify base line and uncertainty regimes Do-nothing case and choice-decision Estimate base line and dispel bias	☑

The symbol ☑ indicates support is demonstrated

centered on the participants' mental models. To make the mental more complete, more textured and nuanced, and with fewer incorrect assumptions and ideas.

5. We use confidence, rather than consensus of forecast figures, as a proxy of forecasting accuracy (Fig. 8.8). Research supports this hypothesis, e.g. Sniezek and Henry (1989) and Rowe et al. (2005).

We address uncertainty very directly using uncontrollable variables and uncertainty regimes.

The objective of this section has been to verify the efficacy of our methodology for the Solution Space. Namely, can a user use our methodology to systematically specify the entire solution space and the spectrum of uncertainty regimes, the base line and finally debias it effectively. Table 8.9 summarizes the efficacy of this phase of the methodology.

8.4 Exploring the Operations Space

8.4.1 Introduction

In this step of our methodology, the key question are; How do we determine the behavior of the sociotechnical system that will produce the intended outputs? And therefore, how do we predict outputs for any designed decision alternative? Each DMU member is asked to populate the entire data set Table 8.7. Each participant was given a form that was similar to Table 8.7. But the experiments were presented in a different random order to each DMU member. Each DMU member made 12*3 = 36 forecasts, for 12 experiments under three uncertainty regimes. We reminded them **not** to disclose their forecast figures to each other. **But** they were free to consult and discuss with their staffs or people in their managerial and personal networks. To our pleasant surprise, this task was done with dispatch and without any grumblings about complexity or excessive workload. The completed data set is shown in Appendix 8.3.

In this step, we analyze the summary statistics of the data set and to DMUs forecasting capability (Fig. 8.9). In other words, are the data something we can use and learn from?

Fig. 8.9 Schematic of the operations space

8.4.2 Analyses

8.4.2.1 ANOVA Summary Statistics

> Forecasts tell us more about the forecaster than about the future. (W. Buffett)

The ANOVA statistics for this case are interesting for they reveal the thinking of the DMU. First we will examine the ANOVA data. Second we will look deeper and try to understand what lies beneath the surface.

We begin with the ANOVA table for the current uncertainty regime (Table 8.10), we follow with a summary of for all three uncertainty conditions (Table 8.11). In Table 8.10 *leadership* and *contingency's* p values are too high. Only two statistically significant variables—project approach and project delivery. *Project delivery* is a very strong predictor of CSAT with $p = 000$ and value for $F=62.21$. *[Project] Approach* is borderline significant with $F = 3.87$. Leadership and contingency are not statistically significant. The R^2 values indicate that the variables explain a high percentage of the variations. Appendix 8.4 include the ANOVA tables for the other uncertainty regimes. Figure 8.10 shows the residuals for the model under the current uncertainty regime. The residuals are normal, the mean is effectively zero (1.97×10^{-16}, an infinitesimally small number), standard deviation of 0.4654 and $p > 0.025$. Visually all the points also pass the "fat pencil" test (Sect. 3.5.3).

Table 8.10 ANOVA Table for team forecasts for current environment

Analysis of Variance for current environment						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
leadership	2	0.3213	0.3213	0.1607	0.61	0.551
approach	2	2.0520	2.0520	1.0260	3.87	0.030
contingency	2	0.0413	0.0413	0.0207	0.08	0.925
delivery	2	32.9453	32.9453	16.4727	62.21	0.000
error	36	9.5320	9.5320	0.2648		
total	44	44.8920				
S = 0.514566, R-Sq = 78.77%, R-Sq(adj) = 74.05%						

Table 8.11 Team forecasts for current, worst, and best environments

	ANOVA for CSAT forecasts								
	Current uncertainty regime			Worst uncertainty regime			Best uncertainty regime		
	adj MS	%	p	adj MS	%	p	adj MS	%	p
leadership	0.16	0.9	0.55	0.038	0.2	0.89	0.13	0.7	0.55
approach	1.026	**5.7**	**0.030**	1.497	**8.7**	**0.020**	1.53	**8.4**	**0.002**
contingency	0.021	0.1	0.93	0.002	0.01	0.99	0.01	0.03	**0.97**
delivery	16.47	**91.8**	**0.000**	15.34	**89.2**	**0.000**	16.4	**89.7**	**0.000**
error	0.26	1.5	–	0.31	1.8	–	0.21	1.2	–
total	17.94	100%	–	17.19	100%	–	18.28	100%	–
	R^2 78.8	R^2_{adj}	74.1	R^2 74.9	R^2_{adj}	69.3	R^2 82.5	R^2_{adj}	76.6

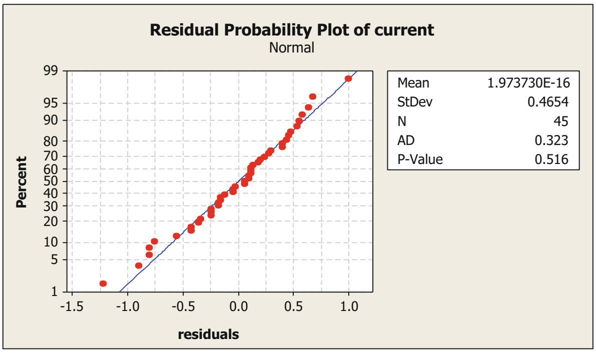


Fig. 8.10 Plot of residual of forecasts in current environment

An abbreviated summary of the ANOVA tables for the three environments, current, worst and best uncertainty regimes are shown in Table 8.11.

Is the model more complete if we include the interaction terms? There are only two controllable variables of significance, the only meaningful interaction is *approach *delivery*. With the interactions of the controllable variables (Appendix 11.8), the findings remain consistent. *Delivery* remains the dominant contributor to the CSAT outcome, *approach* is statistically significant only in the worst and best uncertainty regimes. The *approach*delivery* interaction is not statistically significant. Pooling the *[project] ledership* and *contingency* variables as shown in Table 8.12 does not alter the R^2 values between Tables 8.11 and 8.12. *Approach* and *delivery* individually explain the CSAT outcome.

During the planning sessions for this Yokozuna project, substantial time and energy was spent on the organizational setting, political climate at senior corporate levels of eSvcs and the Yokozuna company. The international nuances of the project also entered into the discussions both from a technical, as well as, a project operations and managerially important considerations. The ability to cover

Table 8.12 Interactions of controllable factors

Uncertainty regime	**ANOVA for CSAT forecasts**								
	current			worst			best		
	adj MS	%	p	adj MS	%	p	adj MS	%	p
approach	1.03	5.7	0.03	1.49	8.7	0.015	1.53	8.4	0.002
delivery	16.47	92.3	0.000	15.34	89.3	0.000	16.39	89.3	0.000
approach* delivery	0.09	**0.5**	**0.85**	0.02	**0.1**	**0.99**	0.069	**0.1**	**0.86**
error	0.27	1.5	–	0.315	1.8	–	0.21	1.8	–
total		100%			100%			100%	
	R^2 78.7	R^2_{adj} 74.1		R^2 74.5	R^2_{adj} 69.3		R^2 82.5	R^2_{adj} 78.6	

development expenses was another factor that was discussed. Yet the data shows that the DMU considers only *approach* and *[on time] delivery* date as important. The JPM data help explain this.

Table 8.13 shows the ANOVA statistics for the JPM and Figure 8.11 is a plot of the residuals. Note that the ANOVA statistics (Table 8.13) from the JPM are superior to the DMU ensemble as a whole (Table 8.10). Without further elaboration, it is clear the residuals are normal and do not carry any information.

In the model for the JPM, *delivery date* overpowers the other controllable variables. This is consistent with the DMU statistics, but very much more important for the JPM. There are two notable differences between the JPM as an individual and the DMU.

1. *Leadership* is statistically important for the JPM. Given that he **is** the leader, this outcome is not surprising.
2. *Contingency* is more statistically significant for the JPM. This is an important divergence from the rest of the DMU. The impact of using or not using the option of contingency funds will rest on the shoulders of the JPM, not on the working engineers, programmers and consultants.

It is not surprising that data from the JPM diverges from that of the DMU. The interests of the JPM differ from the rest of the DMU.

Table 8.13 JPM's ANOVA statistics

Analysis of Variance for current uncertainty regime

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Project leadership	2	0.2122	0.6832	0.3416	11.54	0.022
Project approach	2	0.2966	0.3964	0.1982	6.70	0.053
Contingency	2	0.3279	0.1154	0.0577	1.95	0.256
Delivery date	2	12.2525	12.2525	6.1263	207.00	0.000
Error	4	0.1184	0.1184	0.0296		
Total	12	13.2077				

S = 0.172033, R-Sq = 99.10%, R-Sq (adj) = 97.31%

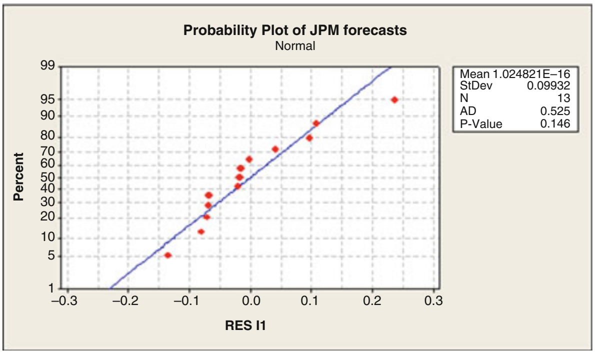


Fig. 8.11 Plot of residual of forecasts in current environment

In Sect. 8.6.1 we will be discussing the overall outcome and the actions of the JPM given his mental model and evaluation of the controllable variables. For that, we need the results in the next Sect. 8.4.2.2.

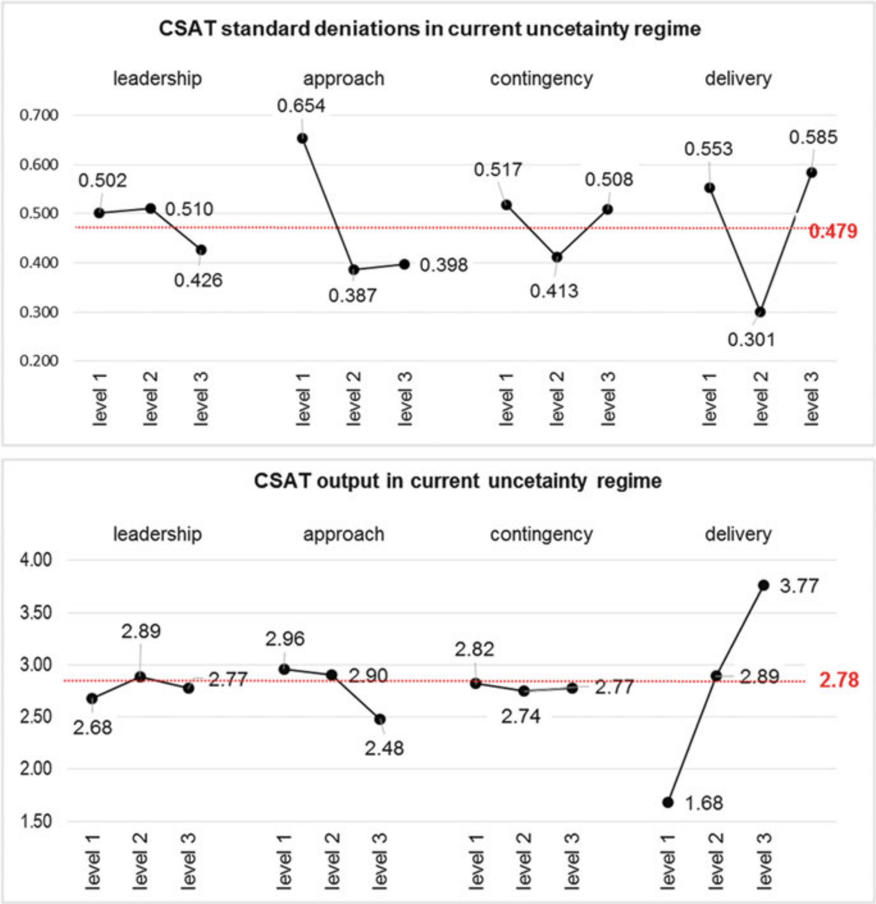
8.4.2.2 Response Tables

Using the forecast data set structure of Table 8.7, we get the response Table 8.14. The top panel shows the CSAT main effects, the bottom panel shows the response table for the associated standard deviations. Delta is the difference between the highest and lowest values of CSAT or for stdev. Rank is an ordering of the variables by Delta. Rank identifies the variable that has the highest influence on the output. (The tables for the worst and best uncertainty regimes environments are in Appendix 8.7.) Figure 8.12 shows the main effects and stdev plots. Inspection of the response tables and graphs reveals that *delivery date* is the dominant contributing factor to CSAT; it has rank 1. The data also show that level 1 of *[project] approach*

Table 8.14 Response Tables for CSAT and Standard Deviations in Current environment

Response Table for Means current environment				
Level	Leadership	Approach	Contingency	Delivery
1	2.680	2.960	2.820	1.680
2	2.887	2.900	2.747	2.893
3	2.773	2.480	2.773	3.767
Delta	0.207	0.480	0.073	2.087
Rank	3	2	4	1

Response Table for Standard Deviations				
Level	Leadership	Approach	Contingency	Delivery
1	0.5022	0.6535	0.5173	0.5526
2	0.5101	0.3868	0.4125	0.3010
3	0.4259	0.3979	0.5084	0.5846
Delta	0.0842	0.2667	0.1048	0.2836
Rank	4	2	3	1


CSAT standard deniations in current uncetainty regime

CSAT output in current uncetainty regime

Fig. 8.12 Response plots of CSAT and Standard Deviations in current environment

(BB, current WW requirements, *du jour*. Renegotiate original requirements.) produces the highest CSAT. Bottom panel of Fig. 8.12 shows that *approach* at level-2, i.e. three-waves *approach*, results in the lowest level of standard deviation. In contrast, Level-3 for *delivery* results in the highest level of standard deviation. The data indicate that delivering on time, in fact, is more risky. A 2–3 months delay, level-2, presents the lowest standard deviation and presents the lowest risk.

Some of the advantages of a three-level specification of forecasts are apparent from Fig. 8.12. At three levels the jagged response of CSAT are revealed for both CSAT and the standard deviation. Notably the standards exhibit V-shaped standard deviations. Should we have assumed two levels standard deviations, this non-linear behavior would not be available for us for analysis. These data will become particularly useful in the next Sect. 8.5 where we discuss the design of alternative decision specifications and prediction of their standard deviations. The interactions for the controllable variables _approach*delivery_ are statistically not significant ($p > 0.8$) for all three uncertainty regimes (Appendix 8.6).

8.4.3 *Synthesis: Construction and Analysis of Alternatives*

Using the controllable and uncontrollable variables, we can design any decision alternative we desire. Moreover, we can predict their outcomes and their standard deviations under any uncertainty regime. We present four examples, applicable to any uncertainty regime, for:

- predicting the outcomes of the decision specifications.
- designing decision alternatives for best and worst outcomes and *predict* their standard deviations
- specifying a hypothetical alternative, *predic*t its outcome and standard deviation
- ***using DOE approach to robust alternatives.***

The process is completely general and can be used for any configuration of controllable variables under any uncertainty regime. This capability gives us the flexibility to pose any hypothetical “what if” question and predict its outcome and associated standard deviation under any uncertainty regime. This gives the DMU unconstrained flexibility to explore the Solution Space.

8.4.3.1 The JPM’s Alternatives

This section discusses the JPM’s design of his decision specification. We begin by showing how to predict the outcomes and the standard deviation for a decision specification. For context, we use Table 8.15 which shows the derived CSAT and standard deviations for three decision designs for six distinct cases.

1. **BAU.** This is the situation right after the JPM arrived on the scene and replaced the project leader (PL) to take control of the project. This is the “as is”, business as usual (BAU).
2. JPM decision. This is the decision specification designed and initiated by JPM for his team to implement and execute.

Table 8.15 Predicted outcomes and standard deviations under three uncertainty regimes for set of decision specifications

		Current uncertainty regime		Worst uncertainty regime		Best uncertainty regime	
	Design	CSAT	stdev	CSAT	stdev	CSAT	stdev
BAU situation	2,1,2,2	2.8	0.23	2.1	0.40	3.6	0.40
JPM decision	3,2,2,3	**3.85**	**0.35**	3.6	0.54	4.2	0.42
Best design	2,1,1,3	4.09	0.76	3.7	0.64	4.2	0.52
Midpoint	geometric	2.7	0.60	2.3	0.32	3.0	0.30
Worst design	1,3,2,1	1.2	0.45	1.0	0.00	1.7	0.17
Max L_9	2,1,2,3	4.0	0.72	3.7	0.94	4.2	0.42
Min L_9	3,3,2,1	1.3	0.35	1.0	0.17	1.7	0.47

3. **Best Design.** The Best Design is the decision specification that will yield the highest CSAT. This is simply obtained by selected the controllable variables at their most optimal level, without regard to feasibility or consideration for risk, *viz.* standard deviations. The Best Design is a hypothetical synthetic design created as a reference point in the solution space.
4. Worst design is the exact opposite of the Best Design, one that will yield the lowest CSAT. Also an entirely hypothetical case.
5. **Midpoint** is simply the geometric midpoint between the Best and Worst Design. Used to divide the solution space into four quadrants.
6. Max L_9. This the L_9 design (2,1,1,3) which yields the highest CSAT. It is included as reference point. Data for this case are obtained from Appendix 8.7 and Table 8.14.
7. **Min L_9.** This the L_9 design (3,3,2,1) which yields the lowest CSAT in the current and worst uncertainty regime. It is included also as reference point. As in Max L_9, data for this case are obtained from Appendix 8.7. Recall this was originally obtained from the DMU. But in the best uncertainty **regime the design is (3,2,1,3).**

The CSAT and standard deviations for the JPM, Best and Worst decisions have to be derived from the L_9 data set. Next we show how.

These results were obtained using the procedure described in Sects. 5.4.3.2 and 7.4.3.1 and the response tables in Table 8.14 and Appendix 8.7. For example, we **can predict the value** for the JPM decision CSAT((3,2,2,3),(1,1,2)) in the current uncertainty-regime, using the procedure of Analysis of Means (ANOM) (e.g. Phadke 1989; Wu and Wu 2000).

First, calculate the grand average *m* of responses,

$$\begin{aligned} \mathrm{m} &= \text{average}(\textit{leadership}\,\text{responses}) = 1/3\ (2.680 + 2.887 + 2.773) = 2.780, \text{and} \\ &= \text{average}(\textit{delivery}\,\text{responses}) = 1/3(1.680 + 2.893 + 2.787) = 2.780 \\ &= \text{average}(\textit{approach}\,\text{responses}) = \text{average}(\textit{contingency}\,\text{responses}) \end{aligned}$$

Then to get the predicted response for CSAT((3,2,2,3),(1,1,2)) in the current uncertainty-regime,

$$\begin{aligned} &= 2.780 + (\text{leader ship}\,3 - \mathrm{m}) + (\text{approach}3 - \mathrm{m}) \\ &\quad + (\text{contingency}2 - \mathrm{m}) + (\text{delivery}3 - \mathrm{m}) \\ &= 2.780 + (2.773 - \mathrm{m}) + (2.900 - \mathrm{m}) + (2.747 - \mathrm{m}) + (3.767 - \mathrm{m}) = \mathbf{3.85} \end{aligned}$$

where for example, leadership2 means that variable at level-2, *viz.* leadership2 = 2.887.

And we can we **predict the standard deviation** for this CSAT((3,2,2,3),(1,1,2)) outcome. Table 8.14 shows standard deviations, which are not additive. However, variances are additive. Variance is defined as *variance = (stdev)*^{2}. We simply transform the stdev to variance, ***v***, and apply our analyses-of-means approach as before. We get a quantity for variance, from which we take the root of that quantity to get the stdev. We first calculate ɱ,

$$
\begin{aligned}
\mathfrak{m} &= \text{average}(\boldsymbol{leadershipvariances}) = \frac{1}{3}(0.252 + 0.260 + 0.181) = 0.251 \\
&= \text{average}(\boldsymbol{leadershipvariances}) = \text{average}(\boldsymbol{approachvariances}) \\
&= \text{average}(\boldsymbol{contingencyvariances}) = \text{average}(\boldsymbol{deliveryvariances}) = 0.251
\end{aligned}
$$

Then using the analyses-of-means, the *variance* for the JPM Decision for CSAT ((3,2,2,3),(1,1,2))

$$
\begin{aligned}
&= 0.251 + (\boldsymbol{leadership}3 - \mathfrak{m}) + (\boldsymbol{approach}2 - \mathfrak{m}) \\
&\quad + (\boldsymbol{contingency}_2 - \mathfrak{m}) + (\boldsymbol{delivery}3 - \mathfrak{m}) = 0.12
\end{aligned}
$$

Therefore, stdev(CSAT((3,2,2,3),(1,1,2))) = √0.12 = **0.35.**

These are key processes of our methodology. **We can predict the outcomes and standard deviation of any decision alternative that has been designed.**

Findings Overall, by inspection of all three panels in Fig. 8.13, we observe that the data are consistent with the JPM's and our understanding of the problem.

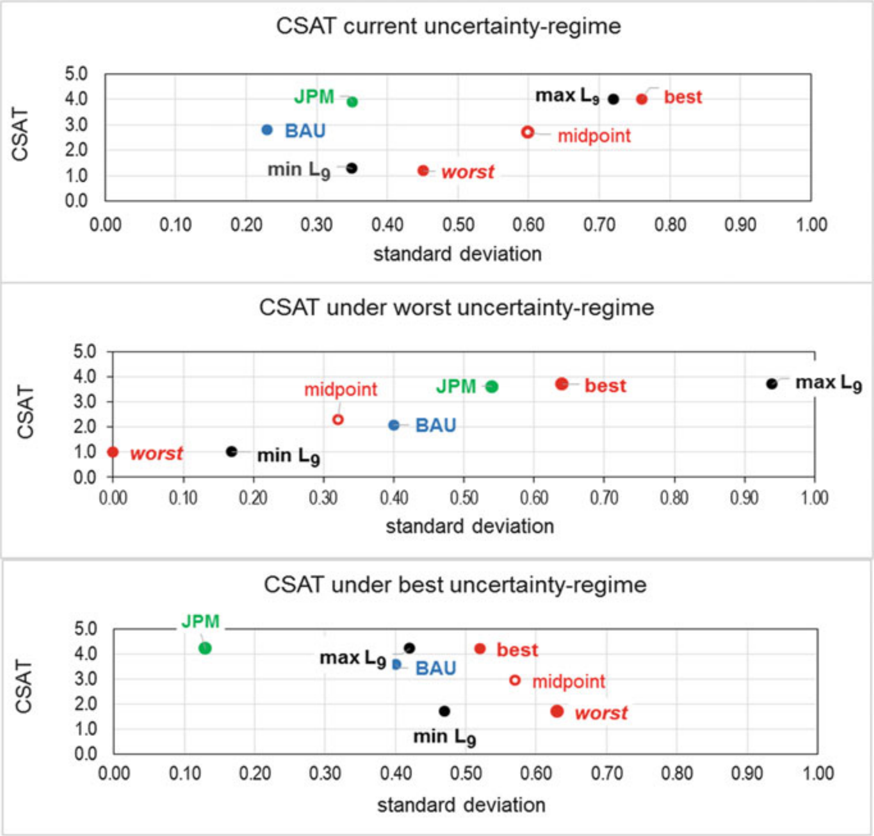


Fig. 8.13 Table 8.15 in graphical form

1. **BAU** (*blue* point) is consistently bracketed between the best design and the worst designs (red points) for CSAT, under every uncertainty regime. In terms of risk, or standard deviations, it is a safer design than the midpoint (red dot with white center), except under the worst uncertainty-regime (panel 2). We judge BAU to be a conventional and very modest design (see also point 5.). The stdev positions do not appear to have a consistent pattern, which is an indication that the DMU did not address risk in a systematic way.
2. **JPM decision** (*green* point) outperforms BAU in terms of CSAT and standard deviations under every uncertainty-regime. It convincingly outperforms BAU CSAT under the current and worst uncertainty-regimes. These results support the effectiveness of the JPM's judgement and his superior managerial abilities over his processor. In contrast to the BAU, the JPM appears to consider risk more thoughtfully. Under the current uncertainty-regime, The JPM has taken more risk (higher standard deviation) for a better CSAT. However, under the uncertainty regime, a degree of caution is revealed (stdev is only incrementally larger than BAU). JPM expects good CSAT and low risk in the best uncertainty-regime.
3. **Best** and **Worst** (*red* points) designs are designed for the highest and lowest CSAT, respectively, without consideration to standard deviation. These attributes are evident in Fig. 8.8. They indeed bracket all other designs for CSAT and stdev.
4. **Max L_9** and **Min L_9** (*black* points) adequately bracket the range of possible designs. This is not surprising, since an orthogonal arrays is a sample of the solution space. That the constructed Max and Min brackets the designs is not unexpected. As shown in the above designed decisions, there exist many potentially superior and inferior designs relative to the ones in the L_9 array. This calls for creativity and managerial judgement. The JPM's designs exhibit some of these qualities
5. **Midpoint** (*red point* with white center) is positioned as the geographic midpoint between the Best and Worst design specifications. BAU performance in CSAT exceeds the midpoint in all uncertainty regimes except when it exceeds the midpoint's standard deviation in the worst uncertainty-regime. The JPM design convincingly outperforms the Midpoint under every uncertainty-regime.

8.4.3.2 Design of a Robust Alternative

The idea is to design a decision specification that generates a *satisficing* output and is simultaneously rendered *less* sensitive to the behavior of uncontrollable variables, even when they are *not* removed. We will construct a robust solution for the current and the worst uncertainty-regimes (e.g. Taguchi et al. 2000; Otto and Wood 2001). We concentrate on these two because eSvcs' is most concerned about the downside risks. Tactically, their goal is to obtain a high CSAT from Yokozuna. Strategically, to capture upside opportunities, they have pinned their hopes on a lucrative on follow-on project.

Consider Fig. 8.12 and Table 8.14, plots for the main effects and the standard deviation for the current environment. From Table 8.15, the response alternative of the highest CSAT is (2,1,1,3). It produces a CSAT of 4.09 with a stdev of 0.76. The process begins with this design.

Since we are already at the best CSAT, the idea is to see if we can design a decision with a high CSAT and lower standard deviation. The idea is to reduce with the least possible impact on CSAT one step at a time, until a satisficing solution is revealed. Therefore, we focus on the standard deviations, i.e. the lower half of Table 8.14 and Fig. 8.12. We ratchet CSAT downwards, one step at a time, simultaneously reducing stdev (Table 8.16). Note that the bold values identify the controllable variable that is analyzed.

Step # 1 We consider the variable with the lowest means-Delta, rank-4, *contingency* level-1. Since we started with the highest CSAT, we want to protect the high CSAT, but lowering the stdev for robustness. *Contingenc*y is at level-1. It has stdev of 0.517 relative to the average of 0.479. Changing *contingenc*y to level-2, lowers the stdev to its lowest point, at the cost of a miniscule drop in CSAT. The decision alternative is now (2,1,2,3). The predictions are: CSAT(2,1,2,3) = 4.02 with a stdev (2,1,2,3) = 0.71.

Step # 2 The next lowest means, Delta, with rank-3, is *leadership* with specified level-2 with a CSAT = 2.89. Changing leadership to level-3 barely lowers the CAST from 2.89 to 2.77. Setting *leadership* at level-3 lowers stdev from 0.510 to 0.426. Stdev at 0.510 is greater than the mean stdev of 0.479. Changing *leadership* to level 3 is a good move. The decision alternative is now (3,1,2,3) with predicted CSAT(3,1,2,3) = 3.9 with a stdev(3,1,2,3) = 0.63.

Step 3 Next lowest means Delta has rank 2, with *approach* specified at level-3, with stdev = 0.654, which is much greater than the mean stdev of 0.479. But *approach* at level-2, stdev = 0387, which is much smaller than the mean stdev of 0.479. Results is a vast an improvement is stdev. Therefore, we change the level specification of *approach* to level-2. The decision alternative is now (3,2,2,3). The predicted resultant CSAT(3,1,2,3) = 3.85 and stev(3,1,2,3) = 0.36.

Step 4 Next lowest means Delta has rank 1, with *delivery* specified at level-3, with stdev = 0.585 which is much greater than the mean stdev of 0.479. But *delivery* at level-2, stdev = 0.387, which is much smaller than the mean stdev of 0.479. Results is a vast an improvement is stdev. Therefore, changing the level specification for *delivery* to level-2 appears attractive. The decision alternative is now (3,2,2,2). The predicted resultant CSAT(3,1,2,2) = 2.93 and stev(3,1,2,2) = 0.33. **This CSAT is too low and unacceptable and is rejected.** Recall that CSAT = 3.0 is ***neutral***, 4.0 is ***satisfied*** and 5.0 is ***very satisfied***. In eSVCS, a neutral level of CSAT is very career limiting.

However, we can find the satisficing robust solution. Inspection of Table 8.16 reveals that the attractive specification CSAT(3,2,2,3) = 3.85 with a stdev (3,2,2,3) = 0.36. This specification is superior to, with CSAT(3,1,2,3) = 3.90 with a stdev(3,1,2,3) = 0.64. We infer that (3,2,2,3) is a satisficing design. It stipulates:

Table 8.16 Summary for stepwise design of robust solution

Step #	Leadership	Approach	Contingency	Delivery	CSAT	stdev	Delta refers to means. Level refers to the controllable level		CSAT	stdev	CSAT/ stdev
	2	1	1	3	4.09	0.76	**highest** CSAT stdev >> 0.479 average stdev	→	4.09	0.76	5.39
# 1	2	1	**2**	3	4.09	0.76	*contingency* rank 4 Reset to level-2. ↓ stdev	→	4.02	0.71	5.66
# 2	**3**	1	2	3	4.02	0.71	*leadership* rank 3 Reset to lvel-3. ↓↓ stdev	→	3.90	0.64	6.10
# 3	3	**2**	2	3	3.90	0.63	*approach* rank 2 Lowest stdev. no level reset	→	3. 85	0.36	10.69
# 4	3	2	2	**2**	3.85	0.36	*delivery* rank 1 High stdev, change to level-2	→	2.93	0.33	8.88

- change the project leader
- use 3-wave project approach and concentrate on US and Japan requirements
- use contingency to cover cost overruns
- deliver the project on time.

This four-step synthesis procedure depends on the DMU to select a design judged to be superior. It does not include a *stopping-rule* (e.g. Gigerenzen and Selten 2001a, b).

We describe a heuristic to identify the robust alternative by means of a stopping rule. The right hand column in Fig. 8.16 is labeled "CSAT/stdev ratio". It singles out at step #3 the decision alternative (3,2,2,3). It delivers the most CSAT per stdev. We can think of this ratio as a normalized figure of merit. CSAT is the benefit, stdev is a "price" for CSAT benefit. Therefore, this ratio is a normalized figure of merit (Fig. 8.14). This ratio is analogous to IBM's heuristic for a computer's figure of merit. A computer can process k*million instructions/second (MIPS), i.e. its computing power. The figure of merit is MIPS/dollars.

8.4.4 Summary Discussion

The goal of this section has been to demonstrate how to explore the operations space with any decision alternative under any uncertainty regime. Given the four controllable variables and four uncontrollable variables specified by the DMU, the DMU populated the orthogonal array for all three uncertainty regimes. The ANOVA statistics show that there are only two variables that are strong predictors of the CSAT outcome. The DMU statistics show that the leadership controllable

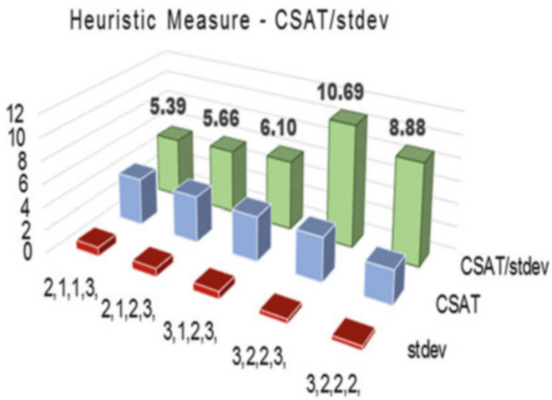


Fig. 8.14 Plot of CSAT/stdev ratio identifying (3,2,2,3) as the superior robust alternative

variable was one of variables that was a modest predictor for CSAT with F = 3.87. This result was moderately consistent with the conditions of the problem and the significant efforts executives exerted to find an experienced and proficient manager to lead the project. This led us to analyze the JPM's data. That data for the JPM supports the statistical importance for *leadership*. We surmise that the DMU members did not have visibility to the issues and actions of management side of the project. Surprisingly c*ontingency* is not a strong predictor of CSAT. Apparently the DMU did not consider this to be a problem. The data reveal they did not feel threatened in this regard.

Using the means and standard deviation response tables, we demonstrated how predict CSAT outcomes and their standard deviations for any designed decision alternative under any uncertainty regime. This capability enables unconstrained exploration of the entire solution space. This is a unique capability of our methodology. We also presented a systematic method to find robust decision design that takes no more steps than there are controllable variables. We presented our approach to identify the most robust design alternative using our CSAT/stdev ratio.

Those familiar with the one-factor-at-a-time method (Frey and Jugulum 2003; Frey et al. 2003) will note a similar hill-climbing approach to finding an extremum. But there are fundamental differences between the two. Unlike Frey's approach (*op cit*), which does not consider standard deviation, in our approach standard deviation is an integral and fundamental part of the method. Moreover, our method also fully considers the interactions between the controllable variables and uncontrollable variables, which are latent in the data of our construct of the orthogonal arrays. In addition, our approach also considers the interactions among the controllable variables,, which are captured in the data in the orthogonal arrays. Although in this example there interactions were very small and not significant, our approach is capable of capturing that information.

We conclude that XRL-3 conditions for efficacy are met (Table 8.17).

Table 8.17 Readiness Level Specifications for Executive Decisions

Readiness Level	Systematic process for the Operations Space	Efficacy
X-RL3 Explore Operations Space	Specify	
	Sample orthogonal array Do-nothing case and choice decision-alternative	☑ ☑
	Predict outcomes	☑
	Design and implement robust alternative Design and implement any what-if alternative	☑ ☑

The symbol ☑ indicates support is demonstrated

8.5 Evaluating the Performance Space as a Production System

8.5.1 *Introduction*

The discussions have concentrated on our methods to construct decision alternatives using DOE experiments to predict their performance and associated risk (using standard deviations as a proxy for risk). Experiments depend on data, but how do we know the data are "good enough"? What is good enough? How do we know the quality of those performing the experiments or the working mechanisms? These are the questions we explore and discuss next. Recall our premise is that the system that implements a decision specification is a **sociotechnical production system** (Fig. 8.15). We evaluate performance with two methods. The first is a simple test of consistency. And the second is using the Gage R&R method of Measurement System Analysis (MSA). This illustrated in Fig. 8.15.

8.5.2 *Evaluation of DMU Consistency*

The purpose of this test is to determine the forecasting consistency of the DMU members. It is a common practice, in surveys, to ask a participant the same question in different ways to determine whether the respondent will answer them in a consistent manner. We apply the spirit of this test of consistency on the DMU as a group. We use the Hat matrix (Sect. 8.3.2) to find three experiments that are very different from the L_9 experiments (Montgomery 2001; Hoaglin and Welsch 1978). They are the high-leverage test-experiments of (1,3,1,1), (3,3,1,1), and (3,1,3,1). We know that data from the L_9 orthogonal array are sufficient to derive the outcome of CSAT and standard deviation for any experimental configuration. Thus, we can compare the values forecast for the test experiments by the DMU against the L_9 derived values to gain insight of the DMU's ability to forecast consistently. **This is a useful test of the DMU's ability to forecast accurately**. If the DMU as a group,

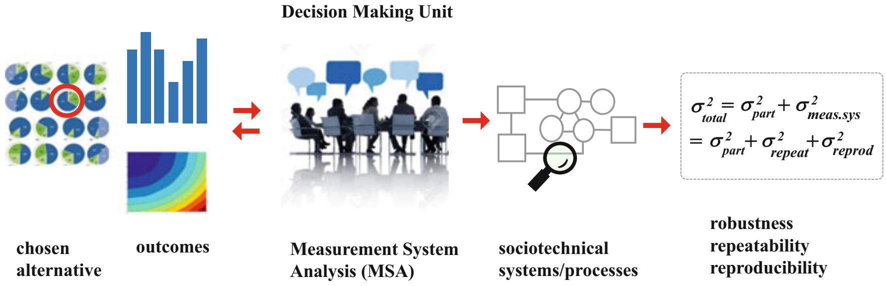


Fig. 8.15 Schematic of the outcomes space

as well as, individuals' forecasts are close to the derived forecasts, then the DMU forecasting abilities are good. This is a form of triangulation (Thurmond 2001), use of multiple sources, and approaches to confirm, or negate, data in order to take corrective action, improve the ability to analyze or to interpret findings (Thurmond 2001; Benzin 2006). This process is analogous to parity checking (Christensson 2011) and checksum error-checking (Christensson 2009) in digital transmission and computer technology.

Thus we can compare the values forecast for BAU, the test experiments. We get Table 8.18.

A close look at the Δ% between the DMU forecast and the predicted (derived) forecast is small. The average of the percentage difference is in the single digits. There is support for the DMU forecasts being consistent. The DMU did their work thoughtfully. There was not much guessing. This is rendered more clearly in a graphical representation of Table 8.18 shown as Fig. 8.16. The red lines (predictions) and the blue lines (DMU forecast) are very close in virtually all cases. The biggest discrepancy is in the BAU case in the worst uncertainty regime. In the next Sect. 8.5.3, we render these ideas more precisely.

Table 8.18 Comparison of team forecasts versus derived forecasts

	CSAT						Δ %		
	Average of forecasts from the team			Average predicted from L_9 data			1 − (forecast)/(predicted) = %		
Experiment	current	worst	best	current	worst	best	current	worst	best
2,1,2,2	2.84	2.12	3.34	3.14	2.70	3.57	9.6	21.5	6.4
1,3,1,1	3.22	3.00	3.58	3.40	3.03	3.72	5.3	1.0	3.8
3,3,1,1	1.44	1.12	1.66	1.41	1.06	1.60	−2.1	−5.7	−3.7
3,1,3,1	1.92	1.64	2.26	1.85	1.58	2.14	−3.8	−3.8	−5.6
Average							**2.2%**	**3.3%**	**0.2%**

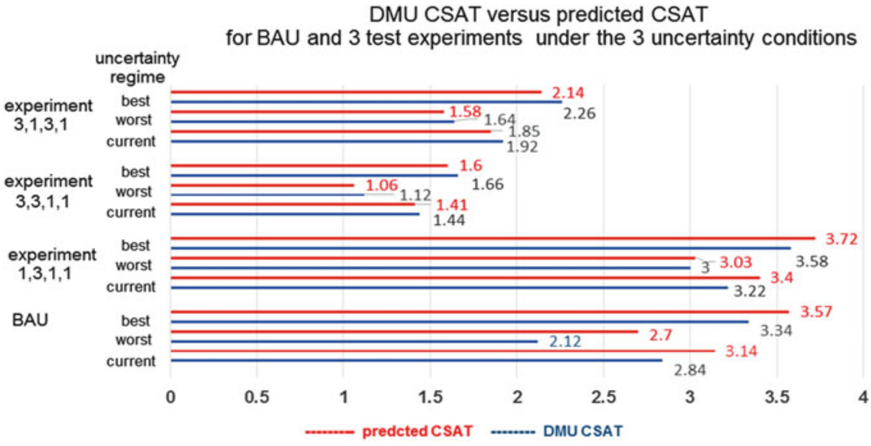


Fig. 8.16 DMU CSAT versus predicted CSAT how high consistency

8.5.3 Production Gage R&R

8.5.3.1 Introduction

How can we determine whether the set of $9 \times 3 = 27$ forecasts for the L_9 are equally "good enough?"

We discussed, in Sect. 3.5.4, how we can apply the engineering method of Measurement System Analysis (MSA) (NIST/SEMATECH 2006) to analyze the sources of variation in a measurement system (Fig. 8.17). We *consider the DMU members who are forecasting, their knowledge, data bases, formal and informal procedures, and their network of contacts as a* ***measurement system***. MSA uses the term "operator" to designate the person making a measurement. Unlike conventional MSA, which is concerned with manufactured parts, each DMU member is making a forecast, i.e. "measuring" a decision alternative. "DMU" is used to identify the collective body. We use "DMU4", for example, to identify member number four. The "parts" to be measured by this measurement system are decision alternatives. Instead of "measuring parts", we have forecasts outcomes of decision alternatives. Since we want to measure the quality of the measurement system, as defined above, the Gage R&R Eq. (3.3), Sect. 3.5.4 now becomes Eq. (8.1), in this section.

$$\sigma_{total} = \sigma^2{}_{forecasts} + \sigma^2{}_{meas.sys.} = \sigma^2{}_{forecasts} + \sigma^{2\,2}{}_{repeability} + \sigma^2{}_{reprodicibility} \tag{8.1}$$

In order to build some intuition about the concepts and vocabulary, we first show examples. We then follow with the application, of the Gage R&R procedure, discuss the results and some of its implications.

8.5.3.2 Reproducibility

Reproducibility is a quantity that indicates the precision of a measurement system. That is to say, *for a given experiment, can different DMU members produce the*

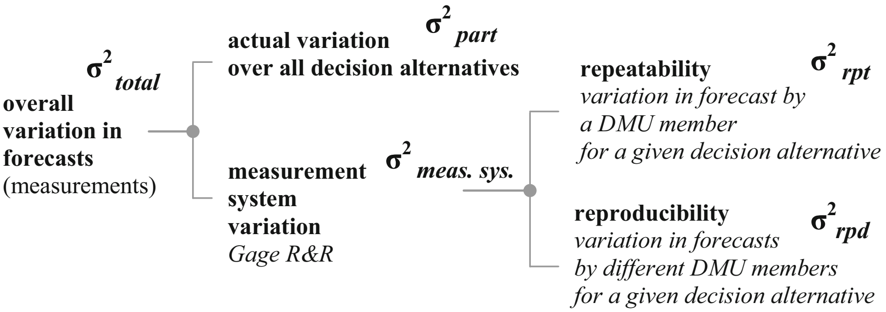


Fig. 8.17 Sources of variability of forecasts for decision alternative

same forecasting result for a decision specification? The individual forecasts for a given experiment, by different DMU members, gives us an indication of *reproducibility* abilities across DMU members.

Using the forecast data in Appendix 8.3, we summarize in Fig. 8.18 the forecasts for the three test experiments (1,3,1,3), (3,3,1,1), (3,1,3 1) and, in addition, BAU, (2,1,2,2) and (1,1,1,1).

The forecasts by each DMU member, are shown as a line connecting their forecasts. The three panels on the left-hand show the forecasts obtained from the DMU1, DMU2, DMU3, and DMU4 obtained during the base-line establishment phase. DMU5 data (green lines) is included on the right-hand panels to highlight its lesser reproducibility. DMU1, DMU2, DMU3, DMU4 forecasts are *close* to each other. They show more *reproducibility*. DMU5 is consistently biased to the low side.

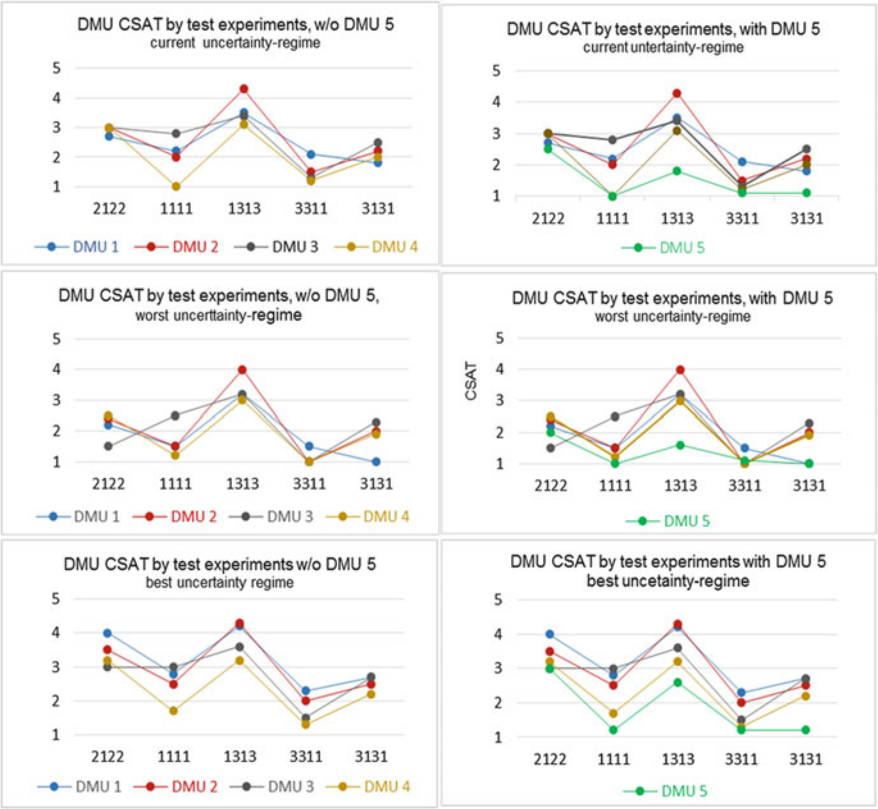


Fig. 8.18 DMU members' reproducibility. For a given experiment, can **different** DMU members produce the **same** forecasting result of a decision specification*?* Are the lines close to each other? Are the horizontally-oriented lines close?

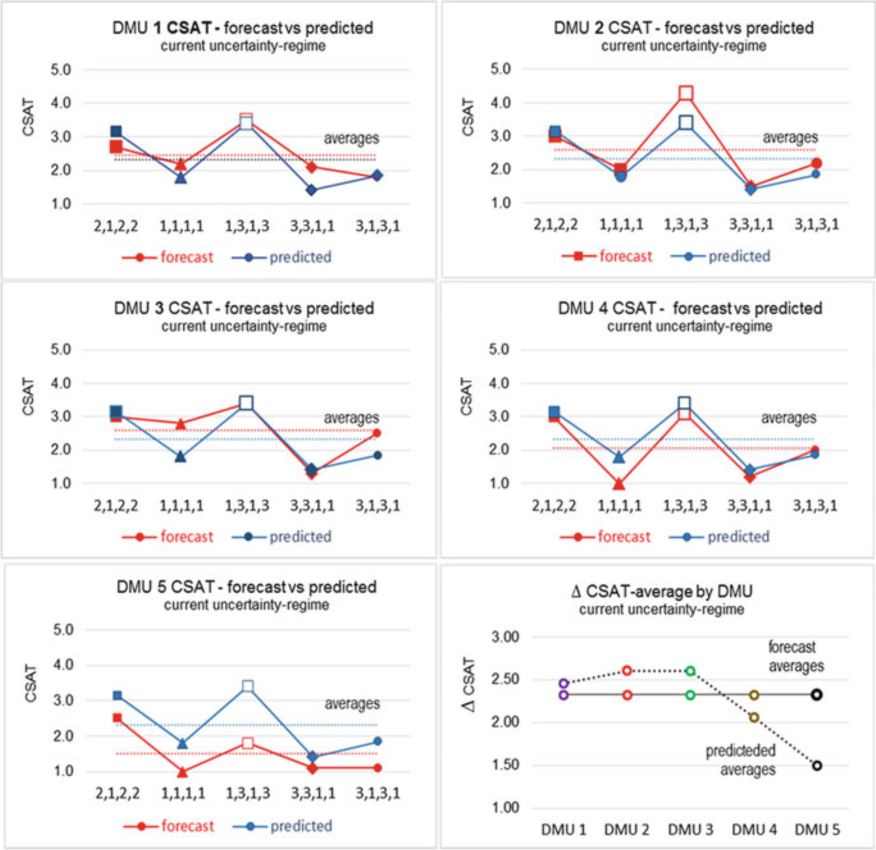


Fig. 8.19 DMU members' repeatability. For a given experiment, can **same** DMU members produce the **same** forecasting result of a decision specification? Are the points for same experiment close to each other? Are the vertical points close?

8.5.3.3 Repeatability

Repeatability is another quantity used to indicate a quality attribute of a measurement system. *For a given experiment, can the* ***same*** *DMU members produce the* ***same*** *forecasting result for a decision specification?* Repeatability the ability of a DMU member to replicate a forecast result, at different times, of a decision specification. Naturally, the best situation is that every DMU member's forecast is repeatable.

Figure 8.19 juxtaposes the forecasts for five test experiments (in the three current, worst, and best uncertainty-regimes), from each of the DMU members, versus their predicted values using the L_9 data. Our method predicts what that forecast ***ought to*** be. If they are "close" then there is good repeatability. Figure 8.19 shows the forecast data and the predicted are indeed very close.

8.5.3.4 New Research Findings

There is a less labor intensive method to determine repeatability, reproducibility, and other significant production performance indicators of quality. This is the Gage R&R method. In Table 8.19 are shown the Gage R&R and ANOVA statistics in the current uncertainty-regime for the L9 data sets. Recall that in our domain of inquiry (executive decisions), for us *treatment* means *experiment* and *operator* means *DMU member*.

Table 8.19 shows p = 0.000 for *treatment/experiment* and p = 0.014 *operator/ DMU member*. They are both strong predictors of CSAT. Of the *Total Variation*, 11.15% is from *Repeatability*, 2.0% from Reproducibility, and 86.83% from part-part (experiment-experiment). See Fig. 8.20. The column on the right-hand side depicts the variations from the measurements from all the DMU members, including DMU5. The column on the LHS depicts the variations from the measurements omitting DMU 5 whom we know exhibits the largest inconsistency. The impact DMU 5 on the Gage R&R statistics is very visible. Absence of DMU 5 has significantly improved the overall Gage R&R statistics.

Table 8.19 ANOVA for measurement variances without DMU 5

ANOVA table with interaction

Source	DF	SS	MS	F	P
Treatment	9	74.5307	8.28119	57.8192	0.000
Operator	3	1.8112	0.60373	4.2152	0.014
Treatment * operator	27	3.8671	0.14323	1.1695	0.321
Repeatability	40	4.8986	0.12246		
Total	79	85.1076			

Gage R&R

		%Contribution
Source	VarComp	(of VarComp)
Total Gage R&R	0.15448	13.17
Repeatability	0.13083	11.15
Reproducibility	0.02364	2.02
Operator	0.02364	2.02
Part-To-Part	1.01879	86.83
Total Variation	1.17327	100.00

	Study Var	%Study Var	
Source	StdDev (SD)	(6 * SD)	(%SV)
Total Gage R&R	0.39303	2.35821	36.29
Repeatability	0.36171	2.17024	33.39
Reproducibility	0.15377	0.92261	14.20
Operator	0.15377	0.92261	14.20
Part-To-Part	1.00935	6.05612	93.18
Total Variation	1.08318	6.49906	100.00

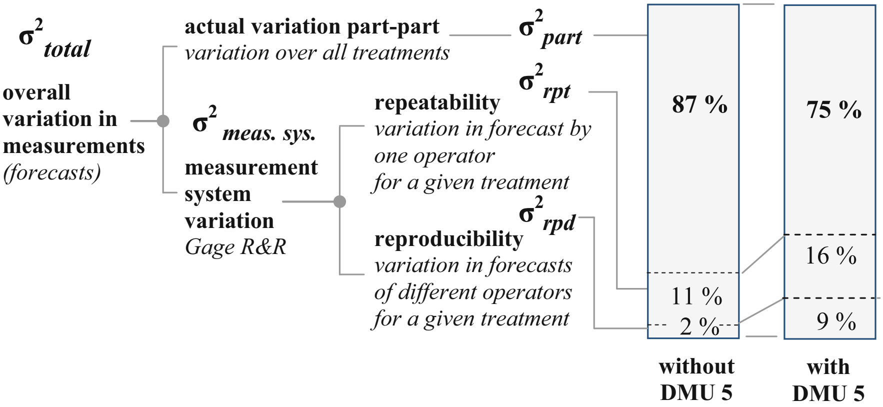


Fig. 8.20 Sources of variability for forecasts

Calculation from the Gage R&R data table, our sociotechnical system, as *measurement system*, has a *discrimination ratio* of 4. Discrimination ratio determines the number of distinct bins the data can be categorized into. These bins are also called *categories* (e.g. Creveling et al. 2002; AIAG 2002). With a discrimination ratio of three, the sociotechnical system is able to resolve data into three categories: high, medium, or low. The discrimination ratio is given by:

$$\begin{aligned}(\text{number of distinct categories}) &= \sqrt{}[\text{Var}(\text{part-to-part})/\text{Var}(\text{total gage R\&R})]^{*}\sqrt{}2\\ &= \left[\sqrt{}1.01879/\sqrt{}0.15449\right]^{*}\sqrt{}2 = 3.63 \doteq 4.\end{aligned}$$

We were also able to improve the dispersion of the forecasts by means of our debiasing approach (Table 8.8). How to produce more dramatic improvements in the discriminatory power of a sociotechnical forecasting system is a subject for new research.

To our knowledge, ***this is the first example*** of the use of Gage R&R for a sociotechnical system. This is a new and worthy subject for further research.

It is important to note that the Gage R&R specifications and standards were co-developed by the AIAG, Ford, GM, and DaimlerChrysler. It is safe to estimate that many person-centuries of manufacturing expertise and supported by data points of millions of different parts went into this effort. Unfortunately, as students of this method in sociotechnical systems, we find the literature absent in its ability to inform us whether the MSA metrics apply equally to sociotechnical processes; such as forecasting or systematic predictions. This is an open area for further exploration. We invite the US National Institute of Technology and Standards (NIST), scientists, engineers and metrologists to tackle this subject. Given the servicization tidal wave in the world's economy (Introduction to this chapter), this is an important gap in the research literature.

Gage R&R, in the context of sociotechnical systems, raises many challenging and unanswered questions about quality of such complex systems. Nevertheless, the

Gage R&R method has shown to be useful and given us new insights, which are consistent with findings obtained by other means. The method has given us an analytic approach to determine the capabilities of a forecasting group or group making systematic predictions, individually and as a structured "composite". The "composite" is a sociotechnical ensemble, their knowledge of the DMU (individually and collectively), organizational data bases, instruments, formal as well as informal procedures, and DMU members' network of contacts. This is consistent with the engineering ethos of our work. We now have rigorous metrics derived from Gage Theory to evaluate important properties of the forecasts and of the sociotechnical composite. We have concentrated on the properties of repeatability, reproducibility, and Gage R&R metrics. We were able to obtain a measure of the discriminatory power of the composite, the sources of forecasting variations, and pinpoint the individuals contributing the most bias to the measuring system. **The use of Gage theory and MSA in forecasting for exploring related management issues is an important, new and useful area for research.**

8.5.4 General Discussion

A decision is a specification designed for implementation and execution. It is not an artifact to merely satisfy a curiosity. A decision specification is intended to enable purposeful action. To act, we view the composite, of people and sociotechnical systems, that executes the decision specification as a production system, like a factory. This section, of the chapter, shows that the engineering method of Gage R&R from Measuring System Analysis (MSA) is effective to measure and evaluate the quality sociotechnical systems. The evaluation measures are reproducibility, repeatability of the Gage R&R method. The measures demonstrate their usefulness for our tests of efficacy for it gives detailed and nuanced insight into the operational elements and system behavior. The Gage R&R method and its guidelines and were formulated with the assistance and an enormous volume of data from the major US automobile manufacturers. We find no data or information about sociotechnical systems. Nevertheless, our application of the method is effective.

The application of the Gage RR&R method for sociotechnical production systems is a gap in the research literature. ***This is an entirely new domain of research.*** The importance and urgency is acute, particularly, when manufacturing has ceased to be a dominant component of the economic engine in the world's most important economies.

We conclude that XRL-4 conditions for efficacy are met (Table 8.20).

Table 8.20 Readiness Level Specifications for Executive Decisions

Readiness Level	Systematic process for the Performance Space	Efficacy
X-RL4 Evaluating Performance Space	• Evaluate performance: analyze 3R • Robustness, repeatability, reproducibility	☑ ☑

The symbol ☑ indicates support is demonstrated

8.6 Enacting the Commitment Space

> You can … gather the numbers, but in the end you have to set a timetable and act. (Lee Iacocca)

The *sine qua non* of executive decisions is a decisive executive. The one person empowered to commit to a decision specification, a schedule for its implementation, an allocation of resources that makes enactment possible (Fig. 8.21). These commitments give meaning to decisive decision-making. In the next paragraph we present JPM's implementation of his decision specification.

8.6.1 What Actually Happened

The eSvcs project is complete and delivered to Yokozuna on schedule. However, the client has requested eSvcs to perform some extra work on the product and documentation. This has in effect caused the project to be extended by 2–3 months, although both parties consider the project to be "complete" in spite of the extension. CSAT is estimated to be 3.5. The environment is (3,3,3), the scenario of the best uncertainty-regime. The overall situation is between (3,2,2,2) the "actual completion" (2-3 months delay), and (3,2,2,3), a "tacit-completion," (on schedule by tacit agreement between parties). The difference is in the fourth element of the 4-tuple (*delivery date*), between a level 2 and level 3, i.e. a tacit and ambiguous "on schedule" with an actual delay of "2-3 months." The actual CSAT of 3.5 is bracketed by the derived CSAT values of "tacit completion" (CSAT of 4.1) and "actual completion" (CSAT of 3.2). The sequence of decisions is listed below on Table 8.21.

CSAT was a dominant concern for the team because they were anticipating a massive follow-on project from the Yokozuna company. It has indicated to eSvcs that it is welcome to participate in bidding for the follow-on project. However, Yokozuna has reformulated its bidding approach. Rather than having one services company, such as eSvcs, perform the vast majority of the work, reap the lion's share of the benefits, and have a hegemonic influence on project management, Yokozuna

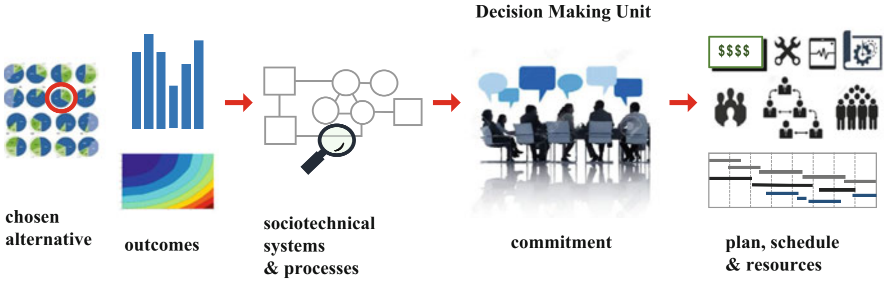


Fig. 8.21 Schematic of the commitment space

Table 8.21 Derived CSAT for post-BAU cases

	CSAT			Standard deviation		
Treatment	current	worst	best	current	worst	best
pre-BAU (1,1,2,2)	2.9	2.6	3.5	0.4	0.6	0.3
BAU (2,1,2,2)	3.1	2.7	3.6	0.4	0.7	0.3
post-BAU (3,2,2,3)	3.8	3.6	4.1	0.4	0.6	0.2
Tacit completion (3,2,2,3)	–	–	4.1	–	–	0.2
Actual completion (3,2,2,2)	2.9	2.7	3.2	0.4	0.3	0.1
Actual situation			**3.5**			–

has partitioned the project into many segments and is requesting bids from a variety of services companies, one of which is eSvcs. eSvcs is skeptical about the client's capabilities to design or system engineer the mega-project they have formulated, nevertheless eSvcs is making a very strong effort to win as much as possible of the follow-on business and it expects to be an important player. Throughout the project, eScvs and Yokozuna were surprised and greatly relieved their respective CEO's requested a limited number of reviews and did not extend any offers to "help". We are told that CSAT is neither helping nor hindering their chances at this time.

8.6.2 DMU Feedback

Overall, the feedback from the DU is constructive and positive. Typical suggestions for improvements were useful:

- "More time upfront to tighten up definitions early".
- "Do two cycles of the exercise".

Favorable comments included:

- "A good framework to reevaluate the decision at a critical timing of the project".
- "This process visualizes the decision instead of intuition".
- "Wonderful experience".

These comments tells us that more pedagogy is required at the front end of the process. However, the overall the process appears useful.

8.6.3 General Discussion

Findings

1. The method is useful. JPM and his counterpart in Yokozuna were satisfied about the work. Most useful to the JPM were the abilities to: (1) construct any hypothetical decision alternative, (2) predict their outcomes under the

uncertainty regimes, (3) know the % contribution; and therefore the relative weight, of each controllable variable to the outcomes, and (4) use the standard deviation of the outcomes of each controllable variable as an indicator of the risk of associated with the variables at those levels.

2. The decision methodology is effective. We found that the DMU had no difficulty forecasting the experiments' outputs for all three uncertainty regimes. This suggests that the team learned how to forecast complex scenarios, even under pressure. Moreover, our methodology was able to produce the data expected by the DMU for analyses and discussions.
3. There is support for our method's conceptual and operational validity.

   Construct validity. We have demonstrated we have a meaningful conceptual framework for our experiment, which can be operationalized. A framework that can be operationalized with accurately specified independent and dependent variables. Our construct is illustrated by the diagram in Fig. 8.22.

   To determine the interactions among the controllable and uncontrollable variables we have the orthogonal array construct (Table 8.7). Our protocol makes our constructs operational (Sect. 8.4). The ANOVA data reveal that not all the controllable variables have unequally strong predictive power; nevertheless, the statistics give us insight into the behavior of the sociotechnical system. We have the Gage R&R construct for quality analyses (Sect. 8.5.3, Eq. 8.1). The ANOVA summary data support their statistical significance of the controllable variables.

   Internal validity. Can we demonstrate that we can draw conclusions about the causal effects of the independent variables on the dependent variables? Address whether the conclusions that can be drawn are plausible and credible to domain experts? The answer is: Yes. Overall the DMU and the project manager, in particular, judged the effects of the controllable variables of the outcome variables to be consistently credible with their domain knowledge.

   External validity. Can we demonstrate that we can generalize from this experiment to a larger and more general population and/or broader settings? Yes, we did so in the previous chapter and we will do so in the next chapters with more examples. Results support that our method is sufficiently general to other complex management decisions in the sociotechnical domain.

uncontrollable variables

1. stakeholders' requirements consensus
2. client's willingness to absorb cost overruns
3. parallel, but separate, project with Yokozuna

controllable variables

1. project leadership
2. project approach
3. use of contingency
4. delivery date

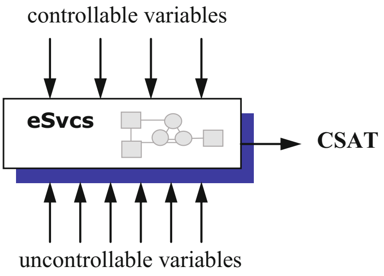


Fig. 8.22 Conceptual construct of our experiment

Table 8.22 Readiness level specifications for executive decisions

Readiness Level	Systematic process for the Commitment Space	Efficacy
X-RL5 Enacting Commitment Space	• Decisive executive • Approval of plan • Commit funds, equipment, organizations	☑ ☑ ☑

The symbol ☑ indicates support is demonstrated

4. *Reliability Use of Gage R&R*. Tests of reliability are used to determine whether the procedures can be repeated to produce consistent results by people and instruments. Earlier in Sect. 8.5.3, we used two rounds of forecasts for the BAU outcomes data. The consistency of the results is high Figs. 8.18 and 8.19. The Gage R&R data support the quantitative metrics for repeatability, reproducibility, and experiment-to-experiment variations. ***These are two new and novel findings in our use of Gage R&R quality heuristics in our domain of executive decisions***. The literature is conspicuously silent on this as a new area of research.

   We conclude that XRL-5 conditions for efficacy are met (Table 8.22).

8.7 Chapter Summary

The goal for this chapter has been to report on the efficacy of our methodology with a real world company, i.e. the methodology is ***ready-for-work*** in the real world. In this case the eSvcs company in Japan. We exercised our methodology to cover the five spaces during eSvcs decision life cycle on the Yokozuna project. We worked with the project manager of the project. He wanted to know whether the decisions he had made would lead to a sufficient level of customer satisfaction such that eSvcs would be invited to participate in a massive follow on project. The project manager also wanted to know what other alternatives that he could hypothetical exercise to improve eSvcs' prospects with Yokozuna.

Using our methodology, we were able to explore a range of diverse hypothetical "what-if" decision alternatives. Our methodology enables us to explore the entire solution space over the wide space of environmental uncertainty. The decision specifications for the alternatives for this exploration can be readily constructed using the controllable and uncontrollable variables. We presented our simple and effective systematic construction process to find the robust alternative. Our systematic procedure has no more steps than there are controllable variables. We introduced DOE and Gage R&R to this new domain. The results in this chapter show that:

- **Use of DOE and Gage R&R for executive-management decisions is meaningful.** This approach yields useful and statistically meaningful results. We can explore the entire solution space over the entire uncertainty space; thus, erasing any constraints to the range of "what if" questions that can be explored.

- **There is support for the validity of our method.** Validity is inferred from executive feedback, statistical analyses of our experiments, validation criteria for tests of construct, internal, and external validity.
- **Engineering approach to analyze data quality using Gage theory is meaningful.** We can consider the executives who are forecasting outcomes, their knowledge, data bases, formal and informal procedures as a measurement system. We can use Gage R&R to evaluate its repeatability and reproducibility. This is new ground in executive-management decision analysis. We plan to study and explore this further with more experiments in other business environments.
- **The senior executives are able to identify the controllable that provide a meaningful representation of the organizational systems.** Tables 8.11, 8.12 and 8.13 data show that the chosen variables of *sg&a, cogs, plant utilization, portfolio actions, sales,* and *financing* explain >90% of the behavior of the system as measured by MS_{adj} data. Moreover, the interactions among the controllable variables are very small. The behavior of the system is almost linear. This property of complex systems is called "near decomposability" (Simon 1997, 2001). The system behavior is exhibits "the robust beauty of linear models". Dawes (1979) that perform well for complex decisions (Dawes 1979, Camerer 1981).
- We stepped through every step of our systematic process to demonstrate the *efficacy* of our method and its readiness, from X-RL1 to X-RL5. Our work with HiTEM demonstrated there is support for the following:

Readiness level	Our systematic process		Strategy
X-RL1	Characterize	Problem Space	Sense making
X-RL2	Engineer	Solution Space	Design and engineer experiments/ alternatives
X-RL3	Explore	Operations Space	Explore entire solution and uncertainty spaces
X-RL4	Evaluate	Performance Space	Measure robustness, repeatability, reproducibility
X-RL5	Enact	Commitment Space	Commit plan with approved resources

X-RL1 In the *Problem Space* the decision situation is very clearly framed as the the evaluation of the JPM's decision on how to manage the Yokozuna project to obtain a sufficiently high CSAT to be able to obtain a massive follow on project. The problem is represented by four controllable variables, three uncontrollable variables, and three uncertainty regimes spanning the uncertainty space. All variables are specified at three levels.

X-RL2 The specifications for *Solution Space* is thoroughly specified using an $\mathbf{L_9}$ orthogonal array and three test experiments. The base line is established with our debiasing procedure. The data demonstrates debiasing reduces bias and improves confidence.

X-RL3 Exploration of the *Operations Space* is exhaustively executed and analyzed. The ANOVA statistics show that although not all the controllable variables are statistically significant for the DMU ensemble, the JPM's ANOVA statistics were more insightful and possibly more accurate. The confirmatory test experiments show that the forecasting capabilities of the DMU, as well as, its members are consistent with the independently predicted values of same. We explored the construction of a wide variety of decision specifications under the uncertainty regimes. Alternatives that are predicted to produce both superior outputs and lower risk. Our methodology finds the satisficing robust solution.

X-RL4 Evaluation of the *Performance Space* is performed to determine robustness, repeatability, reproducibility (3-R's). We use Gage R&R and the response tables for output and standard deviations for the controllable variables. 3-R data support the Gage R&R application for our sociotechnical methodology. Regrettably the literature is conspicuously absent regarding the use of Gage R&R for sociotechnical production systems. The research and applications are dominated by traditional thinking that focus on production of physical products and. ***Our use of Gage R&R and the 3-R metrics in our domain of executive decision design and production is both a first and a novel application of Gage R&R in a new domain.*** This is a new and useful area of research.

X-RL5 Enacting the *Commitment Space* is demonstrated by the actions taken by the JPM and the supporting role in eSvcs HQ in providing contingency funds. Both eSvcs and Yokozuna reached a Nash equilibrium by satisficing themselves with flexible interpretation of their achievements.

- Overall, the results reported in this chapter are evidence for the claim of efficacy of our methodology. We conclude that there is support for the efficacy of our methodology.

Readiness Level	Our systematic process	Efficacy
X-RL1 Characterize Problem Space	Sense making—uncomplicate cognitive load	☑
	Frame problem/opportunity and clarify boundary conditions	☑
	Specify goals and objectives	☑
	Specify essential variables Managerially controllable variables Managerially uncontrollable variables	☑
X-RL2 Engineer Solution Space	Specify subspaces of solution space Alternatives space and uncertainty space	☑
	Specify entire solution space	☑
	Specify base line and uncertainty regimes Do-nothing case and choice-decision Estimate base line and dispel bias	☑
X-RL3 Explore Operations Space	Specify	
	Sample orthogonal array Do-nothing case and choice decision-alternative	☑ ☑
	Predict outcomes	☑
	Design and implement robust alternative Design and implement any what-if alternative	☑ ☑

(continued)

Readiness Level	Our systematic process	Efficacy
X-RL4 Evaluate Performance Space	Evaluate performance: analyze 3R Robustness, repeatability, reproducibility	☑ ☑
X-RL5 Enact Commitment Space	Decisive executive Approval of plan Commit funds, equipment, organizations	☑ ☑ ☑

☑ indicates support is demonstrated

Appendix 8.1 Client Satisfaction (CSAT) Sample Questions

Sample questions from client satisfaction survey	
• How satisfied are you with the value you received on this engagement? Comments ________________________________ ____ ____ ____	( ) **5** very satisfied ( ) **4** satisfied ( ) **3** neutral ( ) **2** dissatisfied ( ) **1** very dissatisfied ( ) **0** no opinion/don’t know
• Demonstrated the necessary level of expertise, knowledge and skills? Comments ________________________________ ____ ____ ____	( ) **5** very satisfied ( ) **4** satisfied ( ) **3** neutral ( ) **2** dissatisfied ( ) **1** very dissatisfied ( ) **0** no opinion/don’t know
• How do we compare with other firms you have engaged for similar work? Comments ________________________________ ____ ____	( ) **5** much more value ( ) **4** more value ( ) **3** comparable value ( ) **2** less value ( ) **1** much less value ( ) **0** no experience with others

Appendix 8.2 BAU Round 1 and Round 2

	BAU forecasts														
	current uncertainty regime					worst uncertainty regime					best uncertainty regime				
DMU	# 1	# 2	# 3	# 4	# 5	# 1	# 2	# 3	# 4	# 5	# 1	# 2	# 3	# 4	# 5
BAU1	2.0	3.0	3.3	2.0	–	1.5	2.0	2.5	1.5	–	2.6	3.6	3.8	3.0	–
BAU2	2.7	3.0	3.0	3.0	2.5	2.2	2.4	1.5	2.5	2.0	4.0	3.5	3.0	3.2	3.0

Appendix 8.3 Complete Forecast Data Sets

Experiments	Project leadership	Project approach	Use of contingency	Delivery date	Current uncertainty-regime							Variance
					DMU 1	DMU 2	DMU 3	DMU 4	DMU 5	Mean	stdev	
BAU	2	1	2	2	2.7	3.0	3.0	3.0	2.5	2.8	0.23	0.05
1	1	1	1	1	2.2	2.0	2.8	1.0	1.0	1.8	0.79	0.62
2	1	2	2	2	2.7	3.0	3.0	2.7	3.0	2.9	0.16	0.03
3	1	3	3	3	4.0	3.8	3.2	3.2	2.6	3.4	0.55	0.31
4	2	1	2	3	4.2	4.6	4.5	4.0	2.8	4.0	0.72	0.52
5	2	2	3	1	2.3	2.0	2.0	1.0	2.2	1.9	0.52	0.27
6	2	3	1	2	2.7	2.8	2.5	2.5	3.2	2.7	0.29	0.08
7	3	1	3	2	2.7	3.3	3.6	3.2	2.5	3.1	0.45	0.20
8	3	2	1	3	4.2	4.6	3.5	3.8	3.5	3.9	0.48	0.23
9	3	3	2	1	1.0	1.9	1.3	1.4	1.1	1.3	0.35	0.12
10	*1*	*3*	*1*	*3*	*3.5*	*4.3*	*3.4*	*3.1*	*1.8*	*3.2*	*0.91*	*0.83*
11	*3*	*3*	*1*	*1*	*2.1*	*1.5*	*1.3*	*1.2*	*1.1*	*1.4*	*0.40*	*0.16*
12	*3*	*1*	*3*	*1*	*1.8*	*2.2*	*2.5*	*2.0*	*1.1*	*1.9*	*0.53*	*0.28*

					Worst uncertainty-regime							
					DMU 1	DMU 2	DMU 3	DMU 4	DMU 5	mean	stdev	variance
BAU	2	1	2	2	2.2	2.4	1.5	2.5	2.0	2.1	0.40	0.16
1	1	1	1	1	1.5	1.5	2.5	1.2	1.0	1.5	0.58	0.33
2	1	2	2	2	2.2	2.8	2.8	2.4	3.0	2.6	0.33	0.11
3	1	3	3	3	3.5	3.5	3.0	3.0	2.1	3.0	0.57	0.33
4	2	1	2	3	4.0	4.4	4.3	3.4	2.1	3.6	0.94	0.89
5	2	2	3	1	1.8	1.4	2.3	0.8	2.0	1.7	0.58	0.34
6	2	3	1	2	1.8	2.2	2.3	2.2	2.5	2.2	0.25	0.07

7	3	1	3	2	2.0	3.2	3.5	2.7	2.0	2.7	0.68	0.47
8	3	2	1	3	4.0	4.3	3.3	3.6	3.0	3.6	0.52	0.27
9	3	3	2	1	0.8	1.2	1.0	1.2	1.0	1.0	0.17	0.03
10	*1*	*3*	*1*	*3*	*3.2*	*4.0*	*3.2*	*3.0*	*1.6*	*3.0*	*0.87*	*0.76*
11	*3*	*3*	*1*	*1*	*1.5*	*1.0*	*1.0*	*1.0*	*1.1*	*1.1*	*0.22*	*0.05*
12	*3*	*1*	*3*	*1*	*1.0*	*2.0*	*2.3*	*1.9*	*1.0*	*1.6*	*0.6*	*0.36*

					Best uncertainty-regime							
					DMU 1	DMU 2	DMU 3	DMU 4	DMU 5	mean	stdev	variance
BAU	2	1	2	2	4.0	3.5	3.0	3.2	3.0	3.3	0.42	0.18
1	1	1	1	1	2.8	2.5	3.0	1.7	1.2	2.2	0.76	0.58
2	1	2	2	2	3.7	3.3	3.2	2.9	3.3	3.3	0.29	0.08
3	1	3	3	3	4.5	4.0	3.5	3.3	3.0	3.7	0.59	0.35
4	2	1	2	3	4.5	4.8	4.8	4.1	4.0	4.4	0.38	0.14
5	2	2	3	1	2.8	2.2	2.4	1.2	2.2	2.2	0.59	0.35
6	2	3	1	2	2.8	3.0	2.8	2.8	3.5	3.0	0.30	0.09
7	3	1	3	2	3.2	3.4	3.8	3.3	3.2	3.4	0.25	0.06
8	3	2	1	3	4.5	4.6	3.7	3.9	3.8	4.1	0.42	0.18
9	3	3	2	1	1.5	2.0	1.5	1.6	1.2	1.6	0.29	0.08
10	*1*	*3*	*1*	*3*	*4.2*	*4.3*	*3.6*	*3.2*	*2.6*	*3.6*	*0.71*	*0.50*
11	*3*	*3*	*1*	*1*	*2.3*	*2.0*	*1.5*	*1.3*	*1.2*	*1.7*	*0.47*	*0.22*
12	*3*	*1*	*3*	*1*	*2.7*	*2.5*	*2.7*	*2.2*	*1.2*	*2.3*	*0.63*	*0.39*

Appendix 8.4 ANOVA Tables

Analysis of Variance for ensemble worst uncertainty regime						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Leadership	2	0.0751	0.0751	0.0376	0.12	0.888
Approach	2	2.9938	2.9938	1.4969	4.76	0.015
Buffer	2	0.0031	0.0031	0.0016	0.00	0.995
Delivery	2	30.6724	30.6724	15.3362	48.74	0.000
Error	36	11.3280	11.3280	0.3147		
Total	44	45.0724				
S = 0.560952, R-Sq = 74.87%, R-Sq(adj) = 69.28%						

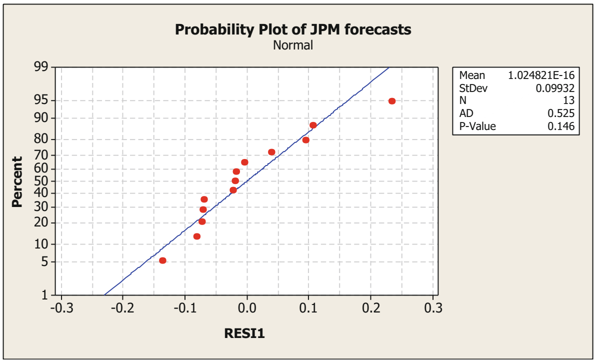
Analysis of Variance for ensemble best uncertainty regime						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Leadership	2	0.2618	0.2618	0.1309	0.61	0.547
Approach	2	3.0698	3.0698	1.5349	7.19	0.002
Buffer	2	0.0124	0.0124	0.0062	0.03	0.971
Delivery	2	32.7964	32.7964	16.3982	76.83	0.000
Error	36	7.6840	7.6840	0.2134		
Total	44	43.8244				
S = 0.462000, R-Sq = 82.47%, R-Sq(adj) = 78.57%						

Appendix 8.5 JPM's ANOVA Statistics

JPM's Analysis of Variance for Current Uncertainty Regime

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Leadership	2	0.2122	0.6832	0.3416	11.54	0.022
Approach	2	0.2966	0.3964	0.1982	6.70	0.053
Buffer	2	0.3279	0.1154	0.0577	1.95	0.256
Delivery	2	12.2525	12.2525	6.1263	207.00	0.000
Error	4	0.1184	0.1184	0.0296		
Total	12	13.2077				
S = 0.172033, R-Sq = 99.10%, R-Sq(adj) = 97.31%						

The residuals are N(0,0.099).



Appendix 8.6 Interaction ANOVA Tables

Ensemble Best Versus Approach, Delivery

Analysis of Variance for ensemble best, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Approach	2	3.0698	3.0698	1.5349	7.19	0.002
Delivery	2	32.7964	32.7964	16.3982	76.83	0.000
Approach* delivery	4	0.2742	0.2742	0.0686	0.32	0.862
Error	36	7.6840	7.6840	0.2134		
Total	44	43.8244				

S = 0.462000, R-Sq = 82.47%, R-Sq(adj) = 78.57%

Ensemble Worst Versus Approach, Delivery

Analysis of Variance for ensemble worst, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Approach	2	2.9938	2.9938	1.4969	4.76	0.015
Delivery	2	30.6724	30.6724	15.3362	48.74	0.000
Approach* delivery	4	0.0782	0.0782	0.0196	0.06	0.993
Error	36	11.3280	11.3280	0.3147		
Total	44	45.0724				

S = 0.560952, R-Sq = 74.87%, R-Sq(adj) = 69.28%

Ensemble Curr Versus Approach, Delivery

Analysis of Variance for ensemble curr, using Adjusted SS for Tests						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Approach	2	2.0520	2.0520	1.0260	3.87	0.030
Delivery	2	32.9453	32.9453	16.4727	62.21	0.000
Approach* delivery	4	0.3627	0.3627	0.0907	0.34	0.847
Error	36	9.5320	9.5320	0.2648		
Total	44	44.8920				
S = 0.514566, R-Sq = 78.77%, R-Sq(adj) = 74.05%						

Appendix 8.7 Response Tables for Worst and Best Environments

Response table for means worst				
Level	Leadership	Approach	Buffer	Delivery
1	2.400	2.620	2.460	1.413
2	2.500	2.647	2.440	2.507
3	2.453	2.087	2.453	3.433
Delta	0.100	0.560	0.020	2.020
Rank	3	2	4	1

Response table for standard deviations				
Level	Leadership	Approach	Buffer	Delivery
1	0.4925	0.7351	0.4515	0.4419
2	0.5938	0.4775	0.4803	0.4223
3	0.4577	0.3314	0.6122	0.6798
Delta	0.1360	0.4038	0.1607	0.2575
Rank	4	1	3	2

Response table for means best				
Level	Leadership	Approach	Buffer	Delivery
1	3.060	3.353	3.107	1.987
2	3.193	3.180	3.093	3.213
3	3.013	2.733	3.067	4.067
Delta	0.180	0.620	0.040	2.080
Rank	3	2	4	1

Response Table for Standard Deviations				
Level	Leadership	Approach	Buffer	Delivery
1	0.5480	0.4636	0.4951	0.5472
2	0.4238	0.4315	0.3175	0.2796
3	0.3185	0.3952	0.4777	0.4635
Delta	0.2295	0.0684	0.1775	0.2676
Rank	2	4	3	1

Appendix 8.8 Gage R&R

Gage R&R for neutral csat

Two-Way ANOVA table with interaction					
Source	DF	SS	MS	F	P
Treatment	9	74.5307	8.28119	57.8192	0.000
Operator	3	1.8112	0.60373	4.2152	0.014
Treatment * operator	27	3.8671	0.14323	1.1695	0.321
Repeatability	40	4.8986	0.12246		
Total	79	85.1076			

Two-Way ANOVA Table Without Interaction					
Source	DF	SS	MS	F	P
Treatment	9	74.5307	8.28119	63.2968	0.000
Operator	3	1.8112	0.60373	4.6146	0.005
Repeatability	67	8.7657	0.13083		
Total	79	85.1076			

Two-Way ANOVA Table With Interaction					
Source	DF	SS	MS	F	P
Treatment	9	89.855	9.98391	44.4212	0.000
Operator	4	10.805	2.70130	12.0188	0.000
Treatment * operator	36	8.091	0.22476	1.1700	0.300
Repeatability	50	9.605	0.19210		
Total	99	118.357			

Gage R&R with DMU5

Source	VarComp	%Contribution (of VarComp)	
Total Gage R&R	0.33055	25.26	
Repeatability	0.20577	15.73	←
Reproducibility	0.12478	9.54	
Operator	0.12478	9.54	
Part-To-Part	0.97781	74.74	
Total variation	1.30836	100.00	

Gage R&R without DMU5

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.15448	13.17
Repeatability	0.13083	11.15
Reproducibility	0.02364	2.02
Operator	0.02364	2.02
Part-To-Part	1.01879	86.83
Total Variation	1.17327	100.00

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)
Total Gage R&R	0.39303	2.35821	36.29
Repeatability	0.36171	2.17024	33.39
Reproducibility	0.15377	0.92261	14.20
Operator	0.15377	0.92261	14.20
Part-To-Part	1.00935	6.05612	93.18
Total Variation	1.08318	6.49906	100.00

Number of Distinct Categories = 4.

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Chapter 9
Verifying Efficacy: Navy Force Structure

. . . as certain as that night succeeds the day, that without a decisive naval force we can do nothing definitive, and with it, everything honorable and glorious.
George Washington

To be there where it matters, when it matters.
US Navy

Ruler that has but ground troops has one hand, but one that has also a navy has both.
Peter the Great

China has neither intention nor capability to challenge the US, let alone to replace US as the world's dominant power.
Qu Xing. Chinese Embassy

Abstract This chapter is a challenging case study that deals with national security. The strategic decision is about the size and structure of the US Navy for the year 2037. This case itself is a grand *gedanken* experiment done with experts. This case is demanding because it is very multidimensional. We had to consider geopolitical issues, economics, recent and not so recent history, international law, national cultures, NATO, and so on. The solution space under the uncertainty conditions specified consisted of 1,374,389,534,720 candidate decision alternatives. We constructed robust decisions using our decision-synthesis methodology without constraining the ability to explore any region of the solution space under any uncertainty. No data or information—in physical, electronic or verbal—in this chapter originate from any classified sources. The analyses and inferences do not represent positions of the US Navy.

John Q. Dickmann PhD is coauthor of this chapter.
Qu Xing. *China-US: Duel of the Century or Partner of the Century?* Chinese Embassy, Belgium. 15 April 2015.

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9.1 Introduction

This chapter continues the progression of our exposition of our paradigm. In **Part I**, we showed the conceptual and technical rigor, as well as, the distinctive and practical nature of our methodology. Our methodology is grounded on engineering-design thinking, complex systems-development methods and proven sociotechnical practices. We presented prescriptions for the systematic design of decisions with specifications that are robust even under uncontrollable uncertainty conditions. We presented our systematic process to identify key managerially controllable and uncontrollable variables. Using these variables, we presented our methodology for the design of desired robust decision-specifications. To mitigate the impact of uncertainty, we use robust engineering-design methods to exploit the interactions between controllable and uncontrollable variables. We presented a new and innovative way to measure and analyze the quality of the socio-technical system by using the manufacturing-engineering methods of gage repeatability and reproducibility (Gage R&R). We have characterized and represented, in detail, the technical and social subsystems of our executive-decision methodology.

In **Part II,** we deconstructed the meaning and pragmatics about whether our paradigm and its methods "**work**". We argued that whether a complex artefact, like our executive-decision paradigm and its methods, "work", not "work", and how to make it "work" better, cannot be resolved as if discussing a light bulb. We argued that our methodology ***works***, if and only if, it simultaneously satisfies two necessary and sufficient conditions, *viz.* it is ready-**to**-work for users ***and*** ready-**for**-work by a user for a specific class of decision situations.

We need to show that our methodology, as an intellectual artefact, is ***functional*** and ***works*** as intended by us. We used extensive simulations using the system dynamics model, of the ADI company, as a test object to demonstrate our methodology is *ready*-***to***-*work*. Due to inherent limitations of simulations, XRL-5 was deferred to Part III. However, by a large measure, our methodology satisfied the X-RL conditions (Table 9.1) for ready-to-work.

In Part **III**, we showed how three non-trivial organizations satisfy themselves that the methodology *works* for them. Namely, that it is ready-**for**-work with evidence of the ***efficacy*** of our methodology (Figs. 9.1 and 9.2). In this chapter, we use the US Navy Force Structure as our real world example.

Table 9.1 Readiness level specifications for executive decisions

Readiness level	Our systematic process		Strategy
X-RL1	Characterize	Problem space	Sense making and framing
X-RL2	Engineer	Solution space	Engineer experiments/alternatives
X-RL3	Explore	Operations space	Explore entire solution & uncertainty spaces
X-RL4	Evaluate	Performance space	Measure robustness, repeatability, reproducibility
X-RL5	Enact	Commitment space	Commit plan with approved resources

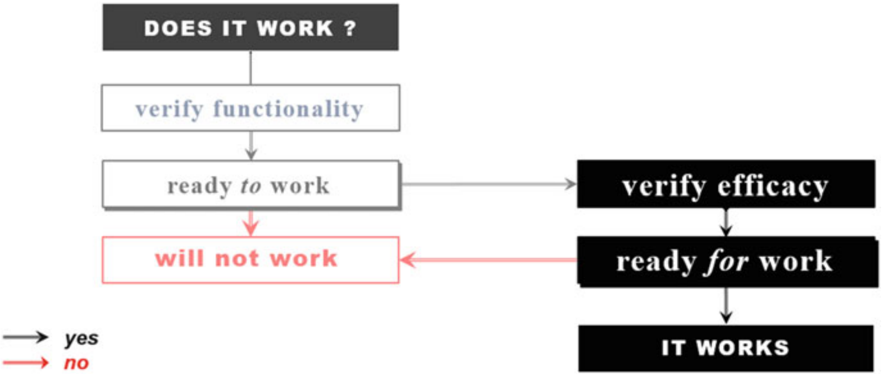


Fig. 9.1 Efficacy is a necessary condition to demonstrate methodology is *ready-for-work*

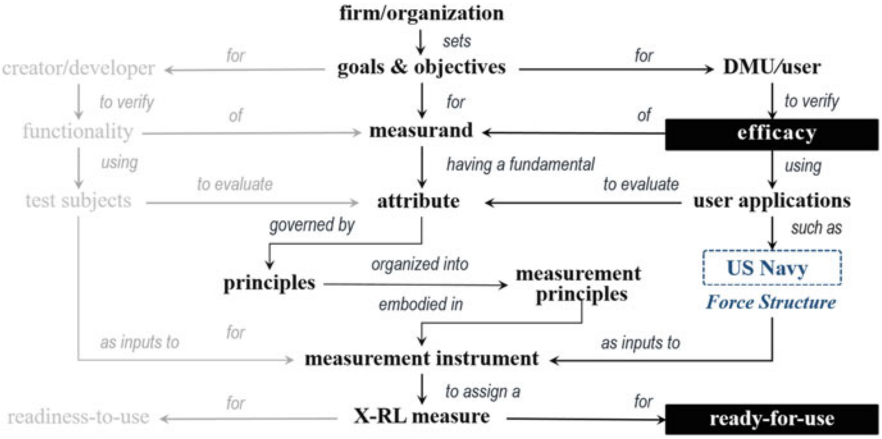


Fig. 9.2 Efficacy is a necessary condition to demonstrate methodology is *ready-for-work*

This is the third chapter of Part **III.** We engage with another real world customer to verify the efficacy of our methodology. In the previous chapters, we worked with HiTEM, a high-technology contract manufacturer of electronics components. HiTEM counts major Fortune 100 companies and the US Defense Department among its valued customers. Then we worked with a world-class e-business service company, eSvcs Japan. eSvcs Japan is a leading IT technology and systems consulting company. It is a richly endowed with world-class implementation, service and maintenance skills.

In this chapter, we want to test *efficac*y of our methodology with an enterprise that could further stress our executive decision paradigm. We move from the commercial high-technology sector to the US military, the US Navy (USN). We will study the question of how to think about what should be the size and structure of the US Navy. This chapter was inspired by an extended seminar we held with the Strategic Studies Group (SSG) at the US Navy War College. This chapter is extends the scale and scope of that seminar. The participants of the seminar were rising naval captains being groomed for further responsibilities. Encouraging feedback from the Commandant of the War College—Admiral Hogg (retired)—and the spirited group discussions were particularly stimulating and exciting. Recent heightened public interest in geopolitical debates and military discussions in the US Congress motivated us to revisit and extend our previous work on the force structure question. It is important to note that this chapter is largely a *gedanken* experiment and does **not** represent a position of the US Navy. All data are in the public domain and no information is from classified sources; other data are synthetically produced to illustrate our methodology.

This is a uniquely challenging case. Working with business enterprises, we can exclude many geopolitical factors, without loss of generality, and concentrate on markets and economics. But that is not be realistic with the Navy Force Structure decision. Many complicated military, political, economic and ideological factors must be considered, e.g. national policy, international relations, balance of power, behavior of nations, national cultures, social justice and history are impossible to avoid. Necessarily, they all enter into the decision-making discovery and analyses. A meaningful analysis must take these factors into consideration simply because they are also an integral part of the USN's ethos and value system. This kind of expansive thinking is deeply engrained in their *Weltanschauung* (e.g. Handel 2007; Mahan 2015a). Alfred Thayer Mahan, one the most original and insightful Naval strategists of our times, presciently wrote that regarding *sea power* "political, commercial, and military needs are so intertwined that their mutual interaction constitutes one problem" (Mahan 2015b). Clearly Mahan was not only a naval strategist, but a profound systems thinker as well. His thinking stands as the naval equivalent of SunTzu's *Art of War* (e.g. SunTzu 2012) and von Clausewitz's *vom Kreige* (e.g. Aron 1986).

The US Navy is a unique enterprise. Its magnificent achievements in warfare, its role in preserving the peace and defending ideals and moral values are unprecedented in history. We judge that this chapter adds a unique dimension to the design, analysis and synthesis of executive decisions. The Force Structure problem is a very rich, highly textured, and at the same time, an intricately nuanced question to resolve. It demands familiarity and understanding of geopolitical history, military history, international relations, surface and underwater ships, in addition to naval military knowledge. It is impossible to discuss the US Navy force structure question without also touching on geopolitical and economic issues. The Appendices present additional detail on some of the more complex issues. They appear there in order to simplify the mainline discussions of our systematic processes.

The Navy Force Structure "comprises the hardware—ships, aircraft, weapons, and systems and human resources (e.g. O'Rourke 2016a, b; O'Rourke and Schwartz 2016)". Among the key questions are: size, mix, affordability, capability, ability to deploy, balance of power, international law, adversaries' military industrial capabilities, national policy, and so on. An indicator of the importance of the Force

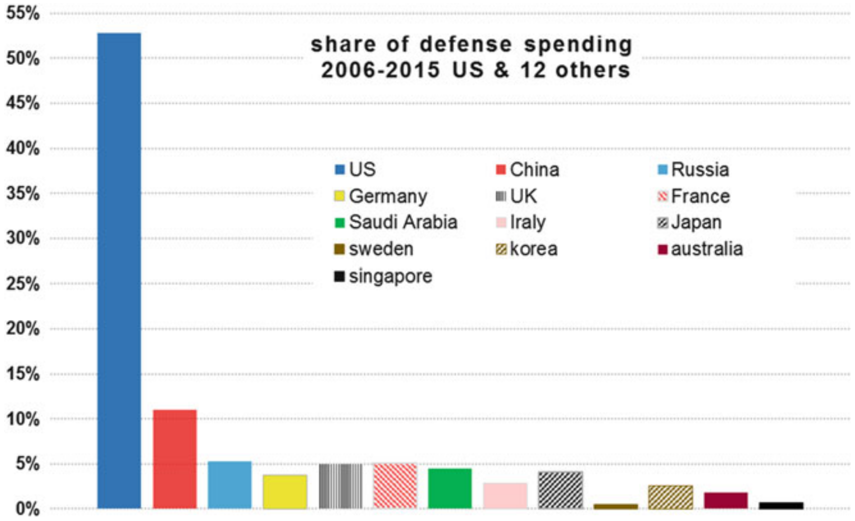


Fig. 9.3 US Navy expenditures dominates those of many other countries

Structure question can be seen in Fig. 9.3 by the magnitude of expenditures of the USN during the past decade relative to other key European and Asian countries (World Bank 2016a, b; Perlo-Freeman et al. 2016). We considered 10 years of cumulative defense expenditures to obtain a more realistic sense of the relative expenditures, and as a quantitative indicator of national commitment and tenacity. A one-year or year-on-year look does not show the sustained commitment needed to build a fleet.

In this chapter, we will verify efficacy of our methodology in addressing the US Navy Force Structure Question. We will demonstrate that our methodology will meet the X-RL specifications (Table 9.1) for *efficacy* in the five spaces of the executive-decision life-cycle (Fig. 9.4).

As in the previous chapter, we devote a section to each of the five spaces of the executive decision life-cycle, *viz*. the *Problem, Solution, Operations, Performance*, and *Commitment Spaces*. The objective is to systematically determine the X-RL readiness at each phase of our methodology. Section 9.2 covers *Characterizing the Problem Space*. We apply our methodology to characterize the decision situation adhering to our principles of *abstraction* and *uncomplication* to develop an uncomplicated, but accurate narrative of the decision situation. In Sect. 9.3, *Engineering the Solution Space*, we identify the essential decision variables, the problem solving constructs used for the solution space, and the representations of the spectrum of the uncertainty conditions by means of *uncertainty regimes*. To render the Uncertainty Space tractable, we discretize the entire uncertainty space into a discrete spanning set of *uncertainty regimes*.

In Sect. 9.4, *Exploring the Operations Space*, we use an array of experiments under our set of uncertainty regimes, which span the entire Uncertainty Space. We use representations, of the many and varied potential decision-alternatives to fully

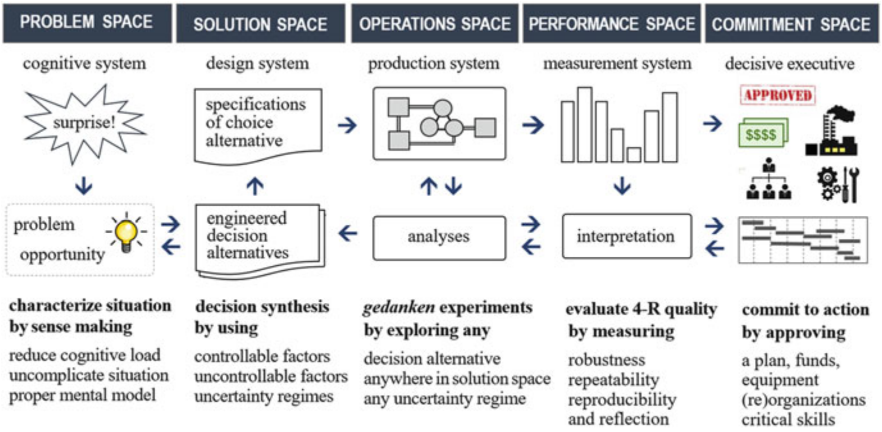


Fig. 9.4 Schematic of the five spaces of the executive-decision life-cycle

explore the Solution Space. We show a procedure for constructing and exploring any hypothetical "what if" decision-alternative for which we can determine a risk profile using its predicted standard deviation. To these ends, we collect data for the evaluations needed in the *Performance Space*, Sect. 9.5. The Analysis of the Performance Space is investigated. We concentrate on the 4-R's of Robustness, Repeatability, Reproducibility and Reflection of the operational performance measures of our decision methodology. We use the Gage R&R methods from the engineering discipline of Measurement System Analysis, (AIAG 2002) to analyze the performance of the sociotechnical system as a production system. This is a new, novel, and *unprecedented* application of Gage R&R. Since this chapter is largely based on synthetic data of *gedanken* experiments of a problem inspired by the Strategic Studies Group in the US Naval War College, we cannot extensively discuss, the *Commitment Space* in Sect. 9.6, These decisions are discussed in the halls of the legislative branch and the Defense Department. Section 9.7 closes this chapter with a summary of the key learnings from this exercise.

No data or information—in physical, electronic or verbal—in this chapter originate from any classified sources. The analyses and inferences do not represent positions of the US Navy.

9.2 Characterizing the Problem Space

We discuss in this chapter our experiment about the Force Structure of the US Navy. The *thin* description of the Force Structure Problem concentrates on the size and structure of the US fleet to meet its mission stipulated by the US Defense Department (Table 9.2). Thin descriptions are useful to develop a base understanding of the Force Structure Problem/Opportunity to develop a more informed

Table 9.2 US Navy's current 308-ship Force Structure Goal

Ship type		Quantity	Description
Submarines	**SSN Virginia**	48	Nuclear attack-submarine, Virginia class
	SSBN	12	Nuclear ballistic missile submarine
	SSGN	4	Nuclear guided missile submarine
Aircraft carriers	**CVN**	11	Powered aircraft carrier
Surface combatants	**DDG 51**	88	Guided missile destroyers, 51 class
	LCS/FF	52	Littoral combat ship/FF
Amphibious	**LPD**	22	Land platform dock, amphibious
	LHA	11	Landing helicopter assault, amphibious ship
Support ships	**CLF**	29	Combat logistics force
Other		34	Acquisition expenditures for ships
Total		$\Sigma =$ **308**	

Source: O'Rourke (2016b)

intuition of the problem we will be trying to discuss. This will be followed by a more *thick* description of the issues of the US Navy Force Structure question (e.g. Geertz 2008; Shenhav 2005; Hoyle et al. 2002). These include the questions of affordability, capability, ability and readiness to deploy, all in the context of geopolitical balance of power, international law, adversaries' capabilities, national policy, national economies, and so on.

Overall, the thin and thick descriptions describe the meaning and significance of the Force Structure executive-decision question.

9.2.1 Sense-Making and Framing

9.2.1.1 Navy Force-Force Structure Defined

The thin definition of the US Navy Force Structure is simply the size of the fleet and its composition. Simply stated it is the number of ships of various types in its inventory (e.g. O'Rourke 2016a, b).

- We think of the US *fleet as portfolio of ships,* i.e. *w*hat is the size and structure of the US Navy's portfolio? The US Navy "projects that if its 30-year shipbuilding plan is fully implemented, the Navy would attain a fleet of 308 ships (though not with the exact mix of ships called for in the current 308-ship force-structure goal in FY 2021 (O'Rourke 2016b, 1)". This is now considered by many as being too modest force structure to meet US defense needs in the coming decades (e.g. MITRE 2016; O'Rourke 2017; McCain 2017).
- As in any portfolio, one can increase or decrease the number of items for any specific asset. Thus altering the portfolio structure (mix).
- The "value" of the portfolio is determined by the mix and the metrics used to evaluate value. We follow Keeney (1996) and define value as "what we really care about". "Assessment of US Navy: Capacity, Capability and Readiness"

(2026) reports that the US Navy cares about are *capacity, capability*, and *readiness*. Capacity is measured by the number of ships. *Capability* is a measure of naval strength relative to other nations, friends and adversaries. This would require comparisons of platforms, weapons, operational concepts, training, education, readiness and other factors. This depth of comparison is beyond the scope of this chapter. We make a simplifying assumption and use cost as a proxy for *capacity*. Since it takes money to develop and deploy platforms, as a first order, cost of acquisition is a useful approximation to capacity. *Readiness* is ability to fulfill the Navy's mandate "to be where it matters, when it matters", with what matters. This measure is even more complicated than capacity, for one has to consider the age of the platforms, the quality of maintenance, the proficiency of personnel, the intensity and length of potential deployments, and so on. Assessment of readiness is also beyond the scope of this chapter, but could be included in a more detailed and extensive application of this method.

Therefore, we frame the US Navy Force Structure question as a "portfolio" of ships of different types and costs. The portfolio has three properties we will measure.

- **Capacity**. We "focus on ships on being, not on ship building" (Levy and Thompson 2010).
- **Cost**. We determine fleet cost measured by the acquisition cost of each ship type and the quantities of each ship type (Table 9.11).
- **Power**. Overall ability of the fleet to satisfy its mandate: *Protect* the homeland, *Build* global security, *deter* adversaries, and *take action* if deterrence fails. Power is measured relative to the 308-ship fleet by naval and national security experts. Power is a composite index as we have defined it.

However, this framing does not exclude external contextual factors that impinge on the measures that must be identified. For example, the defense spending data of NATO allies and Japan indicate that the US is bearing a disproportionate financial burden. Figure 9.1 illustrates this remarkable asymmetry. The phenomenon of free-riding suggests itself. Appendix 9.1 provides more detailed discussion of this phenomenon. Other examples of key external geopolitical factors are; rules of the game such as United Nations Convention on the Law of the Sea (UNCLOS), residual unresolved issues of social justice from WWII, and so on. These factors are fundamental elements that form unstable uncertainties and contribute to national security risks. They enter our analyses as uncertainty factors, which are integral to this work.

9.2.1.2 Why Is It Important?

Simply stated, the Navy Force Structure question is important because it is a fundamental element of the US defense strategy for national security. This strategy was formerly publicly published by the US Department of Defense in the Quadrennial Defense Review (Quadrennial Defense Review 2014). The Secretary of

Defense was responsible to conduct a comprehensive examination of the US defense strategy, force structure, modernization plans, budget, and other elements of the defense program and policies of the United States with a view toward determining and establishing a defense program for the next 20 years. The last Quadrennial Defense Review was published in 2014 and further documents are not planned. A new process is in the making at this time. However, the 2014 document is still useful, in as much as, it explicitly states the goals of the US DOD, for the Army, Navy and the Air Force. Updated by US Navy (2026), they are:

> . . .preparing for the future by rebalancing our defense efforts in a period of fiscal constraint.
> . . .emphasizing three pillars:

- Protect the homeland, to deter and defeat attacks on the United States.
- Build security globally, to preserve regional stability, deter adversaries, support allies and partners, and cooperate with others . . .
- Project power and win decisively, to defeat aggression, disrupt and terrorist networks, and provide humanitarian assistance . . .
- “Winning decisively”. This fourth pillar is per update from the US Navy.

The DOD’s construct of goals and pillars are consistent with the principles of our procedure in Sect. 3.2.3. Namely, goals are superordinate and objectives are the means to fulfill goals. For example as stated above, the goal is “preparing for the future. . .defense . . . in a period of fiscal constraint.” In addition, we observe that our “No Free Lunch” principle (Sect. 3.3.2.2) is also explicitly embodied in the DOD goal statement of “. . . fiscal constraint.”

The recursive decomposition of goals and objectives, we discussed in Chap. 3, is also visibly present in DOD’s thinking. The three pillars are further decomposed. For example, to “build global security” can be decomposed into the “how” by articulating the objective to “deter aggression and assure allies *in multiple regions* through forward presence and engagement”, and “. . . imposing unacceptable costs on—second aggressor in *another region*”. [italics are ours].

This leads us to the next section, the DMU, which will direct this experiment to achieve these Goal and Objectives of the experiment in this chapter.

9.2.2 The DMU: Decision Making Unit

In practice, flag officers assign much of the analyses and key deliberations to staffs, direct reports, and experts. The flag officer leads this working group to make better decisions (e.g. Northhouse 2010). We call this organizational ensemble, a *decision-making unit,* a DMU. Flag officer decision-situations require special expertise. In these cases, experts are invited to participate as adjunct or temporary members. DMU members, because they are also generals or naval field grade officers, also have staffs, organizations, and experts they can assign for special work. This extended network effectively expands an officer’s and organizational cognitive aperture, implementation, and execution resources. The DMU and its adjuncts serve as sociotechnical mechanisms during the executive-management decision life-cycle. DMU's exist for "participants [to] develop a shared understanding of the issues, generate a sense of common purpose, and gain commitment to move forward (Phillips 2007, 375)".

In the problem space, the DMU's key responsibilities are *sense-making* and specifying the goals and objectives of the decision situation (Fig. 9.5). This process is mediated by DMU members' *mental models,* which must to be *harmonized*. Harmonized does not mean made identical. Traditional thinking emphasizes "the creation of appropriately shared mental models of the system" (Fischhoff and Johnson 1997, 223) for a group to do its work efficiently and effectively (e.g. Jones and Hunter 1995). However, our experience and current research reveal a more comprehensive and complete view of the meaning of *shared mental models* (e.g. Banks and Millward 2000; Mohammed et al. 2010). Shared does not necessarily mean identical or same; but consistent, aligned to the same goal, and complementary to satisfice goals and objectives. Each DMU member must understand the game plan. No one wants a basketball-team made up of players who see the game as consisting entirely of free throws.

In this example, the DMU is a synthetic construct. The authors of this chapter act as the DMU and implicitly as its chair. Five other synthetic DMU members were added. Each DMU member was designed to represent a type of officer to generate an evaluation and score for different force structures based on a specific professional profile. The profiles were: Surface Heavy, Submariner, Marine, CNO staff, and Frugal Congressman. Surface Heavy is one that favors big ships that engage the enemy on the ocean surface with carriers, destroyers, and frigates. The Submariner profile, obviously, would prefer a fleet that has a strong concentration of submarines. Marines take pride in knowing that they are "first to deploy" in war and the fact they are a special branch of the military that was created by the Continental Congress. It is natural that Marines have an institutional culture that associates amphibious and landing ships with their service. Their judgements would naturally favor a fleet that enables decisive success in terrain for beach landing and deployments with direct contact with the enemy. Recall our discussion on the dialectical nature of specialization and synthesis, of analysis and synthesis. The presence of the former necessitates the enactment of the latter to understand the whole (Sect. 1.4.3, Sect. 3.2.2). Seasoned executives invariably have such synthesizers as an integral part of their DMU. This is a form of the well-known attribute of organizational ambidexterity (Tushman and O'Reilly 1996) and skillful exercise of deductive/

Fig. 9.5 Schematic of the problem space

inductive processes for integration of organizational knowledge (e.g. Nonaka 1988). To provide the role of synthesizers, (O'Reilly and Tushman 2004; Tushman and Nadler 1978), we developed the Chief of Naval Operations staff (CNO staff) whose mission is to serve the CNO without favoring any branch of the US Navy. This is similar to the role of Executive Assistants in IBM, whose job is to behave as their principal, but reserve the decision-making to them. The other synthesizer is what we called the *Frugal Congressman*, from the Ways and Means Committee, whose purpose in life is not to raise taxes. This person acts as the enforcer of the "no free lunch" principle.

9.2.3 Goal and Objectives of the Experiment

Given the policy of a 308-ship fleet, we would like to explore the following questions:

- Are there alternatives, which are potentially superior to the 308-ship force structure?
- Are larger force structures, which are costly but disproportionately superior to the 308-ship fleet?
- Are there more modest force structures, which are less costly but equally or more effective?
- What is the impact of geopolitical uncertainty on the decisions about force structure?

There are a multitude of possible force structures. Relative to the 308-ship portfolio configuration (Table 9.3), we can imagine other configurations, which an *admiral* (Table 9.4) or *civilian* (Table 9.5) might design for a 341-ship fleet and 282-ship fleet, respectively.

Table 9.3 Portfolio configuration for 308-ship fleet

Type	SSBN	SSN	SSGN	CVN	DDG51	LCS/FF	LPD	LHA	CLF	Other	Σ
Quantity	12	48	4	11	88	52	22	11	29	34	308

Table 9.4 Portfolio configuration designed by a hypothetical *Surface-Heavy Admiral*

Type	SSBN	SSN	SSGN	CVN	DDG51	LCS/FF	LPD	LHA	CLF	Other	Σ
Quantity	12	48	0	11	106	62	24	12	32	34	341

Table 9.5 Portfolio configuration designed by a hypothetical *Frugal Congressman*

Type	SSBN	SSN	SSGN	CVN	DDG51	LCS/FF	LPD	LHA	CLF	Other	Σ
Quantity	10	40	0	9	88	47	22	9	29	31	282

These examples illustrate that clearly a very large number of configurations are possible. The configurations are determined by ship type, e.g. DDG, SSBN, CVN, etc. or a new ship type to be added to the portfolio. Thus ship types and their quantities are **managerially** controllable variables.

9.2.4 The Essential Variables

Essential variables are the factors that directly influence the outcomes and attainment of goals and outcomes (e.g, Phadke 1989, Taguchi et al. 2000). They are either managerially controllable or managerially uncontrollable. The uncontrollable variables shape the uncertainties that directly, positively or negatively, impact the intended outcomes and, therefore, the attainment of goals.

9.2.4.1 Managerially Controllable Variables

As discussed in Sect. 9.2.3, it is natural that the controllable variables **are** the ship types and the quantities we want in the fleet. The ***characteristic*** is *more-is-better*, i.e. a larger quantity of ships is more desirable. For example in the 308-ship fleet, the appropriate quantity of carriers (CVN) is 11. The Frugal Congressman will want 9, too many is a less desirable. Table 9.6 is the force structure template identifying the controllable variables for the design of a force structure portfolio.

How many of each ship type do we need? Table 9.6 structures the specification by levels as in Table 9.7. What do the levels mean? We explain this one-step at-a-time.

First. We turn our attention to Table 9.7 and the **level 2** column for the 308-ship fleet. This column specifies the force structure specification for the 308-ship fleet. It calls for 12 SSBN's, 48 SSN's, 4 SSGN's, 11 CVN's, and so on. The quantity of

Table 9.6 Force Structure Template—ship types and their quantities

Ship type		Quantity	Description
Submarines	**SSBN**	$\mathbf{n_1}$	Nuclear ballistic missile submarine
	SSN Virginia	$\mathbf{n_2}$	Nuclear attack submarine. Virginia class
	SSGN	$\mathbf{n_3}$	Nuclear guided missile submarine
Aircraft carriers	**CVN**	$\mathbf{n_4}$	Powered aircraft carrier
Surface combatants	**DDG 51**	$\mathbf{n_5}$	Guided missile destroyers, 51 class
	LCS/FF	$\mathbf{n_6}$	Littoral combat ship/FF
Amphibious	**LPD**	$\mathbf{n_7}$	Land platform dock, amphibious
	LHA	$\mathbf{n_8}$	Landing helicopter assault, amphibious ship
Support ships	**CLF**	$\mathbf{n_9}$	Combat logistics force
Other		$\mathbf{n_{10}}$	Acquisition expenditures for ships
Total quantity of ships		$\mathbf{\Sigma n_i \quad i = 1,2,\ldots,10}$	

Table 9.7 Ship types and their quantity are the controllable

Ship type		Level 1	Level 2. 308-ship	Level 3	Level 4
Submarines	**SSBN**	10	12	–	–
	SSN	40	48	60	70
	SSGN	0	4	6	8
Aircraft carriers	**CVN**	9	11	12	15
Surface combatants	**DDG 51**	79	88	97	106
	LCS/FF	47	52	57	62
Amphibious	**LPD**	18	22	24	30
	LHA	9	11	12	15
Support ships	**CLF**	26	26	32	35
Other		31	34	37	40
Total quantity of ships		**269**	**308**	**332**	**381**

Table 9.8 Portfolio configuration for 308-ship fleet

Type	SSBN	SSN	SSGN	CVN	DDG51	LCS/FF	LPD	LHA	CLF	Other	**Σ**
Quantity	12	48	4	11	88	52	22	11	26	34	308
Level	2	2	2	2	2	2	2	2	2	2	

ships by type specifies the **required mix** for the 308-ship fleet. **This is the Force Structure for the 308-ship fleet** (Table 9.8).

Second. For a given ship type, **level 1** is a lesser quantity of ships by type relative to the quantity required in the 308-ship force structure. Now suppose that, hypothetically speaking, it is judged that 48 attack submarines (SSN) is excessive. The quantity is lowered to 40 SSN's, while all the other ship quantities remain at the 308-ship level. The result is fewer ships in this hypothetical force structure. Clearly, without much analysis, we are **worse-off** with this 300-ship force structure relative to the 308-ship fleet (Table 9.12). This is the *Reagan* evaluation of: "are we *better off*, or are we *worse off*", with this change? For illustrative purposes, we'll judge it with a score of $\boldsymbol{R} = 4$ (***R*** for "Reagan" index), Table 9.9. The reason for this evaluation is that **the remainder** of the 308-fleet remains unchanged.

Third. Consider a different situation. For a given ship type, **level 4** is a larger quantity relative to the quantity required in the 308-ship force structure. Given the characteristic of our controllable variables, level 4 with more ships, is better. Suppose, hypothetically speaking, that it is judged that 11 aircraft carriers (CVN) is insufficient given China's carrier building program, tensions in the Korean peninsula, Iran's belligerence and the importance of the Strait of Hormuz. The CVN quantity is raised to **level 4** for 15 carriers. This is the design of the force structure shown in Table 9.12. We now have a force structure of 304 ships, consisting of a **much better** CVN quantity but a **worse** SSN quantity. We have better surface capacity, but worse attack submarine capacity (Table 9.10). In this case, we have opposing objectives. Clearly different DMU members will rate this structure differently.

Table 9.9 Evaluation measures of force structure relative to 308-ship fleet

R measure	Evaluation relative to 308-ship fleet
10	**Superb**
9	**Much better**
8	Better < intermediate < much better
7	**Better**
6	308-ship fleet < intermediate < better
5	**Equivalent to 308-ship level**
4	Worse < intermediate < 308-ship fleet
3	**Worse**
2	Much worse < intermediate < worse
1	**Much worse**
0	**Disaster**

Table 9.10 Evaluation of 308-ship fleet with fewer SSN's, from 48 to 40

Type	SSBN	**SSN**	SSGN	**CVN**	DDG51	LCS/FF	LPD	LHA	CLF	Other	**Σ**	***R***
Quantity	12	**40**	4	**15**	88	52	22	11	26	34	**304**	$\boldsymbol{\alpha}$
Level	2	**1**	2	**4**	2	2	2	2	2	2		

Using Table 9.9

Table 9.11 Force Structure Template—unit acquisition costs

Ship type		Unit cost $B	Description
Submarines	**SSBN**	$4.90	Nuclear ballistic missile submarine
	SSN Virginia	$2.87	Nuclear attack submarine. Virginia class
	SSGN	$4.90	Nuclear guided missile submarine
Aircraft carriers	**CVN**	$12.90	Powered aircraft carrier
Surface combatants	**DDG 51**	$1.15	Guided missile destroyers, 51 class
	LCS/FF	$0.58	Littoral combat ship/FF
Amphibious	**LPD**	$1.63	Land platform dock, amphibious
	LHA	$3.40	Landing helicopter assault, amphibious ship
Support ships	**CLF**	$0.55	Combat logistics force
Other		$0.15	Acquisition expenditures for ships

Sources: Department of Defense Fiscal Year 2017 (FY2017) President's Budget Submission, Navy Justification Book, Vol. 1 of 1, Shipbuilding and Conversion, Navy. February 2016
Department of the Navy Fiscal Year 2012 (FY2012) Budget Estimates, Justification of Estimates, National Defense Sealift Fund. February 2011

What evaluation score to give this force structure in Table 9.10? A judgement has to be made as to whether the force structure is superior or inferior relative to the 308-ship fleet. DMU members have to individually score the outcome of this evaluation of this 304-ship fleet. We can average the DMU members' vote to get $\boldsymbol{\alpha}$**.**

Four. We turn our attention to the cost of a force structure. Our simplifying assumption to this is multiplying the unit acquisition cost by the quantity specified by the force structure specification. The unit costs are shown in Table 9.11.

Table 9.12 Evaluation of 300-ship fleet with fewer SSN's, from 48 to 40

Type	SSBN	**SSN**	SSGN	CVN	DDG51	LCS/FF	LPD	LHA	CLF	Other	**Σ**	***R***
Quantity	12	**40**	4	11	88	52	22	11	26	34	**300**	**4**
Level	2	**1**	2	2	2	2	2	2	2	2		

R- index = 4

Information in Table 9.11 enables us to calculate the cost of any hypothetical force structure, e.g. Table 9.13. For example, the acquisition cost of the 308-ship fleet is \$581.74 B, for the 360-ship fleet cost is \$651.9 B and for the 274-ship cost is \$479.48 B. What remains is for the DMU members to score the specific force structure for a specific fleet configuration. This is similar to the idea of determining the value of a financial portfolio comprised of different securities from various industries. This is the ***R*** value shown, for example, in Tables 9.12 and 9.10 and yet to be determined for Table 9.13. We defer showing how to do this in the discussion of the Solution Space.

9.2.4.2 Managerially Uncontrollable Variables

US Navy Force Structure is a national security issue. It is of strategic importance and significant international and geopolitical implications. The Force Structure question is uniquely challenging, many complicated military, political, economic and ideological factors must be considered. National policy, international relations, balance of power, behavior of nations, and history, are impossible to avoid. A meaningful analysis must take these factors into consideration. They emphatically make their presence and influence felt by uncertainty variables. The nexus of many of these variables are located in many parts of the world. These variables are uncontrollable or so difficult costly to control that, in effect, they are not controllable (Table 9.14).

Take Russia for example. It has a navy that has a 300-year history. It has a coast line that is 1.5 times as long as its territorial land boundaries (The Russian Navy 2015). Russia wants to assert its naval heritage. On January 2017, Russia deployed its only and aging aircraft carrier, the Admiral Kuznetsov, with the battlecruiser Petr Velkiv to the Mediterranean in a very modest show of force. A very lean move relative to the powerful days of the Soviet Union. Russia's navy is now about a quarter the size of the Soviet Navy, with a force that is on average 30 years old (The Russian Navy 2015). Even so, it was able to project power in the Mediterranean. It controls the Southern Kuril Islands, which Japan stills claims as its own, in spite of being defeated in WWII. To communicate its intentions, Prime Minister Medvedev visited them in 2015. And held joint naval exercises in the East Sea with China. Russian people have a remarkable capacity to bear immense burdens and display a prodigious tenacity to carry on under the most adverse conditions. They have a stockpile of 7000 nuclear weapons with 1790 of them deployed (Kristensen and Norris 2017). It is not surprising that Russia intends to rebuild its Navy. However,

Table 9.13 Example of three different fleets and acquisition costs. Three panels. 308-ship fleet, 360-ship fleet, and 274-ship fleets

Type	SSBN	SSN	SSGN	CVN	DDG51	LCS/FF	LPD	LHA	CLF	Other	**Fleet**
Level	2	2	2	2	2	2	2	2	2	2	
Unit cost	$4.90	$2.87	$4.90	$12.9	$1.15	$0.58	$1.63	$3.40	$0.55	$0.15	
Quantity	**12**	**48**	**4**	**11**	**88**	**52**	**22**	**11**	**26**	**34**	**308**
Total $	$58.8	$137.76	$19.6	$141.9	$101.2	$29.95	$35.75	$37.4	$14.27	$5.10	**$581.74**
Level	1	4	2	1	4	4	4	3	1	2	
Unit Cost	$4.90	$2.87	$4.90	$12.9	$1.15	$0.58	$1.63	$3.40	$0.55	$0.15	
Quantity	**10**	**70**	**4**	**9**	**106**	**62**	**30**	**12**	**26**	**31**	**360**
total $$	$49.0	$200.9	$19.6	$116.1	$121.9	$35.71	$48.75	$40.80	$14.27	$4.65	**$651.9**
Level	2	1	0	1	1	2	1	1	1	1	
Unit cost	$4.90	$2.87	$4.90	$12.9	$1.15	$0.58	$1.63	$3.40	$0.55	$0.15	
Quantity	**10**	**40**	**0**	**9**	**79**	**52**	**18**	**9**	**26**	**31**	**274**
Total $$	$49.0	$114.8	$–	$116.1	$90.85	$29.95	$29.25	$30.6	$14.27	$4.65	**$479.48**

Table 9.14 Uncontrollable variables and summary of the drivers of uncertainty

1	Russia	• Rebuilding navy • Sea of Japan, East China and South China Seas. Middle East
2	China	• Expanding Naval Force Structure • South China Sea and beyond 1st Island Chain • Asymmetric weapons development, investments in military technology • Assertive adult supervision and discipline North Korea • More liberal "Chinese socialism" and human rights
3	Japan	• Article 9, neo-militarism and right-wing extremism • Lack of trust or commitment to build trust with China and Korea • Use of the *wag-the-dog* strategy • provoking China, Korea, and Russia, positively or negatively
4	Korean Peninsula	• Intensity and progress in nuclear weapons and delivery systems
5	Germany	• Earned, stronger and expanded role in Europe
6	Budget	• US Congressional budget flexibility • CBA, sequestration and usual budgeting process
7	Med Sea & Middle East	• Timidity of European naval powers • Mix of competing national interest, friends and adversaries • Access Strait of Bab-el-Mandeb
8	Iran	• Access Strait of Hormuz • Nuclear proliferation
9	USA	• Tolerance of free-riders: its pervasiveness, high costs, and strategic risk • Dangers of being exploited by wag-the-dog strategy, Serbia syndrome • Visible erosion in moral high-ground. Others step in, not always in US' interest • World needs new/updated naval thinking

the size and composition planned for its naval force structure is unknown except to those in the Russian seats of power. But increases are expected consistent with their economic ability (Gady 2015). Therefore Russia is an uncontrollable factor and a source of uncertainty when it comes to establishing the US Navy force structure.

The second uncontrollable factor is China. This is a particularly complicated one. We follow Handel's (2007) approach and concentrate on two key contributing factors of uncertainty. One are China's intentions and the others are its abilities. We touch on its capacity, capability and readiness as determinants of ability. In terms of capacity, China has made large gains in the size of its size of its fleet. Affordability has fueled this growth. Its GDP is second only to the US and its defense budget is a modest 1.5% of its GDP. However, considering capability and readiness there is room for much improvement. For example, RAND reports that its strategic oil reserves are only 10 days (Gompert et al. 2016), jet engines for its advanced fighters are imported from Russia, it imports engines for some of its ships. How fast indigenous technology can catch up is an unknown. Readiness could be China's Achilles heel. China has not engaged, e.g. Allen & Clemens (2014), in a large military campaign in decades. It has never engaged in large fleet-level naval combat, nor engaged in any amphibious landings of any magnitude. Its naval capabilities and readiness in a major conflict are uncertain. How about its intentions? We believe their intentions are not that uncertain (e.g. Kristof 1993). Very high in its national priorities is economic development. Raising the standard of living gives the regime legitimacy. On this, China is on track. And according to the World Bank, since 1978, China has lifted 715 million people out of poverty. Second, it is seared in the Chinese mind that the Opium Wars and WWII all came via foreign navies. Chinese military observers note that while the US had one Pearl Harbor and one 911, China was the victim of hundreds of such cases during WWII. China is obsessed to avoid repetition of such humiliations. Third, they are very realistic about their navy. The quote at the beginning of this chapter is an official pronouncement. Military conflict does not appear to be part of the national agenda. Their policy is to be assertive, but not belligerent. Their doctrine stipulates that they will respond decisively to military action, but will not initiate one. The trigger points are what they identify as "core" national interests (中国的军事战略 2015; Zhao 2013). The US is the only power in the world that can influence potential bilateral and multilateral miscalculations.

The third uncontrollable variable is the emergent right-wing in Japan. Its negative impact on uncontrollable variables of China, Korea, Russia and the US are substantial and largely unnoticed. The intensity of the Japan right-wing and its actions to overlook its moral responsibility for historical atrocities on its neighbors serve to erode its, post WWII, hard earned position of statesmanship and claims to moral high ground. Irredentist initiatives exacerbates this negative trend. Among the visible parameters its neighbors use to gauge the neo-militarist right-wing are the memorials for Class A war criminals in Yasukuni, denial of their role in coercing comfort women into military brothels, their persistent irredentist claims to the DiaoYu/Senkaku, Dokto, and Kuril Islands. These actions erodes trust and reinforce suspicions about Japan's intentions to preserve Article 9 in its constitution. The contrast with post war Germany is stark. The extent to which the US can play a constructive role without letting the tail wag-the-dog is uncertain. The limits of US's wink-and-nod reticence in reigning in the nascent neo-militarists rise in Japan is an uncertainty that affects American position in the moral high ground and the stability of the region.

The fourth uncontrollable variable is the Korean Peninsula. The striking uncertainty element, in that region, is the North Korean regime and its leader. This regime can only be described as a rogue state and its leader as an Idi Amin with rockets. The actions emanating from this country are designed, no doubt, to provoke the US and its neighbors, and to destabilize the region. The flagrant disregard of nuclear non-proliferation, limits of American patience, degree of Chinese acquiescence, Japanese fear, and visions of waves of refugees escaping the country are the alarming elements stoking uncertainty. All this adds pressure and responsibilities to the US Navy. Some sort of US China bricolage of mutual interests and indifferences can potentially cut this Gordian knot.

Germany has emerged from WWII as the strongest economic engine of Europe, reliable ally of the US, and a force of peace and stability in the free world. It is the de facto political leader of the EU. Germany's admission and contrition regarding its role in WWII and inhuman treatment of Jews and conquered countries is unequivocal and completely unambiguous. So that when Germany speaks, it is trusted and respected. However, it is hesitant and tentative to take on a leadership role in European world affairs. This is reflected in its reluctance to a larger military budget. Overcoming this leadership reluctance can serve as a strong stabilizing factor in the region and the world at large. This reluctance is understandable, but it adds to the load the US must bear. To this extent, uncertainty is augmented on the question of the force structure.

The Mediterranean region and the Middle East is a major source of uncertainty. Strait of Bab-el-Mandeb, one of the world's major choke points, is in this region. It is a vital link between the Mediterranean, Red Sea and the Gulf of Aden and the Suez Canal. About $700 billion annual trade between Europe and Asia, 4% of the world's oil and 18% of the LNG pass through this narrow 18-mile wide strait (e.g. Pothecary 2016; Bab-el-Mandeb 2016). To what extent European navies will increase their participation with naval assets to safeguard commercial transport is an unknown. It is in their interest to do so. But they appear content to have the US be guarantor of safe passage. A change will require them to increase spending in defense, and will also decrease dependence on the US Navy.

Iran is the next uncertainty variable. Across the Persian Gulf is Saudi Arabia. The Gulf, a body of water and a fundamental sectarian animosity separates them. Iran is about 90% Sunni and 10% Shi'ite, while Iran is 90% Shi'ite and 10% Sunni. This contrast creates two adversaries near the Strait of Hormutz through which 40% of the world crude oil passes. At various times Iran has confronted the US Navy and declared that it can block the Strait. To deny passage, the Iranian navy would have to rely on cruise missiles, mine laying, and face the US Navy. Sustained built up its navy makes this threat a possibility, but how probable is uncertain. But its nuclear ambitions are the most serious threat, which the recent nuclear P5+1 agreement has put a lid on. But lifting economic sanctions as a *quid pro* quo has liberated billions to potentially cause mischief. Iranian Sh'ite fighters in Iraq raise political and oil control and supply risks in the region. The US Navy is the only party that can exert an effective influence in this region.

It is impossible to extract the US from the uncontrollable variables above. As a result, US expenditures on the military overwhelms the combined total of the next dozen countries (Fig. 9.1). Many in the US Congress are understandably nervous about burdens on US taxpayers and bearing an asymmetric share of the costs to protect the political stability and routes of international commerce. Figure 9.6 shows defense spending, 2006–2015, for Russia, Japan, China, and the US. While the US' and China's expenditures expand, *Japan's diminish*. The US is spending more than its fair share in the Pacific Area. Turning our attention to Fig. 9.7, the same trend prevails. Wealthy countries appear content to have the US bear a disproportionate burden for security that also benefits them. How deep is US' patience and how persistent is its sense of obligation to put its troops in harm's way when the sacrifice is asymmetric. The evidence for US claims of "free riding" is not unfounded. The issue is more complex than meets the eye (Appendix 9.1). Post WWII, American values were the envy of the world, even in Iron Curtain countries under Soviet rule. These were the foundations of *Pax Americana*

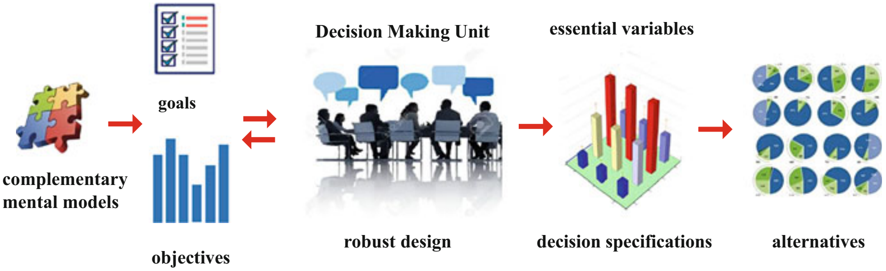


Fig. 9.6 Schematic of the operations space

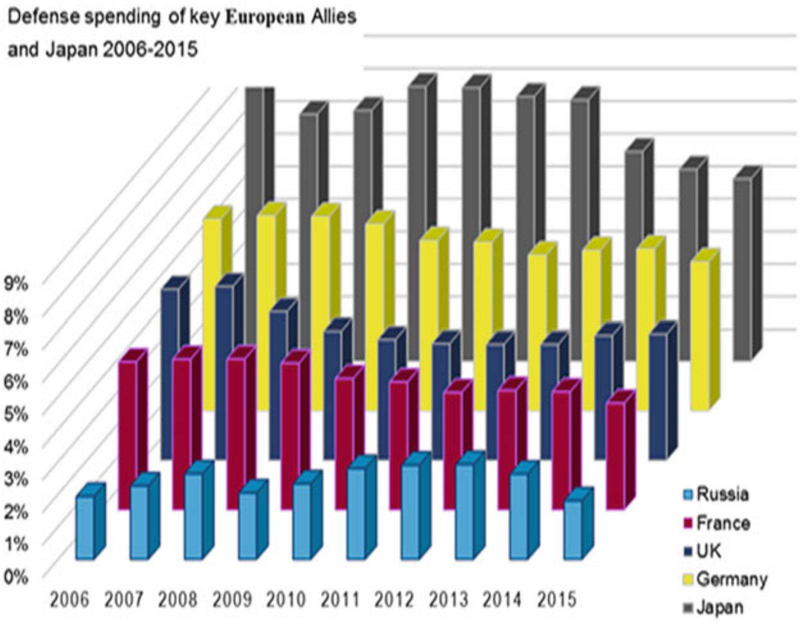


Fig. 9.7 Defense spending Russia, France, UK, Germany and Japan

established by blood, treasure and values. With few exceptions, the economies of the US' major allies are now, at least, as vigorous as ours; but their desire to bear an equitable share for defense spending to maintain regional and world peace is not resolute. This intensifies and enlarges the uncertainties about the requirements of US Navy's force structure.

Tables 9.15 through Table 9.23 specify the uncontrollable variables. The drivers of uncertainty are specified at four levels. Each level specifies elemental uncertainty-conditions, e.g. *very good* to v*ery bad,* for the uncontrollable variable. For examples, consider Table 9.15, the Russia example. The level-1 (very good) elemental desccriptors, represent conditions or situations which are ***very good*** to

Table 9.15 Russia

Characteristics	Good or bad for **Russia**
Levels	**1.** very good, **2.** good, **3.** bad, **4.** very bad. All relative to current situation
Level 1 *very good*	• Naval force structure improves to *very strong*, reaching Cold War levels • Can deploy simultaneously in ≥ 1 naval theater • New scale and scope of military and economic relationship with key players • Large increase in military spending, domestic economy growth improves • Support for its leaders from citizens in spite of many problems
Level 2 *good*	• Force structure improves to *strong*, but not to Cold War levels or China • Scale and scope of military and economic relationship with China strengthened • Overall diplomatic initiatives improve trust and image of Russia • Deploy in ≥ 1 naval theater, only with help from another country • Modest increase in military budget, economy grows but modestly
Level 3 *bad*	• Force structure maintained at *marginal*, lags EU and even Japan • Chinese Navy capability reaches parity with Russia • More relations with EU, NATO. US worsens. China partnership improves • Can deploy in only one theater, and with outdated ships and thin supply lines • Flat navy budget, can barely support military, weapons exports to sustain military
Level 4 *very bad*	• Force structure weak to *marginal*, capability and readiness weakens • China Navy capability overtakes Russia • Except for nuclear weapons, navy not a factor to US, EU, NATO, or Japan • Heavy dependence on China for Pacific Ocean power projection and interventions. • Licenses/Sells advanced naval technology to sustain military budget

Russia, e.g. “naval force structure improves to very strong reaching Cold War levels.” Should this occur, clearly it would be *very good* for Russia. Or consider a level-4 situation “Heavy dependence on China for Pacific Ocean power projection and interventions” would indeed be *very bad* for Russia. Both of these cases are uncertain and the intensity and nature of their effect on Russia are different. Russian and US attitudes after the US elections are also a source of uncertainty (e.g. Parakilas 2016).

Consider another example in Table 9.17, Japan. What can convincingly redefine Japan in the eyes of its neighbors? What would be outstanding for Japan? What can elevate its stature to a historic unprecedented level to become an exemplary nation of moral stature? Japanese government can take a page from Willy Brandt (e.g. Engert 2014), admit to waging aggressive war, stop denials that women, from invaded territories, were coerced into military brothels, and acknowledge that it ruthlessly performed human experiments to develop biological and chemical weapons. Japan can remove the class A war criminals’ memorials from the Yasukuni. A similar German memorial would be unthinkable and a moral outrage. Japan can launch a Mandela-like truth and reconciliation initiative (e.g. Villa-Vicencio 1999; Gohlke and Pritchard 2013). This would redefine Japan’s relationship with its neighbors. This is the level-1 *very go*od specification. In contrast, level-4 are conditions that would be *very bad* for Japan. Namely, the right-wing neo-milutarist minority gains public acceptance. It drives the Japanese Diet to revoke Article 9, intensifies its euphemistic view of WWII, and redoubles its irredentists efforts. Japan scholar Murphy (2009) writes: "Japan will need to understand why it is viewed with such suspicion by neighbors … [must] remove the blanket that smothers debate on the origins of the disasters of the 1930s and 1940s, not so that "rightists" and "leftists" can score points against each other, but in order to understand what happened so that it doesn't happen again—so that a revived military does not, on its own accord, one more time lead Japan down the road to disaster" (Tables 9.16, 9.17, 9.18, 9.19, 9.20, 9.21, 9.22, and 9.23).

The remaining uncontrollable variables China, Japan, Korean Peninsula, Germany, Congressional military budget, Mediterranean region, Iran, and USA.

Table 9.16 China

Characteristics	Good or bad for China
Levels	**1.** very good, **2.** good, **3.** bad, **4.** very bad. All relative to current situation
Level 1 *very good*	• Force structure > US, but not tonnage. Improves capability & readiness. • Strong starts in Kra & Honduras Canal, Brazil-Peru transcontinental railroad, one-belt one road, China Relations with US improve Development Bank • Sought after for military, economic, diplomatic initiatives by many 2nd/3rd tier countries • Philippines, Myanmar, Cambodia, Laos, Thailand,… leaning to China • Battle groups confidently deploy beyond of 1st island chain • Large increase in military spending, economy reform & growth steady • Surprising reduced corruption and improved rule of law. Party fist loosens considerably. Elections at local level expands rapidly.
Level 2 *good*	• Force structure selectively → *strong*, capability & readiness improving steadily • Europe relaxes some key high-tech military exports, they need revenues from China • New military economic, and diplomatic initiatives show meaningful progress • Strong start on Kra & Honduras canals; Australia, Persian and Red Sea ports • Improvements in corruption and human rights. Party grip relaxes more • Sustain acceleration in military budget, economy slows but still one of the best WW
Level 3 *bad*	• Force structure remains at *marginal*, lags NATO and Japan. India catching up • Trying hard, but unconvincing on military, economic & diplomatic progress • Anemic gains in trust and cooperation with US, European, and Asian countries • No significant reversal evident on aging of population • More increase in military budget, stress on economy, improvements disappointing • No significant progress in corruption or improving human rights
Level 4 *very bad*	• Force structure barely expands. Capability and readiness stagnant • Virtually no new or meaningful diplomatic initiatives. Pakistan wavering • Rivals & adversaries demonstrate strong progress in navy, economy & diplomacy • No dramatic increase in military budget, domestic economy slows down • Birth rate decline accelerates so does aging of the population • Strong evidence of emigration trend among the best and brightest young people

Table 9.17 Japan

Characteristics	Good or bad for Japan
Levels	**1.** very good, **2.** good, **3.** bad, **4.** very bad. All relative to current situation
Level 1 *very good*	• Relax Article 9 with US support, ignore protests from key Asian countries & Russia • Japan **adopts** Willy Brandt like approach, apologizes and admits role in war crimes • Militarism declines. Class A war criminals' memorials removed from Yasukuni • Big increases in military spending, force structure improves dramatically • Launches unprecedented new trust-and-confidence, truth-and-reconciliation initiatives • Japan national image takes a strong positive turn, similar to today's Germany
Level 2 *good*	• Article 9 remains as is. Class A criminals' memorials remain from Yasukuni • Forceful and convincing civilian and NGO's present face of "new Japan" to world • Modest Uptick in economy • Modest increases in military spending, force structure improves • Trust and good will to Japan takes a cautious positive turn
Level 3 *bad*	• Article 9 distorted to the limit. Right wing militarism proliferates • Territorial ambitions and assertions intensify. Inflames many Asian countries and Russia • Trust and respect visibly erodes, tarnishes US image and efforts in Pacific region • Aging population accelerates, lethargic economy • No dramatic increase in military budget, strong effort to domestic economy
Level 4 *very bad*	• Article 9 revoked. US supports, ignoring protests from key Asian countries & Russia • Large increases in military spending, force structure improves dramatically • Ramps up aggressive Kabbuki denials/euphemisms. Tensions harden w/neighbors • Right-wing militarism swells. US tacit nod-&-wink erodes its moral high ground • China's gravitational pull strengthens relative to smaller ASEAN countries

9.2.5 Summary Discussion

We framed the US Navy Force Structure question as a "portfolio" of ships of different types and costs. We specified the three properties that we will measure.

- **Capacity**. Measured by the number of ships *in being*.
- **Cost**. Fleet cost measured by acquisition cost of each ship type and quantities of each ship type.
- **Power.** Overall ability of the fleet to satisfy its mandate: *Protect* the homeland, *Build* global security, *deter* adversaries, and *take action* if deterrence fails. Power is measured relative to the 308-ship fleet by naval and national security experts.

Table 9.18 Korean peninsula

Characteristics	Good or bad for Korea
Levels	**1.** very good, **2.** good, **3.** bad, **4.** very bad. All relative to current situation
Level 1 *very good*	• Power coup in North Korea. New leader takes over, but no change in iron fist • NK adopts Chinese model for market economy and communist party loosens • Chinese political coercion to NK works. Major nuclear concessions to Group 6 • SK economy improves, democracy stable • Japan right wing erodes. Relationships improve on positive trend
From level 2 *good*	• N.Korea "Yeltsin" assumes power. Communist party becomes one of many • NK Declares shift to market economy. But progress choppy & uneven • Initiates concrete improvements w/South Korea. Big industrial investments from SK follow. • SK economy and democracy strong • No change in China relations. Japan makes modest political concessions
Level 3 *bad*	• Kim remains entrenched. Nuclear and missile tests continues • NK Territorial ambitions remain at current levels • China relations colder. Japan right wing pressure stronger with US tacit support • SK economic competitiveness declines. Political turmoil continues unabated • SK Military expenditures increase with no visible improvements. Pay the US large
Level 4 *very bad*	• Kim remains in power. Visibly successful nuclear and missile tests. Scalability doubtful and a big drain on the economy • NK Large scale famine, economy on life support. Rejects all forms of foreign help. Large scale refugees flood to China and SK. Destabilizing riots in both countries • More SK economic decline, more political turmoil. More Japan right wing pressure. Russia inserts itself into the mix, increasing tensions • SK Military expenditures increase with no visible improvements. Pay to US is large and increasing, impacting the economy, SK resentment increases • SK turns to China a la Duterte

And we specified the managerially controllable and uncontrollable variables (Tables 9.6 and 9.14).

Therefore we have demonstrated that our methodology meets the criteria for X-RL1 (Table 9.24).

9.3 Engineering the Solution Space

9.3.1 Introduction

We must be able to construct the controllable space and the uncertainty space to collect data to design decision alternatives (Fig. 9.8).

Table 9.19 Germany

Characteristics	Good or bad for Germany
Levels	**1.** very good, **2.** good, **3.** bad, **4.** very bad. All relative to current situation
Level 1 *very good*	• Steps up commitment to EU and NATO, positive influence to region • Becomes default EU and NATO leader. Big contributions in military contributions • Economy is the locomotive for Europe. Democracy vigorous and stable • Actively works to reduce tensions in US, Russia, China, and Middle East • Makes strong positive influence and force in stabilizing Middle East
Level 2 *good*	• German attitude to EU and NATO unchanged. Prefers low profile • Forced to larger military contributions by US for financial and forces, deployment • Economy strongest in EU, but not pulling the rest. Stability envy of EU • Acts usefully as credible honest broker between Russia, China and US • Prefers to concentrates on economic development and exports
Level 3 *bad*	• German attitude to EU and NATO declines. In addition to Brexit, other weak economy/economies considerint exit also • Reluctantly agrees to symbolic increase in military contributions • Lifts Russian ban. Prioritizes oil gas over ideology in Middle East also • Consistently prioritizes economy, exports over ideology or multilateral obligations • Neo right-wing gaining visibility and popularity
Level 4 *very bad*	• German interest in EU and NATO minimal as its usefulness also minimal • Reluctantly agrees to larger military contributions. German military not a priority to its people • Will not get involved in international issues unless its economy is at risk • Behavior like a neutral country. Seeks stronger ties with Russia and China • Neo right-wing gains seats in Parliament, but remains small

9.3.2 The Controllable Space

The controllable space is the entire set of force structures that can be specified with our ten variables. Nine of which are specified at four levels and one at two levels (Table 9.6). The full factorial size of the possible combinations of variables at different levels is very large. It is in fact, 524,288, given by the equation:

$$N = 2^1 \times 4^9 = 524{,}288 \qquad (9.1)$$

The 308-ship force structure is just one of them. We show a few different force structures to illustrate the construction of this set of 524,288 possibilities, the resultant fleet size and ***R*** index. The symbol **# n** is a force structure sequence number, from 1 to 524,288. "lvl" is shorthand for level (Table 9.14). The entire list would have filled thousands of pages. A brute force search, of 524,288 alternatives, is not feasible to identify a force structure of the right mix, of reasonable cost and judged to be at least as good as the 308-ship fleet (Table 9.25).

We use Fig. 9.9 to collect data, with an efficiency of [1 − 36/(2*4^9)] = [1 − 36/524,288] = 99.9931%. The table is sufficient for us to make predictions

Table 9.20 Congressional military budget

Characteristics	Good or bad for **US military**
Levels	**1.** very good, **2.** good, **3.** bad, **4.** very bad. All relative to current situation
Level 1 *very good*	• Congress lifts budget constraints. Launches serious programs with alternative funding. USN refocus on lethality not just numbers. More emphasis on capability, readiness • US new policy reduces tensions vs China, Russia. Mid. East mess diminishes • EU, NATO, Japan step up military budgets in response to US demands • New geoecono-political thinking emerges. Less confrontational/adversary thinking
Level 2 *good*	• Modest relief to budget limitations. New alternative funding approach initiated • EU and NATO position unchanged. Prefers low profile, modest actions • US forces larger military contributions –financial and forces, deployment
Level 3 *bad*	• No change to sequestration. Same traditional funding processes, no new initiatives • EU and NATO weakens, in addition to Brexit, one more exits • Reluctantly agree to symbolic added military contributions
Level 4 *very bad*	• Congress imposes new rules on top of sequestration. Strong public support • Military protests without innovative alternatives. Myopic emphasis on capability precariously trading off capability and readiness • EU, NATO military budgets plunge. Focus on boosting weakening GDP's • Tensions rise vs China, Russia. China Russia bond tightens. Middle East mess worse. Large increase in military expenditures with minimal visible reduction in global tensions • Second tier countries "ally" with US as they try to "wag the dog" • US military prestige sinks. Neo right wing popularity rising in key countries

Table 9.21 Mediterranean region

Characteristics	Good or bad for **Mediterranean region**
Levels	**1.** very good, **2**. good, **3**. bad, **4**. very bad. All relative to current situation
Level 1 *very good*	• Collapse of ISIS, and strong decline in the credibility of its ideology throughout the region • Two state solution established • Jordan, Saudi Arabia and Israel establish formal alliance • No disruptions to navigation through the Strait of Bab-el-Mandeb
Level 2 *good*	• Status Quo Ante Iraq invasion March 2003
Level 3 *bad*	• Current state 2016
Level 4 *very bad*	• Iran controls Iraq. Iran goes nuclear • Turkey exits NATO and allies with Russia • EU collapses • Bab-el-Mandeb requires continuous US intervention for freedom of avigation

Table 9.22 Iran

Characteristics	Good or bad for **Iran**
Levels	**1.** very good, **2.** good, **3.** bad, **4.** very bad. All relative to current situation
Level 1 *very good*	• Dominates Iraq • Successfully tests nuclear weapon and missile delivery • US and EU actions ineffective. Israeli actions fail • Asserts control of strait of Hormuz
Level 2 *good*	• US Iran nuclear deals stands • More trade deals, Economy improves • Relations with Saudis improve
Level 3 *bad*	• Nuclear deals declared null by US. Sanctions restored • Nuclear program withers • Influence in Iraq drops
Level 4 *very bad*	• Economy is a disaster • Broad and frequent civil unrest • Political standing and influence at a nadir

Table 9.23 USA

Characteristics	Good or bad for **USA**
Levels	**1**. very good, **2.** good, **3.** bad, **4.** very bad. All relative to current situation
Level 1 *very good*	• Pax Americana resurgent • Economic growth restored for white & blue collar work. More evenly spread geographically • US acknowledged and accepted as military, economic and values leader
Level 2 *good*	• Status quo
Level 3 *bad*	• Economy stagnant. International political standoffs increases • Confidence erodes from US allies, EU, and NATO • Frequent confrontations with China
Level 4 *very bad*	• NK nuclear device test succeeds • Japan asks US to leave Yokosuka. Renounces Article 9 • Philippines follows suit for Subic Bay • Taiwan declares neutrality, makes major concessions to China • Hole in first island chain is created • NATO commitments erode • US moral stature erodes visibly, others countries step in to fill gaps

Table 9.24 X-RL1 Readiness level specifications for executive-management decisions

Readiness level	Our systematic process for the problem space	Efficacy
X-RL1 Characterize problem space	Sense making—uncomplicate cognitive load	☑
	Framing problem/opportunity–clarify boundary conditions	☑
	Specify goals and objectives	☑
	Specify essential variables Managerially controllable variables Managerially uncontrollable variables	 ☑ ☑

☑ indicates support is demonstrated

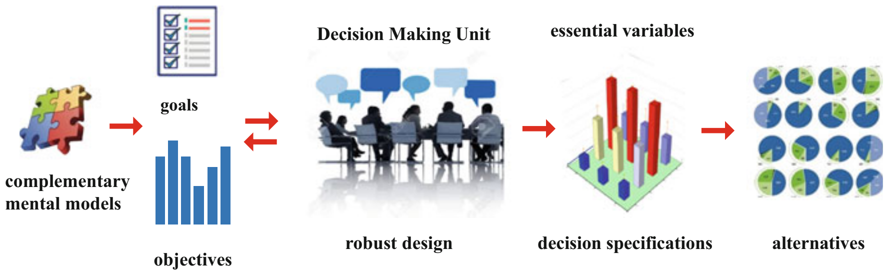


Fig. 9.8 DMU in the Solution Space

Table 9.25 Entire set of possible Force Structures

Force structure	SSBN	SSN	SSGN	CVN	DDG51	LCS/ FF	LPD	LHA	CLF	Other	Fleet size	R
# 1	**lvl 1**	**lvl 1**	**lvl 1**	**lvl 1**	**lvl 1**	**lvl 1**	**lvl 1**	**lvl 1**	**lvl 1**	**lvl 1**	**269**	$\boldsymbol{R_1}$
Quantity	10	40	0	9	79	47	18	9	26	31		
# 2	**lvl 2**	**lvl 1**	**lvl 1**	**lvl 1**	**lvl 1**	**lvl 1**	**lvl 1**	**lvl 1**	**lvl 1**	**lvl 1**	**271**	$\boldsymbol{R_2}$
Quantity	12	40	0	9	79	47	18	9	26	31		
# 3	**lvl 3**	**lvl 1**	**lvl 1**	**lvl 1**	**lvl 1**	**lvl 1**	**lvl 1**	**lvl 1**	**lvl 1**	**lvl 1**	**267**	$\boldsymbol{R_3}$
Quantity	0	40	0	9	79	47	18	9	26	31		
…	…	…	…	…	…	…	…	…	…	…	…	…
# 254,287	**lvl 4**	**lvl 4**	**lvl 4**	**lvl 4**	**lvl 4**	**lvl 4**	**lvl 4**	**lvl 4**	**lvl 4**	**lvl 3**	**378**	$\boldsymbol{R_{254,287}}$
Quantity	0	70	8	15	106	62	30	15	35	37		
# 254,288	**lvl 4**	**lvl 4**	**lvl 4**	**lvl 4**	**lvl 4**	**lvl 4**	**lvl 4**	**lvl 4**	**lvl 4**	**lvl 4**	**381**	$\boldsymbol{R_{254,288}}$
Quantity	0	70	8	15	106	62	30	15	35	40		

about any force-structure in the space of 524,288 alternative force-structures. The levels are represented by only one number, without the prefix **lvl**.

The DMU members populate the columns A, B, C, D, E, F and G. In Fig. 9.9 they are: A. authors of this chapter B. surface heavy officer C. submarine office D: marine officer E. hawk officer F. CNO staff officer G. frugal congressman.

The populated data sets are shown in Fig. 9.11 and Appendix 9.2.

9.3.3 The Uncontrollable Space

The discussion and data collection procedures discussed in Sect. 9.3.2. make one fundamental assumption: The operating environment is assumed to be **as-is**. That is to say that the external environment of the uncontrollable variables remain in their current state, not better, not worse. For a 30-year decision for the US Navy Force Structure, it is not reasonable that the uncertainty conditions will remain unchanged for 30 years. Which is why we will be design a force structure that is **robust**. Robustness means that the designed force structure will *satifice* even when the

	SSBN	SSN	SSGN	CVN	DDG51	LCS/FF	LPD	LHA	CLF	other	fleet size	∑cost $B	R index						
													A	B	C	D	E	F	G
# 1	1	1	1	1	1	1	1	1	1	1	269	$476.00							
# 2	1	1	2	2	2	2	2	2	2	2	301	$550.62							
# 3	1	1	3	3	3	3	3	3	3	3	327	$595.30							
# 4	1	1	4	4	4	4	4	4	4	4	361	$679.08							
# 5	1	2	1	1	2	2	3	3	4	4	318	$539.03							
# 6	1	2	2	2	1	1	4	4	3	3	313	$589.05							
# 7	1	2	3	3	4	4	1	1	2	2	334	$609.44							
# 8	1	2	4	4	3	3	2	2	1	1	325	$655.92							
# 9	1	3	1	2	3	4	1	2	3	4	334	$590.90							
# 10	1	3	2	1	4	3	2	1	4	3	349	$602.75							
# 11	1	3	3	4	1	2	3	4	1	2	321	$674.28							
# 12	1	3	4	3	2	1	4	3	2	1	327	$653.59							
# 13	1	4	1	2	3	3	3	4	2	1	344	$646.75							
# 14	1	4	2	1	4	4	4	3	1	2	360	$651.69							
# 15	1	4	3	4	1	1	1	2	4	3	326	$675.34							
# 16	1	4	4	3	2	2	2	1	3	4	343	$664.97							
# 17	2	1	1	4	1	4	2	3	2	3	308	$591.68							
# 18	2	1	2	3	2	3	1	4	1	4	312	$582.56							
# 19	2	1	3	2	3	2	4	1	4	1	323	$589.62							
# 20	2	1	4	1	4	1	3	2	3	2	323	$576.94							
# 21	2	2	1	4	2	3	4	1	3	2	325	$626.11							
# 22	2	2	2	3	1	4	3	2	4	1	318	$597.79							
# 23	2	2	3	2	4	1	2	3	1	4	330	$616.66							
# 24	2	2	4	1	3	2	1	4	2	3	325	$595.08							
# 25	2	3	1	3	3	1	2	4	4	2	334	$635.49							
# 26	2	3	2	4	4	2	1	3	3	1	342	$688.22							
# 27	2	3	3	1	1	3	4	2	2	4	333	$608.25							
# 28	2	3	4	2	2	4	3	1	1	3	337	$638.44							
# 29	2	4	1	3	4	2	4	2	1	3	345	$674.77							
# 30	2	4	2	4	3	1	3	1	2	4	347	$702.94							
# 31	2	4	3	1	2	4	2	4	3	1	347	$651.08							
# 32	2	4	4	2	1	3	1	3	4	2	336	$658.35							

Fig. 9.9 $L_{32}(2^1 \times 4^9)$ used to predict output of any of the 524,288 force structures

negative factors are not removed. This builds in a high degree of immunity to the decisions of the force structure.

The uncertainty conditions are determined by the uncontrollable variables, Sect. 9.3.2 and specified by Tables 9.15 through 9.23. We have nine uncontrollable variables, each at four levels of specification. The full factorial set of possible uncertainty conditions are:

$$U = 4^9 = 262{,}144 \tag{9.2}$$

And the *current uncertainty* condition is but one of them. Consider the size of the problem we started with. Ten controllable variables, nine of them at four levels, and one at two levels. Full factorial set of possible force structures configurations is:

$$N = 2^1 \times 4^9 = 524{,}288. \tag{9.3}$$

The entire solution space under all the uncertainty conditions are given by the product of Eqs. ((9.2)) and ((9.3)), for a total of:

$$N \times U = 524{,}288 \times 262{,}144 = 1{,}374{,}389{,}534{,}720 \tag{9.4}$$

which is a very large number of alternatives. How to simplify the problem for tractable analyses?

To simplify the uncertainty space, we discretize the uncertainty space into **uncertainty regimes**. An uncertainty regime is a specific configuration of uncertainty variables that represents a specific uncertainty condition. To simplify the analyses, we limit ourselves to three uncertainty regimes.

Worse or **better for the US is defined relative to** the **current** uncertainty condition the US Navy is facing now. More than three uncertainty regimes can be specified. For example by adding two more; such as, much worse-off, and much better-off. This complicates the analyses. But the DMU can decide the level of complexity and increased workload it wishes to assume.

- **Current uncertainty regime *facing the US Navy*.** Table 9.26. This is the representation of the current uncertainty condition. The descriptors are the level descriptors of the uncontrollable variables that collectively characterize the current situation facing the US Navy. For example, the Russia level-3 *bad*, describes a condition is that ***bad* for Russia,** which is most accurately describes the situation at the time of this writing. Similarly, China level-2 *good*, describes a condition which is ***good* for China**, and which most accurately describes the current situation at this time.
- **Worse uncertainty regime *for US* relative to what the US Navy is now facing.** Table 9.27. This represent the conditions that collectively characterize a worse situation than that facing the US Navy. They are the level descriptors of the uncontrollable variables. For example, China level-1 *very good*. This represents a ***very good*** condition ***for China***, but which makes it ***worse for the US*** relative to the current uncertainty regime in Table 9.26. As another example, consider Korea level-4, ***very bad***. This describes ***very bad*** situation **for Korea**, which makes the environment ***worse* for the US.**
- **Best uncertainty regime *for US* relative to what the US Navy is facing.** Table 9.28. This are the conditions that collectively characterize a better situation than the US Navy is now facing. They are the level descriptors of the uncontrollable variables. For example, China level-1 *very good*. This represents a ***very good*** condition ***for China***, but which makes it ***worse for the US*** relative to the current uncertainty regime in Fig. 9.10. As another example, consider Korea

Table 9.26 Current uncertainty regime facing the US Navy

Russia Level 3 *bad*	• Force structure maintained at *marginal*, lags EU and even Japan • Chinese Navy capability reaches parity with Russia • More erosion of relations with EU, NATO and US. But Chinese partnership improves • Can deploy only one theater, and with outdated ships and thin supply lines • Flat navy budget, can barely support military, weapons exports to sustain military
China Level 2 *good*	• Force structure selectively → *strong*, Capability & readiness improving steadily • EU relaxes some key high-tech military exports, need revenues from China • New military economic, and diplomatic initiatives show meaningful progress • Strong start on Kra & Honduras canals; Australia, Persian and Red Sea ports • Improvements in corruption and human rights. Party grip relaxes more • Sustain acceleration in military budget, economy slows but still one of the best WW
Japan Level 2 *good*	• Article 9 remains as is. Class A criminals' memorials remain in Yasukuni • Forceful and convincing civilian and NGO's present face of "new Japan" to world • Modest Uptick in economy • Modest increases in military spending, force structure improves • Trust and good will to Japan takes a cautious positive turn
Korea Level 3 *bad*	• Kim remains entrenched. Nuclear and missile tests continues • NK Territorial ambitions remain at current levels • China relations cooler. Japan right wing pressure stronger with US tacit support • SK economic competitiveness declines. SK political turmoil continues unabated • SK Military expenditures increase with no visible improvements. Pay the US large for military
Germany Level 2 *good*	• German attitude to EU and NATO unchanged. Prefers low profile, modest actions • Forced to larger military contributions by US for financial and forces, deployment • Economy strongest in EU, but not pulling the rest. Political stability envy of EU • Acts usefully as credible honest broker between Russia, China and US • Prefers to concentrates on economic development and exports
Congressional Budget Level **2** *good*	• Modest relief to budget limitations. Pilot alternative funding strategies initiated • EU and NATO position unchanged. Prefers low profile, modest actions • US forces larger military contributions –financial and forces, deployment
Med Sea & Middle East Level **3** *bad*	• Current state 2016
Iran Level 2 *good*	• US Iran nuclear deals stands • More trade deals, economy improves • Relations with Saudis improve
USA Level 2 *good*	• Status quo

Table 9.27 Worse uncertainty regime

Relative to the current condition facing the US Navy	
Russia Level 2 *good*	• Force structure improves to *strong*, but not to Cold War levels or China • Scale and scope of military and economic relationship with China strengthened • Overall diplomatic initiatives improve trust and image of Russia • Deploy in $\geq$ 1 naval theater, only with help from another country • Modest increase in military budget, economy grows but modestly
China Level 1 *very good*	• Force structure > US, but not tonnage. Better capability & readiness • Strong starts in Kra & Honduras Canal, Brazil-Peru transcontinental railroad, one-belt, one road, China Development Bank • Sought after for military, economic, diplomatic initiatives by many 2nd/3rd tier countries • Philippines, Myanmar, Cambodia, Laos, Thailand,. . . leaning to China • Battle groups confidently deploy beyond of 1st island chain • Large increase in military spending, economy reform & growth steady • Surprising reduced corruption and improving human rights. Party fist loosens
Japan Level 3 *bad*	• Article 9 distorted to the limit. Right wing militarism proliferates • Territorial ambitions and assertions intensify. Inflames Russia and many Asian countries • Trust and respect visibly erodes, tarnishes US image and efforts in Pacific region • Aging population accelerates, lethargic economy • No dramatic increase in military budget, strong effort to domestic economy
Korea Level 4 *very bad*	• Kim remains. Visibly successful nuclear and missile tests. Scalability doubtful • NK Large scale famine, economy on life support. Rejects all forms of foreign assistance. Large scale refugees to China and SK. No aid from other countries • More SK economic decline, more political turmoil, more Japan right wing pressure • SK Military expenditures increase with no visible improvements. Pay the US large • SK turns to China a la Duterte
Germany Level 3 *bad*	• German attitude to EU and NATO declines. In addition to Brexit, other(s) leaves • Reluctantly agrees to symbolic increase in military contributions • Lifts Russian ban. Prioritizes oil gas over ideology in Middle East also • Consistently prioritizes economy, exports over ideology or multilateral obligations • Neo right-wing gaining visibility and popularity
Congressional budget Level 3 *bad*	• No change to sequestration. Same traditional funding processes, no new initiatives • EU and NATO weakens, in addition to Brexit, one more exits • Reluctantly agree to symbolic added military contributions
Med Sea & Middle East Level 4 *very bad*	• Iran controls Iraq • Iran goes nuclear • Turkey exits NATO and allies with Russia • EU collapses

(continued)

Table 9.27 (continued)

Iran Level 1 *very good*	• Dominates Iraq • Successfully tests nuclear weapon and missile delivery • US and EU actions ineffective. Israeli actions fail • Asserts control of strait of Hormuz
USA Level 3 *bad*	• Economy stagnant. International political standoffs increases • Confidence erodes from US allies, EU, and NATO • Frequent aggressive confrontations with China. No weapons fired

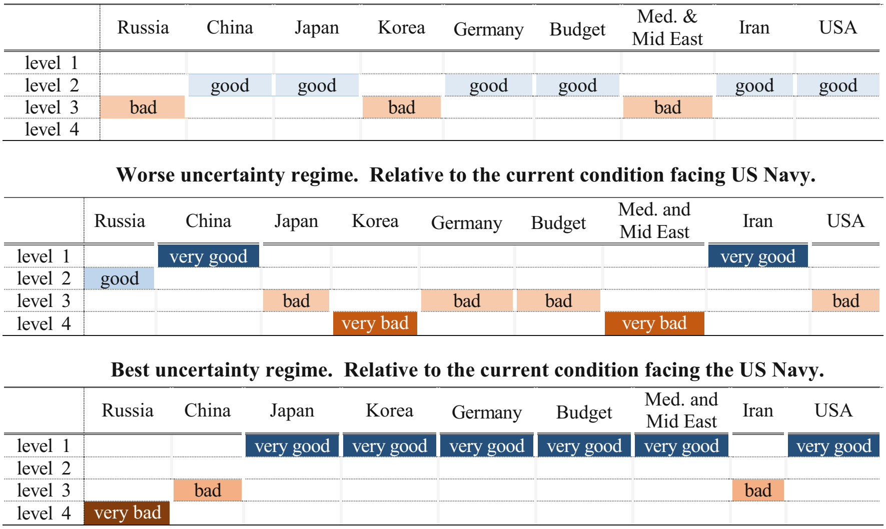
Table 9.28 Best uncertainty regime

Relative to the current condition facing the US Navy	
Russia Level 4 *very bad*	• Force structure weak to *marginal*, capability and readiness weakens • China Navy capability overtakes Russia • Except for nuclear weapons, navy not a factor to US, EU, NATO, or Japan • Heavy dependence on China for Pacific Ocean power projection and action • Licenses/Sells advanced naval technology to sustain military budget
China Level 3 *bad*	• Force structure remains at *marginal*, lags NATO and Japan. India catching up • Trying hard, but unconvincing on military, economic & diplomatic progress • Anemic gains in trust and cooperation with US, European, and Asian countries • No reversal evident on aging of population • More increase in military budget, stress on economy, improvements disappointing • No significant progress in corruption or improving human rights
Japan Level 1 *very good*	• Relax Article 9 with US support, ignore protests from key Asian countries & Russia • Japan **adopts** Willy Brandt like approach, apologizes and admits role in war crimes • Militarism declines. Class A war criminals' memorials removed from Yasukuni • Big increases in military spending, force structure improves dramatically • Launches unprecedented new trust-and-confidence, truth-and-reconciliation initiatives • Japan national image takes a strong positive turn, similar to today's Germany
Korea Level 1 *very good*	• Power coup in North Korea. New leader takes over, but no change in iron fist • NK adopts Chinese model for economy—market economy, communist party loosens • Chinese political coercion to NK works. Major nuclear concessions to Group 6 • SK economy improves, democracy stable • Japan right wing erodes. Relationships improve on positive trend
Germany Level 1 *very good*	• Steps up commitment to EU and NATO, positive influence to region • Becomes default EU and NATO leader. Big contributions in military contributions • Economy is the locomotive for Europe. Democracy vigorous and stable • Actively works to reduce tensions in US, Russia, China, and Middle East • Makes strong positive influence and force in stabilizing Middle East

(continued)

Table 9.28 (continued)

Congressional Budget Level 1 *very good*	• Congress lifts budget constraints. Launches serious programs with alternative funding. USN refocus on lethality not just numbers. More emphasis on capability, readiness • US new policy to reduce tensions vs China, Russia. Middle East mess diminishes • EU, NATO, Japan step up military budgets in response to US demands • New geoeconopolitical thinking emerges. Less confrontational/adversary thinking
Med Sea & Middle East Level 1 *very good*	• Collapse of ISIS • Two state solution established by Israel and Palestine • Jordan, Saudi Arabia and Israel establish formal alliance
Iran Level 3 *bad*	• Nuclear deals declared null by US. Sanctions restored • Nuclear program withers • Influence in Iraq drops
USA Level 1 *very good*	• Pax Americana resurgent • Economic growth restored for white and blue collar alike. More Evenly spread geographically • US acknowledged and accepted as military, economic and values leader



	Russia	China	Japan	Korea	Germany	Budget	Med. & Mid East	Iran	USA
level 1									
level 2		good	good		good	good		good	good
level 3	bad			bad			bad		
level 4									

Worse uncertainty regime. Relative to the current condition facing US Navy.

	Russia	China	Japan	Korea	Germany	Budget	Med. and Mid East	Iran	USA
level 1		very good						very good	
level 2	good								
level 3			bad		bad	bad			bad
level 4				very bad			very bad		

Best uncertainty regime. Relative to the current condition facing the US Navy.

	Russia	China	Japan	Korea	Germany	Budget	Med. and Mid East	Iran	USA
level 1			very good	very good	very good	very good	very good		very good
level 2									
level 3		bad						bad	
level 4	very bad								

Fig. 9.10 Summary of uncertainty regimes. Relative to the 308-ship force structure

level-4, ***very bad***. This describes a situation which is ***very bad*** **for Kore**a, which makes the environment ***worse*** **for the US.** Or the ***bad*** for Iran in the event the US restores sanctions and their nuclear arms industry withers.

These three uncertainty regimes are summarized in Fig. 9.10 in three panels, each representing an uncertainty regime. Their detailed specifications are in Tables 9.26, 9.27, and 9.28.

9.3.4 Establishing the Data Sets for the Solution Space

Figure 9.11 and in Appendix 9.4 give us the data required in all two uncertainty regimes to design robust force structure decisions. Given the 30-year time horizon of force structure decisions, robustness is very important. The first line in Fig. 9.11 is a hypothetical 321-ship case defined by us. This is used to establish a “base line”. This will be the topic of Sect. 9.3.4.1.

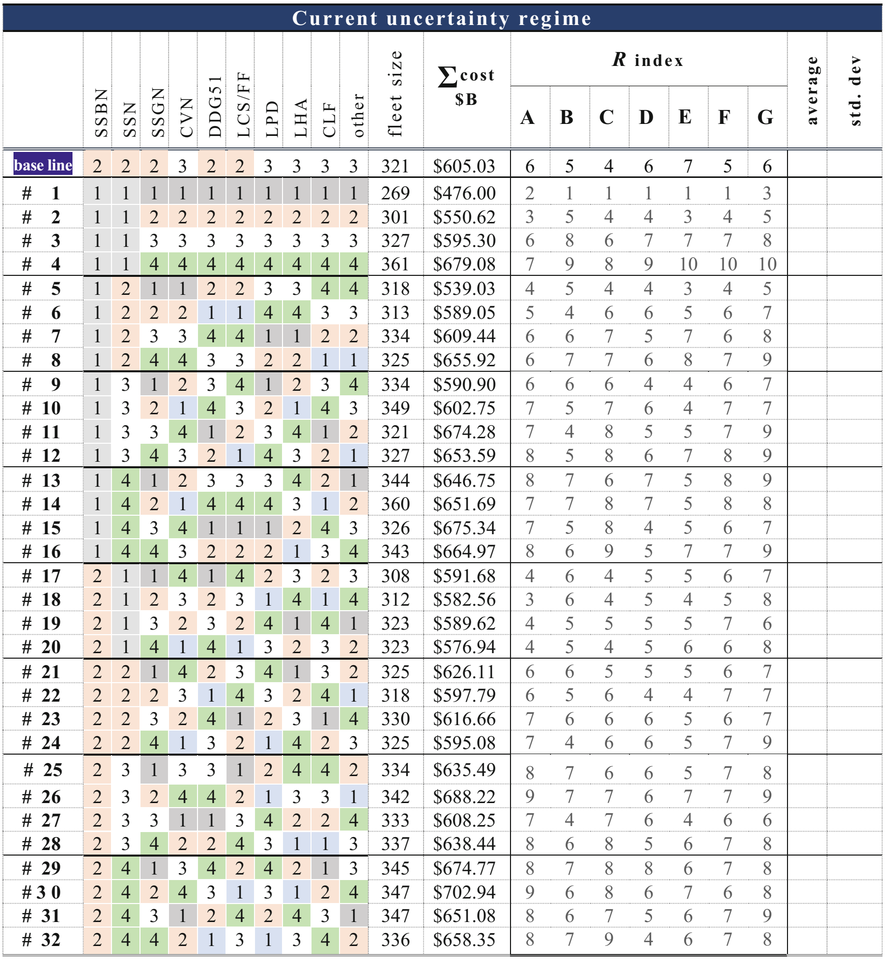
9.3.4.1 Base-Line

Data for the 321-ship base-line in Fig. 9.11 is the hypothetical 321-ship case. The row was populated by the authors acting in their role as synthetic DMU members. In practice, this work is completed by the DMU member using the de-biasing procedure, which we will describe in Sect. 9.3.4.2. The authors used a streamlined version of the process. However because it is a fundamental step in our executive-decision life-cycle with a full DMU quorum, we include a full description for completeness and understanding of the pernicious effect of bias on individual and group judgement.

Recent documents recommend force structures of 355-ships (e.g. Lewellyn et al. 2016; Clark et al. 2017) thus a “base line” of 321-ships is a reasonable place to locate this synthetic base line (Table 9.29).

9.3.4.2 Debiasing Procedure

The process of populating the base-line row with data is an important sociotechnical step. The objective is to obtain an $\boldsymbol{R}$ value to the “base” force structure configuration. A DMU member needs to form a judgement whether the US Navy is *better off* or *worse off* relative to the 308-ship fleet. In effect the DMU members are making ***an evaluation*** based on their individual **mental models** to forecast whether the US Navy will be better off, worse off. Thus this evaluation is also considered as a **forecasts** of an outcome. These individual mental models will be applied to all the



Current uncertainty regime

	SSBN	SSN	SSGN	CVN	DDG51	LCS/FF	LPD	LHA	CLF	other	fleet size	∑cost $B	R index							average	std. dev
													A	B	C	D	E	F	G		
base line	2	2	2	3	2	2	3	3	3	3	321	$605.03	6	5	4	6	7	5	6		
# 1	1	1	1	1	1	1	1	1	1	1	269	$476.00	2	1	1	1	1	1	3		
# 2	1	1	2	2	2	2	2	2	2	2	301	$550.62	3	5	4	4	3	4	5		
# 3	1	1	3	3	3	3	3	3	3	3	327	$595.30	6	8	6	7	7	7	8		
# 4	1	1	4	4	4	4	4	4	4	4	361	$679.08	7	9	8	9	10	10	10		
# 5	1	2	1	1	2	2	3	3	4	4	318	$539.03	4	5	4	4	3	4	5		
# 6	1	2	2	2	1	1	4	4	3	3	313	$589.05	5	4	6	6	5	6	7		
# 7	1	2	3	3	4	4	1	1	2	2	334	$609.44	6	6	7	5	7	6	8		
# 8	1	2	4	4	3	3	2	2	1	1	325	$655.92	6	7	7	6	8	7	9		
# 9	1	3	1	2	3	4	1	2	3	4	334	$590.90	6	6	6	4	4	6	7		
# 10	1	3	2	1	4	3	2	1	4	3	349	$602.75	7	5	7	6	4	7	7		
# 11	1	3	3	4	1	2	3	4	1	2	321	$674.28	7	4	8	5	5	7	9		
# 12	1	3	4	3	2	1	4	3	2	1	327	$653.59	8	5	8	6	7	8	9		
# 13	1	4	1	2	3	3	3	4	2	1	344	$646.75	8	7	6	7	5	8	9		
# 14	1	4	2	1	4	4	4	3	1	2	360	$651.69	7	7	8	7	5	8	8		
# 15	1	4	3	4	1	1	1	2	4	3	326	$675.34	7	5	8	4	5	6	7		
# 16	1	4	4	3	2	2	2	1	3	4	343	$664.97	8	6	9	5	7	7	9		
# 17	2	1	1	4	1	4	2	3	2	3	308	$591.68	4	6	4	5	5	6	7		
# 18	2	1	2	3	2	3	1	4	1	4	312	$582.56	3	6	4	5	4	5	8		
# 19	2	1	3	2	3	2	4	1	4	1	323	$589.62	4	5	5	5	5	7	6		
# 20	2	1	4	1	4	1	3	2	3	2	323	$576.94	4	5	4	5	6	6	8		
# 21	2	2	1	4	2	3	4	1	3	2	325	$626.11	6	6	5	5	5	6	7		
# 22	2	2	2	3	1	4	3	2	4	1	318	$597.79	6	5	6	4	4	7	7		
# 23	2	2	3	2	4	1	2	3	1	4	330	$616.66	7	6	6	6	5	6	7		
# 24	2	2	4	1	3	2	1	4	2	3	325	$595.08	7	4	6	6	5	7	9		
# 25	2	3	1	3	3	1	2	4	4	2	334	$635.49	8	7	6	6	5	7	8		
# 26	2	3	2	4	4	2	1	3	3	1	342	$688.22	9	7	7	6	7	7	9		
# 27	2	3	3	1	1	3	4	2	2	4	333	$608.25	7	4	7	6	4	6	6		
# 28	2	3	4	2	2	4	3	1	1	3	337	$638.44	8	6	8	5	6	7	8		
# 29	2	4	1	3	4	2	4	2	1	3	345	$674.77	8	7	8	8	6	7	8		
# 30	2	4	2	4	3	1	3	1	2	4	347	$702.94	9	6	8	6	7	6	8		
# 31	2	4	3	1	2	4	2	4	3	1	347	$651.08	8	6	7	5	6	7	9		
# 32	2	4	4	2	1	3	1	3	4	2	336	$658.35	8	7	9	4	6	7	8		

A:authors, **B**:surface heavy, **C**:submariner, **D**:marine, **E**:hawk, **F**:CNO staff, **G**:frugal congressman

Fig. 9.11 Data set from DMU for current uncertainty regime

Table 9.29 The BASE-LINE force structures

	SSBN	SSN	SSGN	CVN	DDG51	LCS/FF	LPD	LHA	CLF	Other	Total	R^{DMU}
BASE-LINE												
var. level	2	2	3	2	3	2	3	3	3	3		TBD
Quantity	12	48	6	11	97	52	24	12	32	37	**331**	
Σ cost $B	58.8	137.8	29.40	141.9	111.6	29.95	39.0	40.8	17.57	5.55	**$612.28**	

32 entries of the $\mathbf{L_{32}}$ $\mathbf{(2^1 \times 4^9)}$ array. Our goal is to diminish bias in these evaluative forecasts as much as possible.

Bias is a class of flaws in judgment caused by mental or social motives that distort reality. They lead people or groups to make incorrect, illogical, or inconsistent inferences about decision situations (e.g. Kahneman and Tversky 2000; Ariely 2008). At the group level, Janis (1983) coined the term *groupthink*. Groupthink is the phenomenon wherein people succumb to peer pressure and suspend critical thinking that negatively influence their judgement. He describes Kennedy's meetings to discuss the invasion of the Bay of Pigs during the Cuban missile crisis. This case has become the poster child of groupthink. Kennedy and his advisors collectively surrendered to wishful thinking. Essser (1998) reports that groupthink is not uncommon. It is persistent. *Risky Shifts*, is a form of group bias. Risky shifts occur when a group adopts a position, which is more extreme than any one person would choose individually; looting, riots during soccer matches, the dot com bubble are examples of risky shifts. At the individual single-person level, biases are well researched and documented by scholars. Kahneman (2002) was awarded a Nobel in economics for pioneering research on personal bias. Baron (2000) discusses over 40 types of bias, and Eisenführ et al. (2010) describe over two dozen. Bias is like noise and friction in the physical world. It is always present and very difficult to eliminate.

The important question is how to mitigate the pernicious effect of biases during the management decision process. This problem is particularly acute in forecasting. We present actionable technical and social procedures, grounded on managerial practice and research findings, on ways to mitigate individual and group biases in forecasting. This has direct applicability to the task at hand, i.e. evaluating and determining the effect of different force structures on the US Navy.

Why is debiasing the judgements on the base-line force structure so important? It is important because we do not want the bias to propagate throughout the process of determining the ***R*** index of force structure configurations. The objective is not for all the DMU to develop the same identical mental model. We want the DMU members to develop more complete and nuanced individual mental models that cohere integratively more correctly (e.g. Ashton 1985). For example, a manufacturing executive, a sales executive, and a technology executive will necessarily have distinct mental modes, by they must cohere for common purpose and coherent action.

Our procedure is designed to diminish information-asymmetry in the DMU. Also to avoid specious anchoring (e.g. Baron 2000) and false convergence. Key to the evaluation and determination of the ***R*** indices is that they must be held private. Disclosure and discussion in the DMU is prohibited. We include counter-argumentation procedures to reduce systematic biases by insisting on explicit, ***but*** anonymous, articulation of the reasons why an evaluation might be correct ***and*** why incorrect (Fischhoff 1999; Russo and Schoemaker 1992; Arkes 2001; Koriat et al. 1980). Counter-argumentation improves the DMU's effectiveness in problem solving by enriching and complementing team members' individual mental models (Mohammed et al. 2010; Mohammed and Dumville 2001; Kray and Galinsky 2003; Lerner and Tetlock 2003). Winquist and Larson (1998) show that information pooling of shared fresh information improves decision quality and conceptualization (Sects. 3.3.5 and 3.3.6). The exact procedure follows next.

Establishing the base line ***R*** index is done in two rounds. In the first round, we obtain an initial evaluation of the base-line from the DMU members. This is to prepare them for the work of populating the entire data set in the other uncertainty regimes. We begin by asking each DMU member to ***independently*** evaluate the base force structure configuration and assign it an ***R*** score. The DMU is reminded that an evaluation is an informed professional judgement, an estimate (March 1997). The DMU are reminded of two rules. **No disclosure of the evaluations and no discussions among DMU members.** We want to avoid peer pressure that can lead to false convergence in the numbers (Mest and Plummer 2003; Hanson 1998; Boje and Mirninghan 1982). This also mitigates the so-called "herd effect", social pressure that drives the DMU to mimic someone else's evaluations with numbers that cluster and falsely converge (e.g. Hanson 1998; Sterman 2000). Each DMU member is then requested to record their confidence-level on a confidential form provided.

The second round concentrates on debiasing and developing an updated judgement of an ***R*** index. This is a process of counter-argumentation and accountability. We request each DMU member to write three reasons why their evaluation forecast is accurate, and three other reasons why their forecast is not accurate. The DMU members are reminded of two more rules. **All inputs are anonymous, no names on the inputs, and no discussions.** Their inputs are printed so that handwriting is not used to recognize the authors. This gives us a total of 15 reasons why the evaluations are considered to be accurate and 15 opposing reasons. We ask the DMU members to read all 30 reasons and then to discuss them. This is a form of accountability, to explain the reasons behind judgments and actions (Lerner and Tetlock 2003). Accountability generates feedback, which improves performance, particularly in groups (Hastie 1986; Hastie and Kameda 2005).

At the end of this discussion, the DMU is requested to again evaluate the base force structure and to record their confidence level once more. The goal for this iterative procedure is to promote organizational learning. Nobel Laurate Simon (2001) writes:

> What an individual learns in an organization is very much dependent on what is already known to (or believed by) other members and what kinds of information are present in the organizational environment... an important component or organizational learning is internal learning—that is transmission of information from one organizational member or group of members to another.

Those familiar with the Delphi Method will find similarities with our base-line and debiasing procedure. However, our process improves the traditional Delphi process. We address the information asymmetry issue of decisions and forecasting, by **not** starting **nor** concentrating on the numbers, but rather on the issue of incomplete and asymmetric **mental models**. Delphi is a group forecasting technique for participants to anonymously exchange and modify data, among each other, over several rounds. The data is then aggregated to a number representing the group's consensus. The goal is to improve forecasting accuracy by having participants reflect, about supporting or opposing inputs, and make adjustments. Delphi is intended to stimulate participants' desire for accuracy, while suppressing detrimental social pressures from its members. Sniezek and Henry (1989) report "group judgements were, with few exceptions more accurate than mean or median individual judgments … Furthermore, 30% of the group's judgement were *more* accurate than the group's *most* accurate individual judgement." Studies show Delphi improves accuracy over other methods (e.g. Rowe et al. 2005; Rowe and Wright 2001). Yousoff (2007) and Hsu & Sanford (2007) present the pros and cons of Delphi. A common failure is ignoring and exploring disagreements, so that an artificial consensus is likely to be generated. **We think that Delphi emphasizes numbers and much less the logic of the numbers.** In our approach, we modified key Delphi method attributes as follows:

1. the anonymity requirement in our process requires non-disclosure of the participants' figures. This has a positive ameliorating effect on anchoring bias, which usually induces negative effects on judgements.
2. the interactions are not based on numbers; but based on *rationale* of member's judgments. The rationale is also anonymous. The input is anonymous, but the discussions about the anonymous input are not. Our procedure requires for the participants discuss the rationales without being able to attribute their source. This is designed to avoid defensiveness and social pressure.
3. though the forecast numbers are not disclosed, so that no one knows their peers' figures, the interactions among members are not anonymous. The discussions are face-to-face in an open meeting format. The discussions are focused on the logic of numbers, not defending numbers.
4. the feedback documented by the participants are not designed to explain adjustment to numbers, but to explicitly give reasons why their figures are right and equal number of reasons why not. Our focus is centered on the participants' mental models, to frame the task of evaluation, in a more complete, richer and with diminished biases.
5. we use confidence, rather than consensus of forecast figures, as an indicator of forecasting accuracy. There is a body of research that supports this hypothesis. Sniezek and Henry (1989) Sniezek (1992) report that group confidence is positively correlated with accuracy. Rowe et al. (2005) write "that not only accuracy tends to increase across rounds in Delphi-like conditions, but subjects' confidence assessments also become more appropriate."
6. We address uncertainty very directly and specifically using uncontrollable variables and uncertainty regimes.

Upon completion of this process, the numbers are recorded. The averages and the standard deviation entries in the Tables are calculated. These data will be used to explore the Operations Space.

9.3.5 Summary Discussion

The objective of this section has been to verify the efficacy of our methodology for the Solution Space. Namely, can a DMU use our methodology to systematically specify the entire solution space and the spectrum of uncertainty regimes, the base line, and finally debias it effectively. We can:

Fig. 9.12 Schematic of the operations space

- Specify the managerially controllable and uncontrollable variables.
- Specify the uncertainty conditions with a spanning set of uncertainty regimes.
- Specify the construct for the solution space.
- Systematically collect and debias the data.

Table 9.30 summarizes the efficacy of this phase of the methodology.

9.4 Exploring the Operations Space

9.4.1 Introduction

The next step is to be able to develop a series of decision alternatives from which a choice alternative that satisfices intended goals and objectives can be found. This step begins with the DMU populating the entire L_{32} $(2^1 \times 9^4)$ data set (Fig. 9.11). To this end, we use the DOE methodology (e.g. Creveling et al. 2002; Montgomery 2008; Phadke 1989; Otto and Wood 2001) with our gedanken experiments. In this example, the DMU is a synthetic social construction, comprised of the authors of this chapter and six synthetically formed members to follow profiles concentrated on professional discipline. They are: the authors, a surface heavy officer, a submarine officer, a marine officer, a naval hawk, a CNO staff officer, and a frugal congressman (Sect. 9.2.2) (Fig. 9.12).

Table 9.30 Readiness level specifications for executive decisions

Readiness level	Systematic process for the solution space	Efficacy
X-RL2 Engineer solution space	Specify subspaces of solution space Alternatives space and uncertainty space	☑
	Specify entire solution space	☑
	Specify base line and uncertainty regimes Do-nothing case and choice-decision Estimate base line and dispel bias	▣

The symbol ☑ indicates support is demonstrated
▣ synthetically demonstrated

9.4.2 Analyses

In this step, we analyze the summary statistics of the data set and the DMUs forecasting capability. In other words, are the data something we can use and learn from? We will be discussing the Operations Space for the Current Uncertainty Regime. The data for the Worse Uncertainty Regime are shown in Appendix 9.2. The Best Uncertainty Regime is omitted; it does not appear very realistic at this book goes to press. The current US administration and the geopolitical situations in various regions do not animate interest to study that case. Instead, we will study a composite case of the current and worse uncertainty regime. It is from this case that will design a robust force structure to compare and contrast against the current and worse uncertainty regime.

9.4.2.1 ANOVA Summary Statistics

Table 9.31 is the ANOVA table for the DMU forecast for force-structure R-value relative to the 308-ship structure under the **current uncertainty regime**. Eight variables have $p << 0.05$ and strong associated F values. These variables are strong predictors of the ***R***-value. The two variables of SSBN and OTHER have $F > 5$ and $p \approx 0.05$, adequate but not as very strong relative the other variables. SSNs (it has the highest Adj MS) are the most influential in determining the relative superiority of the force structure. DDGs are next, closely followed by CVNs. Residuals are random; they do not carry information. The residuals have mean of “zero” (-6.59195E-17), pass the Anderson-Darling test for normality with $AD = 0.422$ and $p = 0.303$.

The ANOVA table for the DMU forecast for force-structure ***R***-index under the **worse uncertainty regime** is in Appendix 9.3. A summary of the ANOVA statistics for the current and worse uncertainty regimes are shown in Table 9.32.

9.4.2.2 Response Tables Under Current Uncertainty Regime

We now turn our attention to the response tables. We will use them to construct alternatives. In the upper panel of Table 9.33 is the response table for the controllable variables. In the bottom panel is the table for the standard deviations for these variables. Figures 9.13 and 9.14 present the same Table information in graphical form.

Table 9.31 ANOVA Table for team forecasts for current uncertainty regime

Analysis of variance for Means—current uncertainty regime						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
SSBN	1	0.1552	0.1552	0.15520	7.40	0.073
SSN	3	13.0193	13.0193	4.33978	206.96	0.001
SSGN	3	9.9547	9.9547	3.31825	158.24	0.001
CVN	3	9.0614	9.0614	3.02048	144.04	0.001
DDG	3	9.7725	9.7725	3.25750	155.35	0.001
LCS/FF	3	3.6124	3.6124	1.20413	57.42	0.004
LPD	3	5.3563	5.3563	1.78543	85.14	0.002
LHA	3	4.3670	4.3670	1.45568	69.42	0.003
CLF	3	0.6409	0.6409	0.21362	10.19	0.044
Other	3	0.2557	0.2557	0.08522	4.06	0.140
Error	3	0.0629	0.0629	0.02097		
Total	31	56.2584				

Table 9.32 ANOVA for team forecasts for current, worse uncertainty conditions

	ANOVA for R-index forecasts					
	Current uncertainty regime			Worse uncertainty regime		
	adj MS	%	p	adj MS	%	p
SSGN	0.15520	0.82	0.073	0.32000	1.69	0.007
SSN	4.33978	23.02	0.001	4.31521	22.81	0.002
SSGN	3.31285	17.57	0.001	3.10804	16.43	0.003
CVN	3.02048	16.02	0.001	3.24974	17.18	0.003
DDG51	3.25750	17.28	0.001	3.34247	17.67	0.003
LCS/FF	1.20413	6.39	0.004	1.11253	5.88	0.003
LPD	1.78543	9.47	0.002	1.53567	8.12	0.008
LHA	1.45568	7.72	0.003	1.44535	7.64	0.009
CLF	0.21362	1.13	0.044	0.21827	1.15	0.115
Other	0.08522	0.45	0.140	0.22283	1.18	0.112
Error	0.02097	0.11		0.04539	0.24	
Total		100	–		100	–

Visual inspection of Fig. 9.13 leads us to some observations. The number of SSBN's produce negligible value to the force structure. SSNs has the most pronounced incremental effect and its importance to the force structure is apparent. The impact, of an inventory of six (level-3) SSGNs versus four at level-2, is very small. CVNs exhibit diminishing returns from level-3 to level-4, *viz.* from 12 carriers to 15 carriers, the increase in ***R***-index is proportionally smaller than form level-1 to level-2 or level-2 to level-3.

The US has the most formidable carrier fleet in the world, combined with the carriers from its allies in NATO, the combined number is very substantial. China has only one carrier with virtually no experience in its use or deployment, Russia

Table 9.33 Response Table for team forecasts for current uncertainty regime

Response Table for Means current uncertainty regime hand-filled sheet

Level	SSBN	SSN	SSGN	CVN	DDG	LCS/ FF	LPD	LHA	CLF	Other
1	6.127	5.343	5.454	5.450	5.571	5.725	5.561	5.773	6.002	6.089
2	6.266	5.888	6.039	5.946	5.759	6.077	6.186	5.905	6.136	6.134
3		6.525	6.284	6.604	6.534	6.350	6.352	6.437	6.379	6.314
4		7.030	7.009	6.786	6.921	6.634	6.688	6.670	6.270	6.248
Delta	0.139	1.688	1.555	1.336	1.350	0.909	1.127	0.896	0.377	0.225
Rank	10	1	2	4	3	6	5	7	8	9

Response Table for Standard Deviations current uncertainty regime hand-filled sheet

Level	SSBN	SSN	SSGN	CVN	DDG	LCS/ FF	LPD	LHA	CLF	Other
1	1.1066	1.0423	0.9227	1.1340	1.2060	1.0571	1.2581	1.0476	1.0960	1.0691
2	1.1497	0.9902	1.1488	1.0782	1.1388	1.1167	1.0573	1.0671	1.2068	1.1335
3		1.2090	1.1078	1.1469	1.1438	1.2198	1.1280	1.1011	1.0483	1.1642
4		1.2711	1.3332	1.1534	1.0239	1.1190	1.0691	1.2967	1.1614	1.1457
Delta	0.0431	0.2809	0.4105	0.0751	0.1820	0.1627	0.2007	0.2491	0.1585	0.0951
Rank	10	2	1	9	5	6	4	3	7	8

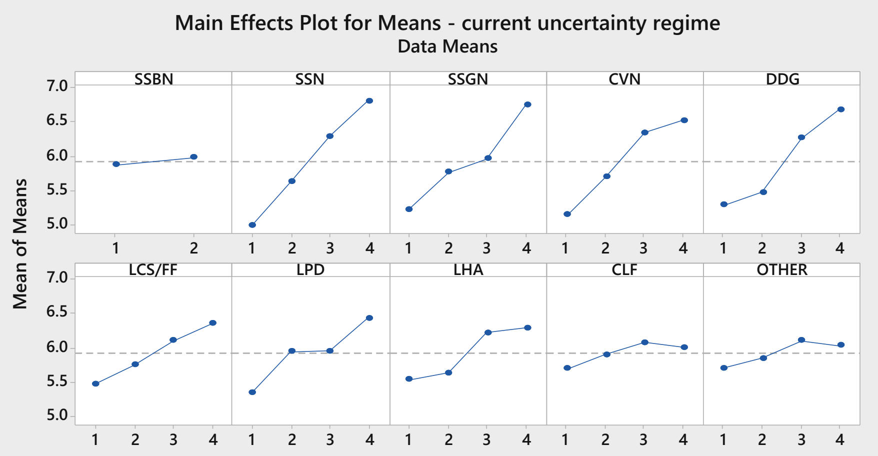


Fig. 9.13 Response plots for the R-value in the current environment

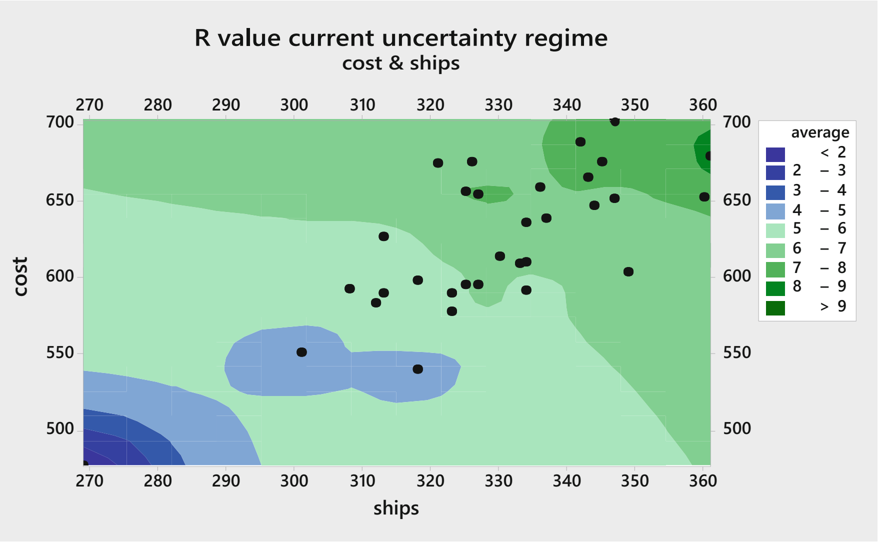


Fig. 9.14 Contour plot for the R-value, cost and number of ships

has one very aging carrier. These facts are reflected in the CVN ***R***-index evaluations. LHAs and CLFs appear worrisome. These could be a vulnerable nexus. Jomini (quoted in Handel 2007, 38) writes: "Strategy … is the art of bringing the greatest part of an army of the forces of an army upon the important point of the theater of war or zone of operations." Logistics support is not something that can neglected.

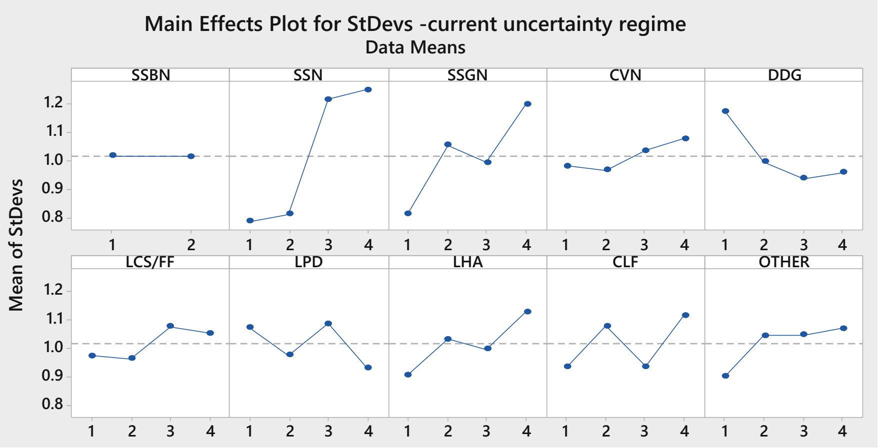


Fig. 9.15 Response plots for the R-value standard deviations in the current environment

Using Fig. 9.11 data, we can produce a contour plot of the relationship of the ships, cost and ***R***-index (Fig. 9.14). The black dots represent the 32 experiments. There is a general tendency for ***R***-index to rise as more ships and more cost from acquisition expenditures. This pattern is consistent with our intuition and domain knowledge of the problem. This is known as ***face validity*** (Yin 2013).

We now turn our attention to the standard deviations of the R-indices (Fig. 9.15). An advantage, of a four-level specification, for the forecasts is apparent from Fig. 9.15. We take standard deviation as an indicator of risk, standard deviation indicates an inability to know for certain. Having ten or twelve SSBNs is not a risky decision for the relative capacity superiority of the force structure. The standard deviation for SSBN is almost flat. The standard deviation for SSGNs actually diminish between level-2 and level-3. On the other hand, having more DDGs is not a risky decision.

All this information is put together to design decision alternatives in Sect. 9.4.3.

9.4.3 Synthesis: Construction and Analysis of Alternatives

9.4.3.1 Alternatives

We designed eight alternative force structures, of different characteristics, for two reasons. First, we wanted to design these different force structures for each "DMU member" to forecast its ***R***-index relative to the 308-ship fleet and populate the entire L_{32} array (Fig. 9.9). The DMU members are identified as A, B. C, D, E, F, and G. With this data, we want to use our methodology to predict the ***R***-index by comparing the predicted value versus the DMU assessment. We can then evaluate the predictive power of our methodology. Second, we want to show how to design robust decisions. A robust decision is one that is highly immune to uncontrollable variables even when they are not removed. Robustness reduces the down-side risk of decisions.

In practice, participation in a DMU for this kind of exercise is necessarily highly selective with experienced subject-matter experts. Each person would have specialized expertise acquired not only through hands-on practice and professional training but also honed in positions of high command. Each is expected to represent their branch of the Navy while simultaneously considering the needs of national security. The eight test experiments were designed with this kind of group mix (Table 9.34). The experiments were:

Table 9.34 Hypothetical force structures

	SSBN	SSN	SSGN	CVN	DDG51	LCS/FF	LPD	LHA	CLF	Other	Total	*R*
DREAM												
var. level	2	4	4	4	4	3	3	3	4	3		**10**
Quantity	12	70	8	15	106	57	24	12	37	37	**378**	
Σ cost $B	58.8	200.9	39.2	193.5	121.9	32.83	39	40.8	20.31	5.55	**752.8**	
DISASTER												
var. level	1	1	1	1	1	2	1	1	1	1		**1**
Quantity	10	40	0	9	79	52	18	9	23	31	**271**	
Σ cost $B	49	114.8	0	116.1	90.85	29.95	29.25	30.6	12.63	4.65	**477.83**	
SURFACE HEAVY												
var. level	2	2	1	2	4	4	3	3	3	2		**8**
Quantity	12	48	0	11	106	62	24	12	32	34	**341**	
Σ cost $B	58.8	137.8	0	141.9	121.9	37.51	39	40.8	17.57	5.1	**598.54**	
MARINE HEAVY												
var. level	2	2	2	2	3	2	4	4	3	3		**7**
Quantity	12	48	4	11	97	52	30	15	32	37	**338**	
Σ cost $B	58.8	137.8	19.6	141.9	111.6	29.95	48.75	51	17.57	5.55	**$622.43**	
FRUGAL												
var. level	1	1	1	1	2	1	2	1	2	1		**2**
Quantity	10	40	0	9	88	47	22	9	26	31	**282**	
Σ cost $B	49	114.8	0	116.1	101.2	27.07	35.75	30.6	14.27	4.65	**$493.45**	
308-SHIP												
var. level	2	2	2	2	2	2	2	2	2	2		**5**
Quantity	12	48	4	11	88	52	22	11	26	34	**308**	
Σ cost $B	58.8	137.8	19.6	141.9	101.2	29.95	35.75	37.4	14.27	5.1	**$581.74**	
BASE-LINE												
var. level	2	2	3	2	3	2	3	3	3	3		**6**
Quantity	12	48	6	11	97	52	24	12	32	37	**331**	
Σ cost $B	58.8	137.8	29.4	141.9	111.6	29.95	39	40.8	17.57	5.55	**$612.28**	
PACIFIC PIVOT												
var. level	2	3	3	2	3	3	2	2	3	2		**8**
Quantity	12	60	6	11	97	57	22	11	32	34	**342**	
Σ cost $B	58.8	172.2	29.4	141.9	111.6	32.83	35.75	37.4	17.57	5.1	**$642.50**	

1. DREAM fleet. This is the force structure that the DMU would create if there were no constraints, financial, political, or otherwise.
2. DISASTER fleet. This the force structure that is considered so anemic that it would be a disaster to national security. The US would not be credible to our allies as a defensive force for world peace.
3. SURFACE HEAVY fleet. This fleet emphasizes surface combatants to engage an enemy on the ocean surface or littoral zones, as well as, to deny the enemy access to the ocean.
4. MARINE HEAVY fleet. This fleet favors amphibious warfare, i.e. using naval and ground forces to assault and occupy enemy shores as a pre cursor to large scale deployment of ground forces to control enemy territory.
5. FRUGAL fleet. Building ships for a fleet is an expensive undertaking. An attack submarine can cost \$2.87 billion and an aircraft carrier \$12.90 billion. A person who fits the Frugal Congressman's profile will serve to remind the DMU that taxpayers are footing the bill. This officer also serves to remind the DMU that "there is no free lunch".
6. 308-SHIP fleet. This is the benchmark to calibrate whether a specific force structure will make the US better-off or worse-off using an ordinal scale of one to ten. This is called the ***R*** *index.*
7. BASE-LINE fleet. This is a base-line we specified that is incrementally more aggressive than the 308-ship fleet.
8. PACIFIC PIVOT fleet. This fleet was constructed on the assumption that the US has strong and emphatic need of a strong fleet in the Pacific to address the US Navy's potential requirements near North Korea, Russia, and China. It is the fleet that apparently Japan needs to feel secure.

Table 9.34 shows the required specification for the controllable variables' levels. For example, the DREAM fleet requires CVNs at level-4 of 15 carriers, each costing \$12.9 B for a total of \$193.5 B. The total column tallies the accumulated number of ships and cost. The ***R*** column are the forecast by the DMU as a unit. Can we predict these forecasts? How strong is the predictive power of our paradigm?

Using the Response Table of Means data in Table 9.33, we can predict the ***R*** index for the *SURFACE-HEAVY* fleet of configuration (2,2,1,2,4,4,3,3,3,2). In Sect. 5.4.3 we showed how to do so using the Analysis of Means method (ANOM). First, we calculate the grand average m of responses,

$$\begin{aligned}\mathbf{m} &= \text{average}(SSBN\,\text{responses}) = ½[6.127 + 6.266)\big] = 6.197\\ &= \text{average}(SSN\,\text{responses}) = ¼[5.343 + 5.888 + 6.525 + 7.030]\\ &= \text{average}(SSGN\,\text{responses})\\ &= \text{average}(CVN\,\text{responses}) = \text{average}(DDG\,\text{responses})\\ &= \text{average}(LCS/FF\,\text{responses})\\ &= \text{average}(LPD\,\text{responses}) = \text{average}(LHA\,\text{responses}) = \text{average}(CLF\,\text{responses})\\ &= \text{average}(OTHER\,\text{responses}) = 6.197\end{aligned}$$

Then to get the predicted response for DREAM (2,2,1,2,4,4,3,3,3,2) in the current uncertainty regime,

$$\begin{aligned} \boldsymbol{R}_{SURFACE-HEAVY} &= 6.197 + (\mathrm{SSBN2} - \mathrm{m}) + (\mathrm{SSN2} - \mathrm{m}) + (\mathrm{SSGN1} - \mathrm{m}) \\ &+ (\mathrm{CVN2} - \mathrm{m}) + (\mathrm{DDG4} - \mathrm{m}) + (\mathrm{LCS/FF4} - \mathrm{m}) + (\mathrm{LPD3} - \mathrm{m}) \\ &+ (\mathrm{LHA3} - \mathrm{m}) + (\mathrm{CLF3} - \mathrm{m}) + (\mathrm{OTHER2} - \mathrm{m}) \end{aligned}$$

Where the number suffix denotes the level of the specified variable. For example, SSBN2 = 6.266, obtained from the Response Table of Means and m = 6.197.

Hence, we get:

$$\begin{aligned} R_{SURFACE-HEAVY} &= 6.197 + (6.226 - \mathrm{m}) + (5.888 - \mathrm{m}) + (5.454 - \mathrm{m}) \\ &+ (5.946 - \mathrm{m}) + (6.921 - \mathrm{m}) + (6.634 - \mathrm{m}) + (6.532 - \mathrm{m}) \\ &+ (6.437 - \mathrm{m}) + (6.379 - \mathrm{m}) + (6.134 - \mathrm{m}) \triangleq 7 \end{aligned}$$

where the symbol $\triangleq$ means rounded to the nearest integer.

The DMU forecast for the $\boldsymbol{R}^{F}{}_{SURFACE\text{-}HEAVY} \triangleq 7$ (denoted by the superscript F) for relative to the 308-ship fleet is higher at $\boldsymbol{R}^{DMU}{}_{SURFACE\text{-}HEAVY} = 8$.

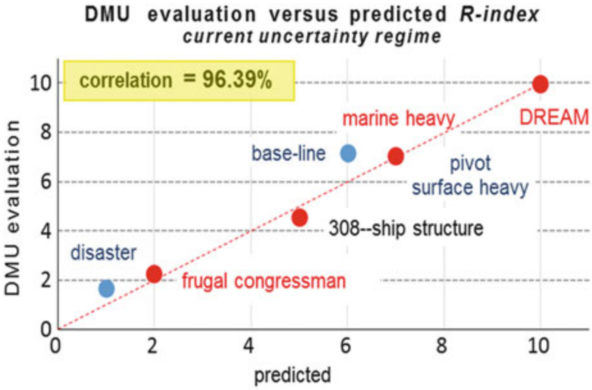
We performed the same calculations for all eight test experiments (Figs. 9.16 and 9.17). The blue points are where the DMU and predictions differ, and the red are the situations for which they are the same. The correlation between the DMU forecasts and the predicted values calculated using our methodology is 96.39%. This is a form of triangulation to confirm consistency (e.g. Thurmond 2001, Benzin 2006).

The ability to predict the output, of any experiment, is a salient feature of our methodology. The ***R*** value of any desired force structure in the space of possible N = $2^1 \times 4^9$ = 524,288 configurations can be predicted. The standard deviation of any R value can be predicted, as well. The Pacific Pivot fleet is very expensive at $642.50 B and is predicted to be overestimated by the DMU according to the calculations. On the other hand, the Base-line fleet is underestimated by the DMU. **Which column in** Fig. 9.16 **is more persuasive? *DMU* or *predicted*?** Predicted is more persuasive. According to Dawes' (1979) celebrated research paper, which has been cited about 3500 times, the *predicted* column is more persuasive. To arrive at the predicted column, we used all the L_{32} array data to capture all the explicit and latent information that is in the collective ensemble of

Fig. 9.16 DMU forecast vs. predicted current uncertainty regime

R *index*	DMU	predicted
Dream	10	10
Disaster	1	2
Surface heavy	8	7
Marine heavy	7	7
Frugal Congressman	5	5
308-ship	2	2
Base-line	6	7
Pacific pivot	8	7

Fig. 9.17 DMU experiments forecasts versus predicted current uncertainty regime



the mental models of the DMU. Our debiasing procedure enabled the synthesis of the DMU mental models into an integrative whole that is more accurate than any single individual mental-model.

9.4.3.2 Design of a Robust Alternative

In this section we want to show how to construct a robust force structure. We combine the *current* uncertainty regime and the *worse* uncertainty regime. We reckon that this blending captures the high degree of uncertainty that pervades the geopolitical situation as we go to press. Present outlook does not suggest that a *best* uncertainty regime is a prospective scenario. We join the data sets from Fig. 9.11 for the current uncertainty regime with the Appendix 9.2 data set for the worse uncertainty regime. This is the composite *current+worse* uncertainty regime. The ANOVA statistics for this blended uncertainty regime are in Table 9.35. The Response Tables are shown in Table 9.36.

And the graphic representation of the response tables are shown in Fig. 9.18. Visual inspection of the plots for the means of the ***R***-index for this *current+worse* uncertainty regime look qualitatively similar to the ones for *current* uncertainty regime. The similarity is not surprising since the controllable variable's characteristic is *more-is-better*. But they are quantitatively very different. Two observations must not be overlooked. First, the mean values are different. $\boldsymbol{R}_{\boldsymbol{current}}\,(mean) = 6.197$ and $\boldsymbol{R}_{\boldsymbol{c+w}}\,(mean) = 5.63$. Uncertainty has made $\boldsymbol{R}_{\boldsymbol{c+w}}\,(mean)$ less optimistic; it is lower. Secondly, the profiles for the standard deviations are different. This difference is important and one we will use to design a robust fleet for the *current+worse* uncertainty environment.

This is the plan for what follows. We will determine the ***R***-index and its associated standard deviation for the BASE-LINE force structure. We will then construct a force structure that is superior in the number of ships but with a *lowe*r standard deviation. The objective is to demonstrate how we can construct a robust alternative.

Table 9.35 ANOVA Table for team forecasts for *current* + *worse* uncertainty regime

Analysis of Variance for Means current + worse

Source	DF	Seq SS	Adj SS	Adj MS	F	P
SSBN	1	0.2302	0.2302	0.23023	4.32	0.129
SSN	3	13.0575	13.0575	4.35251	81.60	0.002
SSGN	3	9.8747	9.8747	3.29156	61.71	0.003
CVN	3	9.6462	9.6462	3.21539	60.28	0.004
DDG	3	10.0264	10.0264	3.34214	62.66	0.003
LCS/FF	3	3.4788	3.4788	1.15960	21.74	0.015
LPD	3	4.4657	4.4657	1.48858	27.91	0.011
LHA	3	4.2891	4.2891	1.42970	26.80	0.011
CLF	3	0.6279	0.6279	0.20931	3.92	0.146
OTHER	3	0.5932	0.5932	0.19775	3.71	0.155
Residual Error	3	0.1600	0.1600	0.05334		
Total	31	56.4498				

BASE-LINE fleet of configuration (2,2,3,2,3,2,3,3,3,3). In Sect. 9.4.3.1, we showed the use of the method of Analysis of Means (ANOM) (e.g. Phadke 1989; Wu and Wu 2000). First, calculate the grand average m of responses,

$$\begin{aligned}
\mathbf{m} &= \text{average}(SSBN\,\text{responses}) = ½[5.545 + 5.175)] = 5.630 \\
&= \text{average}(CVN\,\text{responses}) = ¼[4.836 + 5.411 + 6.054 + 6.219 + 6.219] \\
&= \text{average}(SSGN\,\text{responses}) = \text{average}(SSN\,\text{responses}) = \text{average}(DDG\,\text{responses}) \\
&= \text{average}(LCS/FF\,\text{responses}) = \text{average}(LPD\,\text{responses}) \\
&\qquad\qquad\qquad\qquad\qquad\qquad = \text{average}(LHA\,\text{responses}) \\
&= \text{average}(CLF\,\text{responses}) = \text{average}(OTHER\,\text{responses}) = 5.630
\end{aligned}$$

To get the predicted response for BASE-LINE (2,2,3,2,3,2,3,3,3,3) in the current uncertainty regime,

$$\begin{aligned}
\boldsymbol{R}_{c+w}(BASE\text{-}LINE) = {} & 5.630 + (\text{SSBN2} - \text{m}) + (\text{SSN2} - \text{m}) + (\text{SSGN3} - \text{m}) \\
& + (\text{CVN2} - \text{m}) + (\text{DDG3} - \text{m}) + (\text{LCS/FF2} - \text{m}) + (\text{LPD3} - \text{m}) \\
& + (\text{LHA3} - \text{m}) + (\text{CLF3} - \text{m}) + (\text{OTHER3} - \text{m})
\end{aligned}$$

Where the digit following the variable name indicates its level. For example, SSBN2 = 5.715 from the Response Table of Means and m = 5.630. We get:

$$\begin{aligned}
\boldsymbol{R}_{c+w}(BASE\text{-}LINE) = {} & 5.630 + (5.715 - \text{m}) + (5.343 - \text{m}) + (5.712 - \text{m}) \\
& + (5.411 - \text{m}) + (5.889 - \text{m}) + (5.487 - \text{m}) + (5.700 - \text{m}) \\
& + (5.897 - \text{m}) + (5.798 - \text{m}) + (5.823 - \text{m}) \overset{\circ}{=} 7
\end{aligned}$$

where the symbol $\overset{\circ}{=}$ means rounded to the nearest integer.

The predicted for the $\boldsymbol{R}^{P}(BASE\text{-}LINE) \overset{\circ}{=} 7$ (denoted by the superscript *P*) for relative to the 308-ship fleet is higher than $\boldsymbol{R}^{DMU}\ (BASE\text{-}LINE) = 6$. The predicted

Table 9.36 Response tables for means and standard deviations. *Current+worse* uncertainty

Response Table for Mean current + worse

Level	SSBN	SSN	SSGN	CVN	DDG	LCS/FF	LPD	LHA	CLF	Other
1	5.545	4.755	4.893	4.836	4.962	5.173	5.067	5.226	5.414	5.462
2	5.715	5.343	5.472	5.411	5.223	5.487	5.637	5.316	5.618	5.554
3		5.976	5.712	6.054	5.989	5.814	5.700	5.897	5.798	5.823
4		6.446	6.442	6.219	6.346	6.045	6.116	6.080	5.689	5.681
Delta	0.170	1.690	1.549	1.383	1.384	0.871	1.049	0.854	0.384	0.362
Rank	10	1	2	4	3	6	5	7	8	9

Response Table for Standard Deviations current + worse

Level	SSBN	SSN	SSGN	CVN	DDG	LCS/FF	LPD	LHA	CLF	Other
1	1.200	1.148	1.039	1.221	1.301	1.165	1.317	1.153	1.189	1.207
2	1.241	1.111	1.232	1.162	1.233	1.177	1.159	1.195	1.294	1.243
3		1.291	1.249	1.261	1.186	1.293	1.261	1.155	1.163	1.219
4		1.333	1.362	1.239	1.162	1.248	1.145	1.378	1.236	1.214
Delta	0.040	0.222	0.323	0.098	0.140	0.127	0.173	0.225	0.130	0.035
Rank	9	3	1	8	5	7	4	2	6	10

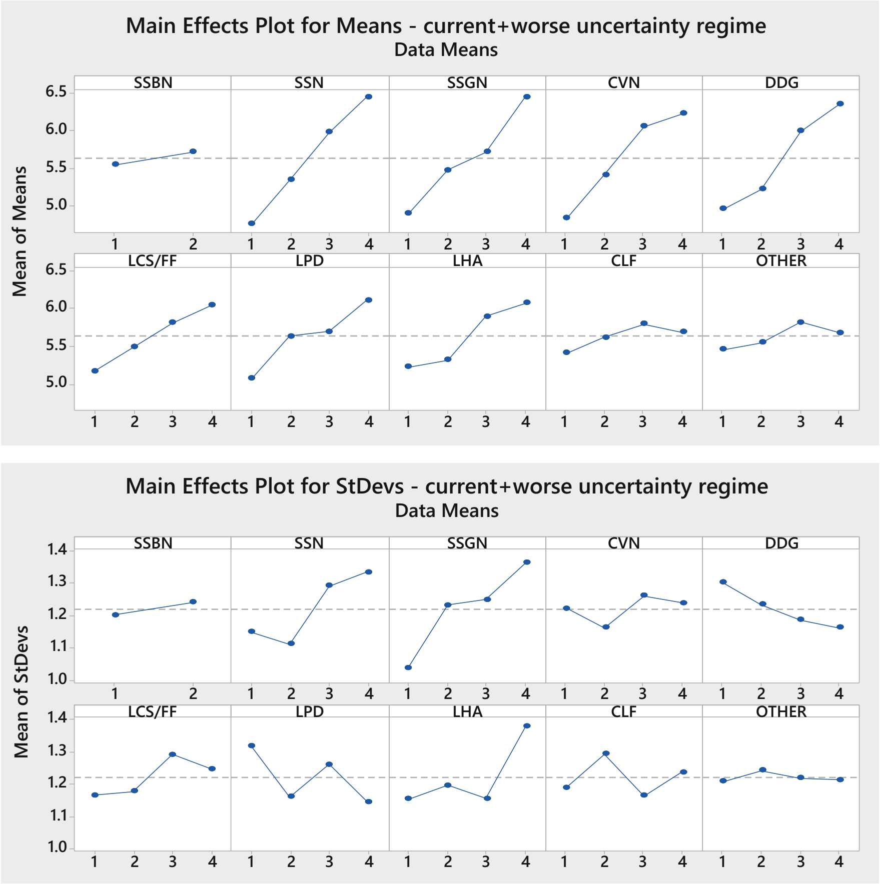


Fig. 9.18 Response plots for means and stdev in the current + worse uncertainty regime

R-index is better than what the DMU's evaluation. The DMU is perhaps too pessimistic.

We now predict the standard deviation we can expect from this force structure. Why is the standard deviation interesting? The standard deviation is a measure of the differencees in the assessments by the DMU members. Under different uncertainty regimes, the differences reflect that the DMU members are not all equally certain about the relative (gain or loss in) position of a different force structure and therefore what the ***R***-index should be. To the extent that these assessments are different, it indicates risk. To calculate the standard deviation, we use the response table of standard deviations (Table 9.36). However, we cannot use the ANOM procedure directly. Standard deviations are not additive. Fortunately, variances are additive. Therefore, we convert the standard deviations to variances (Appendix 9.4), do the arithmetic using variances, and then recover the standard deviations.

$$\begin{aligned}\boldsymbol{var}_{c+w}\,(BASE\text{-}LINE) = {} & 1.221 + (1.241 - \mathrm{m}) + (1.111 - \mathrm{m}) + (1.249 - \mathrm{m}) \\ & + (1.162 - \mathrm{m}) + (1.186 - \mathrm{m}) + (1.177 - m) + (1.261 - \mathrm{m}) \\ & + (1.155 - \mathrm{m}) + (1.163 - \mathrm{m}) + (1.219 - \mathrm{m}) = 0.84\end{aligned}$$

and $\mathbf{stdev}_{c+w}\,(BASE - LINE) = \sqrt{0.84} = 0.92.$

We now want to test the predictive power of our method in this *current+worse* uncertainty regime. We did the same calculation for all eight test experiments (Figs. 9.19 and 9.20). The blue points are where the DMU and predicted differ, and the red are the situations for which they do not differ. The correlation between the DMU forecasts and the predicted values calculated using our methodology is 98.09%. There is support to suggest that the methodology has predictive power.

We now construct a *ROBUST* force structure, specified as (1,2,3,2,3,4,4,3,3,4). The *ROBUST* design is juxtaposed versus the *308-ship* and *BASE-LINE* for structure for comparison. The Robust structure is stronger in submarines, surface combatants, amphibious ships, and for this increased number of ships, there are

Fig. 9.19 DMU forecast vs. predicted current + worse uncertainty regime

***R** index*	DMU	predicted
Dream	10	9
Disaster	1	1
Surface heavy	7	6
Marine heavy	6	7
Frugal congressman	4	4
308-ship	2	2
Base-line	6	7
Pacific pivot	7	6

Fig. 9.20 DMU experiments forecasts versus predicted

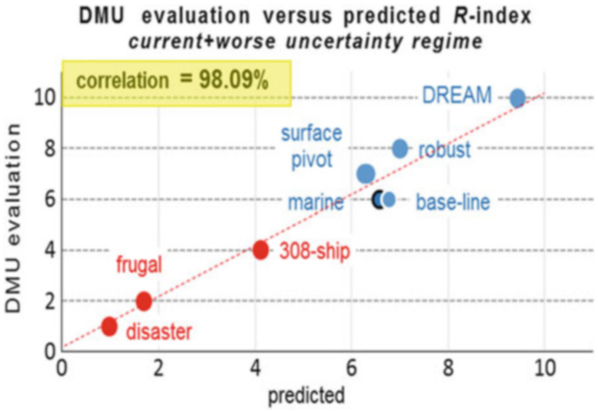


Table 9.37 308-ship, BASE-LINE, and ROBUST force structures

	SSBN	SSN	SSGN	CVN	DDG51	LCS/FF	LPD	LHA	CLF	Other	Total	R^{DMU}
308-SHIP												
var. lvl.	2	2	2	2	2	2	2	2	2	2		
Quantity	12	48	4	11	88	52	22	11	26	34	**308**	**5**
cost $B	58.8	137.8	19.60	141.9	101.2	29.95	35.75	37.4	14.27	5.10	**$581.74**	
BASE-LINE												
var. lvl.	2	2	3	2	3	2	3	3	3	3		
Quantity	12	48	6	11	97	52	24	12	32	37	**331**	**6**
cost $B	58.8	137.8	29.40	141.9	111.6	29.95	39.0	40.8	17.57	5.55	**$612.28**	
ROBUST												
var. lvl.	1	2	3	2	3	4	4	3	3	4		
Quantity	10	48	6	11	97	62	30	12	32	40	**348**	**8**
cost $B	49.00	137.8	29.40	141.9	111.6	35.71	48.75	40.8	17.57	6.00	**$618.44**	

more support ships (CLFs). The Robust *capacity* is superior relative to the *308-ship* structure. Relative to the BASE-LINE, the submarines, CVN and CLF remain at the same level. However, the LCS/FF surface combatants, amphibious ships and other are strengthened. These are the $\boldsymbol{R}^{DMU}$ values (Table 9.37).

But is the eponymous force structure more robust? We use the ANOM method to determine the variance of this *ROBUST* force structure. The general principle is: Change variable level if it lowers the standard deviation **and** is consistent with the goals/objectives of the decision. Otherwise do nothing, **unless** the impact on the output is disproportionately large relative to the increase in stdev. To do this competently, domain knowledge and good professional judgement are always necessary. We illustrate the process with a few examples. We start as follows:

1. We examine the response table for standard deviations (Table 9.36). Identify the variable with the highest rank for stdev. It is SSGN with Rank 1 and Delta 0.323 for stdev. In other words, the peak-to-trough is highest. For the *BASE-LINE,* SSGN is specified at level-3. This is one level higher than *308-ship* force structure. Raising the SSGN to level-4 naturally increases the number of SSGNs from six to eight, but it also increases the stdev by a large amount. Our decision is to keep SSGN at level-3 for the ROBUST structure.
2. The next variable with the highest rank for stdev is LHA. It has Rank 2 and Delta 0.225. Following the same logic of Step 1. The LHA level is kept at level-3 for the *ROBUST* design.
3. Rank 3 stdev is SSN. SSN at level-2 is the specification for the *BASE-LINE* and for the *308-ship force* as well. The standard deviation at this level-2 is at its minimum with a value of 1.111. The submarine force has been strengthened with SSGNs at level-3. Therefore, leave SSN at level-2 for the *ROBUST* design.
4. Rank 4 stdev is for the variable LPD. It specified as in the BASE-Line as level-3 with a stdev of 1.261 and in the *308-ship force* as level-2 with a standard

deviation of 1.159. At level-4 the stdev is lowest with a value of 1.145. This level *both raises* the number of ships to 30 and lowers the stdev to 1.145. For a *ROBUST* force structure this is good choice.

We apply the same general principle and logic, with the objective a stronger fleet with less standard deviation. Tables 9.38 and 9.39 summarize these results.

We have shown, by example, how to construct a robust alternative. Notably, the ***R***-index can be predicted for any force structure configuration. In this example the ***R***-index of the ROBUST force structure is better than all eight experiments (Table 9.34) except for the DREAM, which superb with 378 ships and a cost of $477.83. But its unaffordability is a challenge. **We have also shown how to predict the standard deviation of the outcome of *R*-index.** The standard deviation of the R-index is an indicator of risk. The uncertainty environment is the composite of current and worse uncertainty regimes. This is to capture the fact that, at this time, we cannot accurately, nor precisely know with certitude what the future will look like. By combining the evaluations for all the experiments for the current and worse uncertainty environments as an ensemble, we have the data that represents the judgement from the DMU about the *R*-values. They will vary because they are about different uncertainty conditions and they are from different people. Differences measured by stdev are a measure of risk. In our example, the predicted standard deviation for the ROBUST force structure is better than that for the 308-fleet and the BASE-LINE force structure. It is less risky.

Table 9.38 ROBUST fleet structure variables' level relative to 308-ship, BASE-LINE fleets

	SSBN	SSN	SSGN	CVN	DDG51	LCS/FF	LPD	LHA	CLF	Other	R^{DMU}
ROBUST	**1**	**2**	**3**	**2**	**3**	**4**	**4**	**3**	**3**	**4**	**8**
308-SHIP	↓	=	↑	=	↑	↑↑	↑↑	↑	↑	↑	**6**
BASE-LINE	↓	=	=	=	=	↑↑	↑	=	=	↑	**5**

↑ for *ROBUST* raise by one level, e.g. *308-SHIP(LHA)* is specified at level-2, *ROBUST(LHA)* specified level-3

↑↑ for *ROBUST* raised by two levels

↓ for *ROBUST* lower by one level, e.g. *BASE-LINE(SSBN)* is at level-2, *ROBUST(SSBN)* specified at level-1

= indicates *ROBUST* has no level change

Table 9.39 Resultant stdev for ROBUST fleet relative to 308-ship, BASE-LINE fleets

	SSBN	SSN	SSGN	CVN	DDG51	LCS/FF	LPD	LHA	CLF	Other	*stdev* R^{DMU}
ROBUST	**1**	**2**	**3**	**2**	**3**	**4**	**4**	**3**	**3**	**4**	**0.86**
308-SHIP	↓	=	=	↑	↑	↓	↓	↓	↓	↓	**1.04**
BASE-LINE	↓	↓	=	=	=	↓	↓	↓	↓	↓	**0.92**

↓ resultant *ROBUST* stdev is ***lower*** by one level, e.g. *308-SHIP(LHA)* is higher than *ROBUST (LHA)*

= indicates *ROBUST* has no level change

9.4.3.3 Systematic Design of Robust Alternatives

In this section, we show how to **systematically** construct a robust alternative that has satisficing outcomes and low standard deviations. This is a fairly daunting undertaking given that the entire solution space under all the uncertainty conditions contains a total of *524,288* × *262,144* = *1,374,389,534,720* alternatives (Sect. 9.3.2 of this chapter). *More than a trillion alternatives.*

We present systematic design-synthesis process described in the paragraphs that follow. The steps are keyed to Fig. 9.18, Tables 9.7, 9.36 and 9.40. We begin with the Dream Fleet configuration. This the most desirable fleet configuration, which has a DMU rating of ***R_{DMU} (dream fleet)*** = **10**. This can be considered as our "utopia" point.

Step #1 We start with the Dream force structure of (2,4,4,4,4,3,3,3,4,3). The highest ranking for data-means is for SSBN, with Rank = 10. SSBN is specified at level-2. Inspection of Fig. 9.18 (SSBN graphs) and Table 9.7 show that level-1 and level-2, signify we have 12 or 10 SSBNs, respectively. Changing from level-2 to level-1 lowers the stdev from 1.241 to 1.200 and brings it below the average of the stdev's (Table 9.36). There is no change in the ***R***-value of 9.25, but the stdev has dropped from 1.49 to 1.45 (Table 9.40, step #1). For these reasons, the specification for **SSBN is changed from level-2 to level-1**. The force structure is now (**1**,4,4,4,4,3,3,3,4,3). The cost of this fleet is lower at $743 B, with fewer ships, and less risky. The cell for SSBN in step #1 is in boldface to show the change.

Step #2 We enter this step with the force structure of (**1**,4,4,4,4,3,3,3,4,3). The next highest Rank = 9, the variable is "*other*" (Table 9.40). "Other" is set at level-3 which has the highest means with a value of 5.823 (Table 9.36). Changing the level-3 to level-2 will lower the ***R***-value and raise the stdev from 1.219 to 1.243. Changing it from level-3 to level-4, lowers the contribution to the ***R***-value, although it lowers the stdev by a miniscule amount, from 1.219 to 1.214. A level change for "*other*" is not meaningful. The force structure at this step remains **unchanged**, (**1**,4,4,4,4,3,3,3,4,3).

Step #3 We begin this step with (**1**,4,4,4,4,3,3,3,4,3). Rank 8 variable is CLF (Table 9.40). It is set at level-4. This case is relatively simple situation to make a call, *viz*. change the level-4 specification to level-3. This makes the ***R***-value better and its stdev lower (Fig. 9.18 CLF graphs). New force structure specification is (1,4,4,4,4,3,3,3,**3**,3). The predicted ***R*** = 9.36 and predicted stdev = 1.39. Both are improvements over step # 2.

Step #4 We enter this step with (1,4,4,4,4,3,3,3,3,3). Rank 7 variable LHA is set at level-3. At this level, the stdev is lowest at 1.155 (Fig. 9.18, Table 9.36). Lowest stdev = 1.153 requires LHA to move to level-1 from level-3, and the negative impact on ***R*** is most pronounced. Therefore, we make **no** change the LHA specification and keep it at level-3. The result is a ***R*** = 9.36 and a stdev = 1.35, See Table 9.40. The force structure specification is unchanged at (1,4,4,4,4,3,3,3,3,3).

Table 9.40 Systematic decision synthesis of robust alternatives

Means	SSBN	SSN	SSGN	CVN	DDG51	LCS FF	LPD	LHA	CLF	Other		*R*		*[R predicted] ÷*
rank	10	1	2	4	3	6	5	7	8	9	Total	*predicted*	*R stdev*	*[R stdev]*
Dream														
var. level	2	4	4	4	4	3	3	3	4	3		9.25	1.49	**6.208**
Quantity	12	70	8	15	106	57	24	12	37	37	378			
Σ cost $B	58.8	200.9	39.2	193.5	121.9	32.83	39.0	40.8	20.31	5.55	$752.80			
Step # 1														
var. level	**1**	4	4	4	4	3	3	3	4	3		9.25	1.45	**6.379**
Quantity	**10**	70	8	15	106	57	24	12	37	37	376			
Σ cost $B	**49**	200.9	39.2	193.5	121.9	32.83	39.0	40.8	20.31	5.55	$743.00			
Step # 2														
var. level	1	4	4	4	4	3	3	3	4	**3**		9.25	1.45	**6.379**
Quantity	10	70	8	15	106	57	24	12	37	**37**	376			
Σ cost $B	49	200.9	39.2	193.5	121.9	32.83	39.0	40.8	20.31	**5.55**	$743.00			
Step # 3														
var. level	1	4	4	4	4	3	3	3	**3**	3		9.36	1.39	**6.734**
Quantity	10	70	8	15	106	57	24	12	**32**	37	371			
Σ cost $B	49	200.9	39.2	193.5	121.9	32.83	39.0	40.8	**17.57**	5.55	$740.25			
Step # 4														
var. level	1	4	4	4	4	3	3	**3**	3	3		9.36	1.39	**6.734**
Quantity	10	70	8	15	106	57	24	**12**	32	37	371			
Σ cost $B	49	200.9	39.2	193.5	121.9	32.83	39.0	**40.8**	17.57	5.55	$740.25			
Step # 5														
var. level	1	4	4	4	4	**4**	3	3	3	3		9.59	1.35	**7.104**
Quantity	10	70	8	15	106	**62**	24	12	32	37	376			
Σ cost $B	49	200.9	39.2	193.5	121.9	**37.71**	39.0	40.8	17.57	5.55	$743.13			

(continued)

Table 9.40 (continued)

Means	SSBN	SSN	SSGN	CVN	DDG51	LCS FF	LPD	LHA	CLF	Other		*R*		*[R predicted] ÷*
rank	10	1	2	4	3	6	5	7	8	9	Total	*predicted*	*R stdev*	*[R stdev]*
Step # 6														
var. level	1	4	4	4	4	4	**3**	3	3	3		9.59	1.35	**7.104**
Quantity	10	70	8	15	106	62	**24**	12	32	37	376			
Σ cost $B	49	200.9	39.2	193.5	121.9	37.71	**39.0**	40.8	17.57	5.55	$743.13			
Step # 7														
var. level	1	4	4	**4**	4	4	3	3	3	3		9.59	1.35	**7.104**
Quantity	10	70	8	**15**	106	62	24	12	32	37	376			
Σ cost $B	49	200.9	39.2	**193.5**	121.9	37.71	39.0	40.8	17.57	5.55	$743.13			
Step # 8														
var. level	1	4	4	4	**4**	4	3	3	3	3		9.59	1.35	**7.104**
Quantity	10	70	8	15	**106**	62	24	12	32	37	376			
Σ cost $B	49	200.9	39.2	193.5	**121.9**	37.71	39.0	40.8	17.57	5.55	$743.13			
Step # 9														
var. level	1	4	**3**	4	4	4	3	3	3	3		8.86	1.24	**7.147**
Quantity	10	70	**6**	15	106	62	24	12	32	37	374			
Σ cost $B	49	200.9	**29.4**	193.5	121.9	37.71	39.0	40.8	17.57	5.55	$733.33			
Step # 10														
var. level	1	**3**	4	4	4	4	3	3	3	3		8.39	1.19	**7.05**
Quantity	10	**60**	6	15	106	62	24	12	32	37	364			
Σ cost $B	49	**172.2**	29.4	193.5	121.9	37.71	39.0	40.8	17.57	5.55	$704.63			

Step #5 Start with fleet structure of (1,4,4,4,4,3,3,3,3,3). Rank 6 variable is LCS/FF specified at level-3. At this level the stdev = 1.293 is highest (Fig. 9.18 LCD/FF stdev gtaph). We lower the stdev to robustize the force structure. Therefore change the level specification from level-3 to level-4. This improves the ***R***-value to R = 9.59 and lowers the stdev of the force structure to stdev = 1.35 (Table 9.40). The force structure specification is improved to (1,4,4,4,4,4,3,3,3,3).

Step #6 We enter this step with (1,4,4,4,4,4,3,3,3,3). Rank 5 variable is LPD, with a specification at level = 3, which has a high stdev = 1.261 at level-3. We need to robustize the force structure specification. LPD at level-4 makes a maximum positive contribution to R-value (Fig. 9.18, LPD graph) with the lowest stdev = 1.145 (Table 9.36, stdev = 1.145 at level-4). Thus, no change to LPD. The force structure configuration is unchanged from its entry configuration (1,4,4,4,4,4,3,3,3,3).

Step #7 Start with (1,4,4,4,4,4,3,3,3,3). Rank 4 variable is CVN, with a specification at level = 3, which has a high stdev at level-3, stdev = 1.261 (Table 9.36, CVN data). We need to robustize this force structure. LPD at level-4 makes a maximum positive contribution to R-value (Fig. 9.18, CVN graph) with the lowest stdev = 1.145 (Table 9.36, stdev = 1.145 at level-4). Thus, no change to CVN l-4. The force structure configuration is unchanged from its entry configuration (1,4,4,4,4,4,3,3,3,3).

Step #8 We start with (1,4,4,4,4,4,3,3,3,3). Rank 3 variable is DDG51, with a level-4 specification, which has a high stdev = 1.162 (Table 9.36, DDG). We do not need to robustize the force structure. DDG level-4 makes a maximum positive contribution to R-value (Fig. 9.18, DDG graph) with the lowest stdev = 1.162 (Table 9.36, DDG, Fig. 9.18 DDG graph). Thus, no changes to the entry force structure configuration of (1,4,4,4,4,4,3,3,3,3).

Step #9 We start with (1,4,4,4,4,4,3,3,3,3). Rank 2 variable is SSGN, at level-4, which has a highest stdev = 1.362 (Table 9.36, SSGN). We need to robustize the force structure. SSGN level-4 makes a maximum positive contribution to R-value (Fig. 9.18, SSGN graph) with the highest stdev = 1.362 (Table 9.36, SSGN). Changing level-4 specification to level-3 lowers stdev significantly to stdev = 1.249. The resultant force structure configuration is (1,4,**3**,4,4,4,3,3,3,3). The predicted ***R*** = 8.86 with a predicted stdev = 1.24. Relative to step #8, the ***R***-value has decline, and the stdev has improved.

Step #10 We enter this step with (1,4,3,4,4,4,3,3,3,3). Rank 1 variable SSN is set at level-4, which mazkes the highest contribution to ***R*** and also to a high stdev. In Fig. 9.18, the SSN graphs for the means-data, as well as, stdev, both peak at level-4. To robustize this force structure, we change SSN from level-4 to level 3. The resultant ***R*** = 8.36 and stdev = 1.19.

This systematic process takes no more steps than there are controllable variables. It has an automatic stopping rule (Gigerenzer and Selten 2001. Although Step #10 yields the lowest stdev, it is not the “best decision”. Its ***R***-value is lower

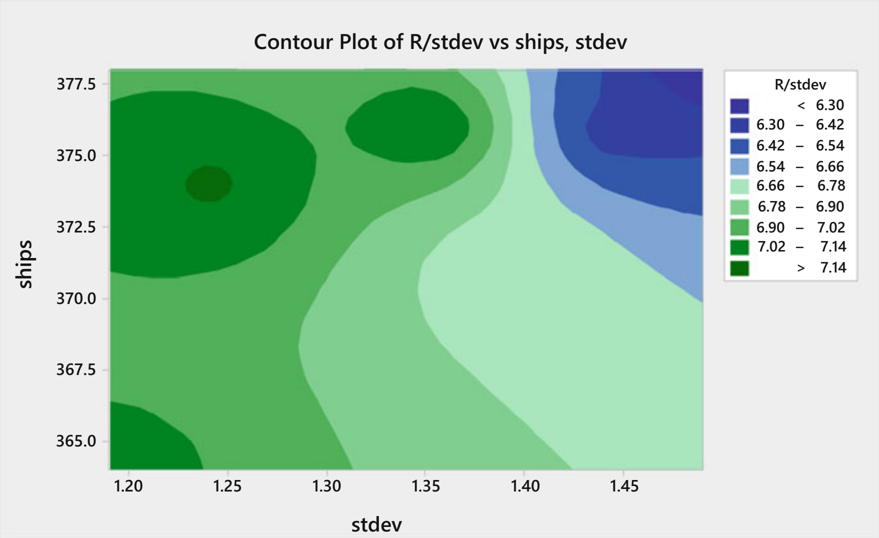


Fig. 9.21 Countour plots of the force structures obtained from the systematic steps to construct robust alternatives

than the force structure obtained from step #9. In terms of "cost-benefit", it can be argued that it is the superior decision relative to the one from step #10. We can think of the R-value as the benefit and the stdev as the cost. We made a similar argument in Sect. 8.4.3, where we discussed the R/stdev ratio as an indicator of benefit/cost or performance/price. This ratio is derived and shown in the right-hand column in Table 9.40. Considering this ratio, step #9 yields the most desirable robust force structure, it shows the highest R/stdev ratio. Beyond the numbers, the key difference between the step #9 and step #10 are the differences in attack submarines (SSN) and guided missile submarines (SSGN). The R-values reveals that the DMU considers ten more attack submarines worth the price of a small increment in stdev.

This situation can be illustrated with the contour plot Fig. 9.21. The colors indicate the magnitude of R/stdev ratio as function of the stdev and number of ships of the force structures in Table 9.40. The plot shows that more ships do not necessarily yield better R/stdev ratios, *viz.* more desirable fleets. The region of darker green are the more desirable force structures. The small dark green in the North West quadrant is our step #9 force structure.

9.4.4 Discussion

The purpose of this section has been to demonstrate executive-decision synthesis, namely how to:

Table 9.41 Readiness level specifications for executive decisions

Readiness Level	Systematic process for the operations space	Efficacy
X-RL3 Explore operations space	Specify	
	Sample orthogonal array	☑
	Do-nothing case and choice decision-alternative	☑
	Predict outcomes	☑
	Design and implement robust alternative	☑
	Design and implement any what-if alternative	☑

The symbol ☑ indicates support is demonstrated

- design and construct a force structure of any configuration
- predict its R-index, a measure of how superior or inferior it is relative to the 308-ship fleet
- predict the resultant risk of the force structure in the uncertainty space.
- produce realistic examples with supporting data and analyses.

We conclude that XRL-3 conditions for efficacy are met. Table 9.41.

9.5 Evaluating the Performance Space as a Production System

The discussions have concentrated on our methods to construct decision alternatives using DOE experiments to predict their performance and associated risk. Experiments depend on data, but how do we know the data are "good enough"? How do we know the quality of those performing the experiments or the production mechanisms?

We consider the sociotechnical system that implements a decision specification as a **production system, a factory** (Fig. 9.22). We evaluate production quality in two ways. One is simple and the other more involved. The first is a simple test of consistency. The second is using the Gage R&R method of Measurement System Analysis. In Sects. 9.4.3.1 and 9.4.3.2, we have shown the test of consistency, *viz.*

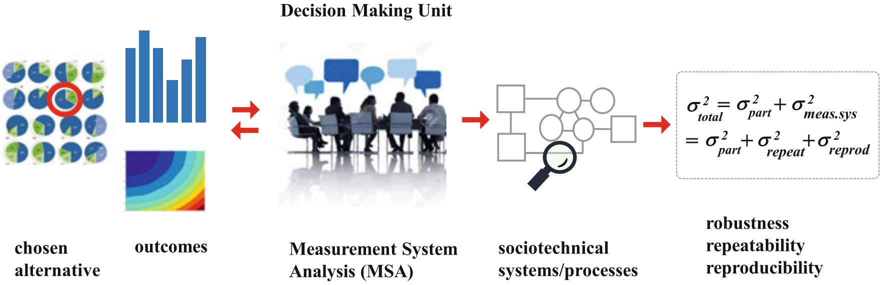


Fig. 9.22 Schematic of the outcomes space

how well does the ***R***-index predicted by our methodology predict the R^{DMU} evaluated by the DMU? We reported the correlations to be 96.4% and 98.1%. Consistency between DMU and predictions is supported.

9.5.1 Gage R&R

The R&R of Gage R&R are abbreviations for repeatability and reproducibility. We introduce these two distinct concepts.

9.5.2 Repeatability

Repeatability is a quantity that is used to indicate a property of a measurement system. Repeatability indicates the ability of a DMU member to replicate its own judgement and quantitative measure for a result of the ***same*** decision specification, under the same conditions. The individual measurement for a given force-structure experiment, by the same DMU member, gives us an indication of *repeatability*.

We had one replicate. We have data for the full L_{32} taken two times (Fig. 9.23). On the left hand side are the first and original ***R*** index values entered by the DMU

original	A	B	C	D	E	F	G
1	2	1	1	1	1	1	3
2	3	5	4	4	3	4	6
3	6	8	6	7	7	7	8
4	7	9	8	9	10	10	10
5	4	5	4	5	3	4	5
6	5	4	6	6	5	6	7
7	6	6	7	5	6	6	8
8	6	7	7	6	8	7	9
9	6	6	6	4	4	6	7
10	7	5	7	6	4	7	7
11	7	5	8	5	6	7	9
12	8	5	8	6	7	8	9
13	8	7	7	7	5	8	9
14	7	7	8	7	5	9	8
15	7	5	8	4	5	6	7
16	8	6	9	5	7	7	9
17	4	6	4	5	5	6	7
18	3	6	4	5	4	5	8
19	4	6	5	5	5	7	6
20	4	5	5	6	6	6	8
21	6	6	5	5	5	6	7
22	6	6	6	5	4	7	7
23	7	6	6	6	5	6	7
24	7	4	5	6	5	7	9
25	8	7	6	6	5	7	8
26	9	7	7	6	7	7	9
27	7	4	7	6	4	6	6
28	8	6	8	5	6	7	8
29	8	7	8	8	6	7	8
30	9	6	8	6	7	6	8
31	8	6	7	6	6	7	9
32	8	6	9	4	6	7	8

replicate	A	B	C	D	E	F	G
1	2	1	1	1	1	0	4
2	2	5	4	5	5	4	7
3	6	8	6	6	6	8	8
4	7	8	9	10	10	10	9
5	3	4	4	4	3	5	4
6	6	4	6	6	4	6	8
7	7	6	7	4	6	6	9
8	6	8	7	6	8	6	8
9	6	6	5	4	5	5	7
10	7	6	8	5	5	7	8
11	7	6	8	5	5	6	10
12	8	6	8	6	7	8	8
13	9	6	7	7	5	8	7
14	8	8	9	7	4	9	7
15	7	6	9	4	5	6	7
16	8	6	9	5	8	7	9
17	4	7	3	5	5	7	8
18	3	6	4	4	4	6	8
19	4	6	5	4	5	7	6
20	5	4	5	6	6	5	7
21	5	5	6	5	5	5	7
22	6	6	6	6	4	7	8
23	7	6	7	6	6	6	7
24	7	5	6	6	5	7	9
25	7	7	5	5	5	7	8
26	9	7	7	6	6	8	9
27	7	3	7	6	5	5	6
28	8	6	9	5	5	7	7
29	8	7	8	7	6	7	8
30	9	6	9	7	8	6	9
31	8	6	6	5	6	7	10
32	8	6	9	4	6	7	7

A:authors, **B**:surface heavy, **C**:submariner, **D**:marine,
E:hawk, **F**:CNO staff, **G**:frugal congressman. Prime indicates replicate values

Fig. 9.23 The original L32 data set from the DMU and the replicates

Table 9.42 Correlations % between data and replicates by DMU members

	A′	B′	C′	D′	E′	F′	G′	
A	**96**	47	82	47	56	60	57	Authors
B	43	**90**	44	66	68	77	48	Surface heavy
C	86	56	**96**	48	67	65	57	Submariner
D	51	90	49	**92**	59	81	53	Marine
E	59	68	66	67	**94**	71	72	Hawk
F	69	76	66	74	67	**94**	64	CNO staff
G	69	68	65	63	77	78	**90**	Frugal congressman

Prime indicates DMU members' replicates

members. On the right are the ***R*** values during a second round of evaluation. These data are called replicates. The replicates on the right hand side, which have different ***R*** values from the first round, are shown by shaded cell colors. Note that the data are not identical. Statistical correlation will reveal the extent of differences.

The correlations are shown in Table 9.42 (bold values). The between DMU members correlation (the diagonal) is high. They are all $> 90\%$ with an overall average of $\approx 93\%$. The among DMU members correlation is much lower than the between member correlations, with an overall average of $\approx 63\%$. Overall, the correlation table strongly suggests repeatability. It also shows that professional expertise exerts its influence on the judgements. Thus, the off-diagonal data reveals that herding is weak. The correlation table also suggests face validity (Yin 2013).

9.5.3 Reproducibility

Reproducibility is a quantity that indicates the precision of a measurement system. Reproducibility is the ability of a DMU member to replicate a forecasting result of a decision specification, by a ***different*** experimenter DMU member. The individual forecasts for a given experiment by different DMU members give us an indication of *reproducibility* across DMU members. We use the following approach to obtain an indication of reproducibility. The left hand panel in Fig. 9.23 are the data for the fully populated $\mathbf{L_{32}}$ array for the current uncertainty regime and with its associated replication data in Fig. 9.24.

Recall that each column is labeled to identify the officer who populated that column. The column *avg* ***R****-index* is the average of the entries in each row for the experiment identified by # k, where $1 \leq k \leq 32$. The right panel shows the same data with all the authors' entries set to zero. The column *avg* $\boldsymbol{R'_A}$*-index* is the average of a row's entries without the authors' data. The correlation:

$$correlation\left(avg\boldsymbol{R}\text{-}index, avg\boldsymbol{R}_{A'}\text{-}index\right)\Big|_{authors} = 72.6\% \qquad (9.5)$$

provides an indication of reproducibility. Namely are the evaluations of the DMU members *without* the authors' data is 72.6% "consistent" relative to the data *with* the authors' data. This is an indication of reproducibility of the authors' evaluations.

	A	**B**	**C**	**D**	**E**	**F**	**G**	avg ***R***
1	2	1	1	1	1	1	3	1.400
2	3	5	4	4	3	4	5	4.000
3	6	8	6	7	7	6	8	6.914
4	7	9	8	9	10	10	10	9.000
5	4	5	4	5	3	4	5	4.286
6	5	4	6	6	5	6	7	5.571
7	6	6	7	5	6	6	8	6.286
8	6	7	7	6	8	7	9	7.100
9	6	6	6	4	4	6	7	5.500
10	7	5	7	6	4	7	7	6.143
11	7	5	8	5	6	7	9	6.714
12	8	5	8	6	7	8	9	7.286
13	8	7	7	7	5	8	9	7.286
14	7	7	8	7	5	9	8	7.286
15	7	5	8	4	5	6	7	5.971
16	8	6	9	5	7	7	9	7.214
17	4	6	4	5	5	6	7	5.286
18	3	6	4	5	4	5	8	5.000
19	4	6	5	5	5	7	6	5.429
20	4	5	5	6	6	6	8	5.643
21	6	6	5	5	5	6	7	5.714
22	6	6	6	5	4	7	7	5.857
23	7	6	6	6	5	6	7	6.143
24	7	4	5	6	5	7	9	6.143
25	8	7	6	6	5	7	8	6.643
26	9	7	7	6	7	7	9	7.357
27	7	4	7	6	4	6	6	5.700
28	8	6	8	5	6	7	8	6.857
29	8	7	8	8	6	7	8	7.514
30	9	6	8	6	7	6	8	7.143
31	8	6	7	6	6	7	9	7.000
32	8	6	9	4	6	7	8	6.829

	A′	**B′**	**C′**	**D′**	**E′**	**F′**	**G′**	*avg* ***R′***
1	**0**	1	1	1	1	1	3	*1.114*
2	**0**	5	4	4	3	4	5	*3.571*
3	**0**	8	6	7	7	6	8	*6.057*
4	**0**	9	8	9	10	10	10	*8.000*
5	**0**	5	4	5	3	4	5	*3.714*
6	**0**	4	6	6	5	6	7	*4.857*
7	**0**	6	7	5	6	6	8	*5.429*
8	**0**	7	7	6	8	7	9	*6.243*
9	**0**	6	6	4	4	6	7	*4.643*
10	**0**	5	7	6	4	7	7	*5.143*
11	**0**	5	8	5	6	7	9	*5.714*
12	**0**	5	8	6	7	8	9	*6.143*
13	**0**	7	7	7	5	8	9	*6.143*
14	**0**	7	8	7	5	9	8	*6.286*
15	**0**	5	8	4	5	6	7	*4.971*
16	**0**	6	9	5	7	7	9	*6.071*
17	**0**	6	4	5	5	6	7	*4.714*
18	**0**	6	4	5	4	5	8	*4.571*
19	**0**	6	5	5	5	7	6	*4.857*
20	**0**	5	5	6	6	6	8	*5.071*
21	**0**	6	5	5	5	6	7	*4.857*
22	**0**	6	6	5	4	7	7	*5.000*
23	**0**	6	6	6	5	6	7	*5.143*
24	**0**	4	5	6	5	7	9	*5.143*
25	**0**	7	6	6	5	7	8	*5.500*
26	**0**	7	7	6	7	7	9	*6.071*
27	**0**	4	7	6	4	6	6	*4.700*
28	**0**	6	8	5	6	7	8	*5.714*
29	**0**	7	8	8	6	7	8	*6.371*
30	**0**	6	8	6	7	6	8	*5.857*
31	**0**	6	7	6	6	7	9	*5.857*
32	**0**	6	9	4	6	7	8	*5.686*

A:authors, **B**:surface heavy, **C**:submariner, **D**:marine, **E**:hawk, **F**:CNO staff, **G**:frugal congressman.
Prime indicates replicates

Fig. 9.24 *correlation*(avg R-index, avg R'-index)$|_{authors}$

We perform these calculations for every DMU member. And the results are shown on the right hand side of each bar in Fig. 9.25. The last bar, at the bottom, represents the correlation we calculated at 73% for the authors. The frugal congressman's correlation is the highest at 88%. The overall average of the correlations is 79% shown by the vertical dashed-line. These data suggest strongly that the reproducibility of the evaluations is high.

9.5.4 Gage R&R: Evaluation of Production Quality

9.5.4.1 Gage R&R Construct

In the previous sections we used statistical correlations to develop support for repeatability and reproducibility. W*e consider the DMU members who are determining the R-values, their knowledge, data bases, formal and informal procedures, and their network of contacts as a* ***measurement system***. (Fig. 9.26), We apply the engineering method of Measurement System Analysis (MSA) (AIAG 2002) to analyze the sources of variation in this measurement system (Fig. 9.27).

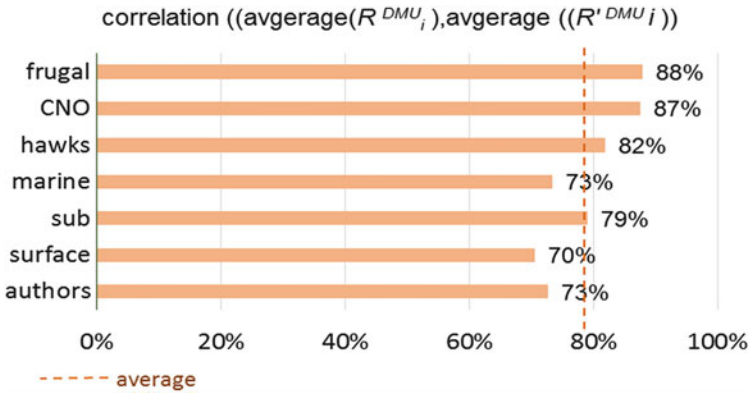


Fig. 9.25 Correlation of the average R-index with and without a DMU evaluation

uncontrollable variables

1. Russia
2. China
3. Japan
4. North Korea
5. Germany
6. Congressional budget
7. Mediterranean Middle East
8. Iran
9. USA

controllable variables

1. SSBN
2. SSN
3. SSGN
4. CVN
5. DDG
6. LCS/FF
7. LPD
8. LHA
9. CLF
10. other

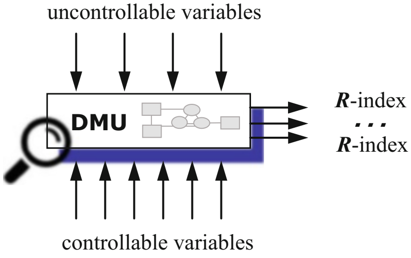


Fig. 9.26 DMU and its sociotechnical systems as a measurement system

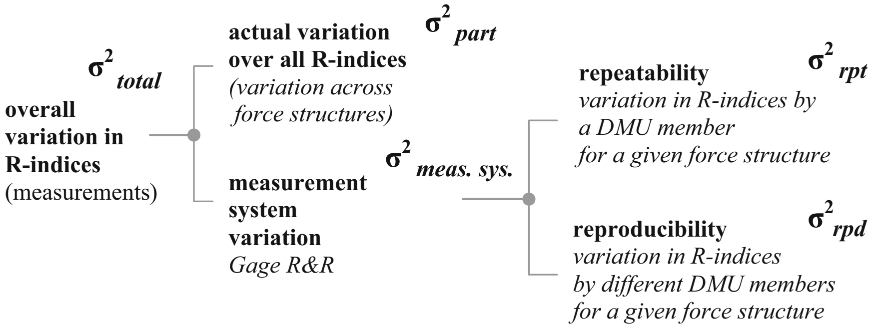


Fig. 9.27 Sources of variability of R-index evaluations for force structures

MSA uses the terminology of "operator" to designate the person making the measurement. We use the term "DMU member" or "DMU participant". Instead of measuring a manufactured part, each DMU member is "measuring" the ***R***-index of a force structure. We use "DMU" to identify the collective body. Since we want to measure the quality of the measurement system, as defined above, the Gage R&R Eq. (3) of Sect. 3.5.4 becomes Eq. (9.6) in this chapter. In the graphical form of the equation (Fig. 9.27). We show the MSA nomenclature inside the parentheses

$$\sigma^2{}_{total} = \sigma^2{}_{R\text{-}indices} + \sigma^2{}_{meas.sys.} = \sigma^2{}_{R\text{-}indices} + \sigma^2{}_{repeability} + \sigma^2{}_{reprodicibility} \tag{9.6}$$

9.5.5 New Research Findings

We get the ANOVA table for our Gage R&R statistics (Table 9.43). The two-way ANOVA table shows the p = 0.000 values for "treatment" (force structures), "operator" (DMU member), "*treatment* × *operator*" (*DMU-member* × *experiment*), and repeatability. They are all statistically significant.

The Gage R&R statistics show that of the total variation, 0.0% is from repeatability. This shows there is no visible contribution from repeatability variations. This is consistent with our correlation analysis of repeatability in Sect. 9.5.2.

The data show the variations in reproducibility contributes 45.79% of the variations in the recorded ***R***-indices. This 45.79% variation contribution is the sum of variations from DMU members variations (17.94%) and the

Table 9.43 GR&R ANOVA for measurement variances

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Parts	31	773.14	24.9401	1.46287E+01	0.000
Operators	6	221.18	36.8631	2.16221E+01	0.000
Parts * Operators	186	317.11	1.7049	1.97598E+14	0.000
Repeatability	224	0.00	0.0000		
Total	447	1311.43			

Gage R&R

		%Contribution
Source	VarComp	(of VarComp)
Total Gage R&R	1.40179	45.79
Repeatability	0.00000	0.00
Reproducibility	1.40179	**45.79**
Operators	0.54935	**17.94**
Operators*Parts	0.85244	27.84
Part-To-Part	1.65966	54.21
Total Variation	3.06144	100.00

*DMU*force-structure* interaction variations. The 17.94% variation contribution should be put in context relative to the 72.6% of Eq. (5). 72.6% is a correlation quantity, the converse is non-reproducibility of $(100\% - 72.6\%) = 27.4\%$. The quantity 17.94% is a measure of variation, 27.4% is a measure of correlation. Comparing these number is like apples and oranges and inappropriate. Nevertheless, the magnitude of the numbers is suggestive of information.

AIAG (2002) has guidelines, for measurement-system statistics, applicable to production systems. Accordingly, our variations for reproducibility are **too large** and the ***R***-indices (part-to-part) are **too small**. The AIAG benchmarks stipulate that that the Gage R&R variation should be $< 10\%$, whereas in our case it is 45.79% and the part-part should be $> 90\%$, whereas in our case, it is 54.21%. The ASQC and AIAG guidelines specify a 10–90 split. And the Gage R&R of 10% should be split 5% and 5% for repeatability and reproducibility. The contrast between the AIAG/ASQC and our measurements is shown in Fig. 9.28.

The Gage R&R method was developed to measure differences in the manufacturing of standard parts. Parts that by definition are designed to the same specifications. Of course, no manufacturing process comprised of machines and people will produce parts that have all exactly the same measurements. Variations, in how well the specifications are met, are unavoidable. Gage R&R was designed to determine the sources and magnitudes of these variations. That our measurements are not consistent with the AIAG guidelines is not surprising, but what our measurements reveal are consistent with the intent of the method. In this chapter, every part, i.e. every one of the 32 experiments are **purposely designed to be different,** not **the same**. Therefore, that reproducibility is low is not surprising. The Gage R&R method data supports this fact.

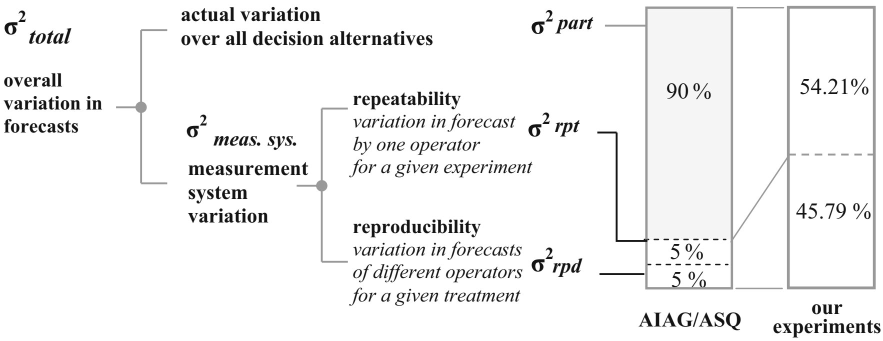


Fig. 9.28 Sources of variability for forecasts

9.5.6 Reflection

9.5.6.1 General Discussion

It is significant that the Gage R&R specifications and standards were co-developed by the AIAG, Ford, GM, and DaimlerChrysler, the cradles of mass production. It is safe to estimate that many of person-centuries of manufacturing expertise and production data went into this effort. It is also safe to say that data from the manufacturing measurements of millions of parts were part of the development of the Gage R&R effort. *We have not found any literature to tell us whether the manufacturing measurement standards apply in equal measure to sociotechnical processes;* such as the experiments in this chapter. This is an open area for new research. We invite the US National Institute of Technology and Standards (NIST), scientists, engineers and metrologists to tackle this subject. This research is important.

Gage R&R, in the context of sociotechnical systems, raises many challenging and unaddressed questions about the quality of such complex systems. Nevertheless, this chapter shows that the Gage R&R method has shown to be useful and has given us new insights, which are consistent with findings obtained by other means. The method has given us a sophisticated analytic approach to determine the capabilities of a DMU, individually and as a "composite", tasked to make evaluations. The "composite" is a sociotechnical ensemble, including their knowledge, organizational data bases, formal as well as informal procedures, and the DMU-members' networks of contacts (Table 9.44).

We find no data or information of similar data about sociotechnical systems to calibrate its efficacy. To our knowledge, the chapters in this book are the first *examples* the Gage R&R's use for sociotechnical systems. This is a new and worthy subject for further research. We conclude that XRL-4 conditions for efficacy are conditionally met (Table 7.24).

9.6 Enacting the Commitment Space

A decision is not complete until the empowered executive commits to an implementation schedule, an allocation of resources and executes the decision. These commitments and enactment give real meaning to decisive decision-making (Fig. 9.29).

Table 9.44 Readiness level-4 specifications for executive decisions

Readiness level	Systematic process for the performance space	Efficacy
X-RL4 Evaluating performance space	• Evaluate performance: analyze 4R • Robustness, repeatability, reproducibility • Reflect	☑ ▣ ☑

The symbol ☑ indicates support is demonstrated. ▣ indicates tentative support is demonstrated

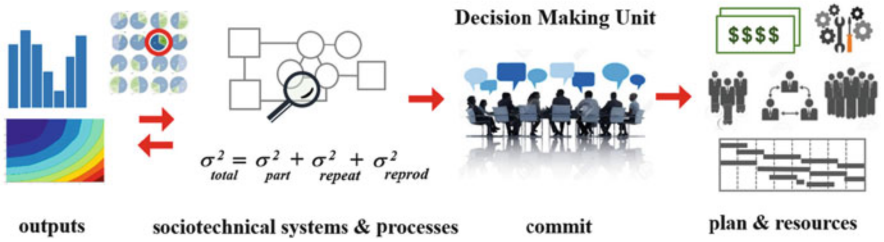


Fig. 9.29 The DMU in the Commitment Space

Table 9.45 Readiness level specifications for executive decisions

Readiness level	Systematic process for the commitment space	Efficacy
X-RL5 Enacting commitment space	Decisive executive Approval of plan Commit funds, equipment, organizations	☐ ☐ ☐

The symbol ☐ indicates support is not tested in this experiment

We do have in writing a letter, from Admiral Hogg (retired) the Commandant of the US Navy War College, in which he wrote that our seminar wass "certain to prove immensely valuable in our future efforts". As a *gedanken* experiment of high-level staff officers, this work of this chapter has not been implemented. We conclude that XRL-5 conditions for efficacy are tentatively met (Table 9.45).

9.7 Chapter Summary

The goal has been to demonstrate **efficacy**, i.e. that the methodology is ***ready-for-work*** in a real world environment. We stipulated that our methodology ***works***, if and only if, two conditions are simultaneously satisfied, *viz.* it is ready-***to***-work for users in general, as well as, ready-***for***-work by a user to satisfy a specific set of needs. The former is demonstration of *functionality*, the latter of *efficacy*. This chapter is a case to show efficacy on the question of the US Navy Force Structure (Table 9.46).

- We characterized the US Navy Force Structure decision as a portfolio structure challenge. The goal is to create a portfolio of ships that is superior to the specified 308-ship force structure, for the year 2037. The problem is non-trivial considering the variety of ships needed and the scale and scope of the US Navy's responsibilities. We defined superiority in terms of capacity, capability, and readiness. We focused on capacity in being, viz. actual ships that

Table 9.46 Readiness level specifications for executive decisions

Readiness level	Our systematic process	Strategy
X-RL1	Characterize the problem space	Sense making
X-RL2	Engineer the solution space	Design and engineer experiments/alternatives
X-RL3	Explore the operations space	Explore entire solution and uncertainty spaces
X-RL4	Evaluate the performance space	Measure robustness, repeatability, reproducibility
X-RL5	Enact the commitment space	Commit plan with approved resources

exist. Capability and readiness are outside the scope of this chapter, but worthy of further study.

- Study of the force structure problem must consider the uncertainties that will be facing the US Navy in the next 20 years. To address US Navy's force structure problem, we specified ten managerially controllable variables and nine managerially uncontrollable variables. Using these variables we defined the construct for the solution space and the uncertainty space. These spaces enabled us to make predictions about hypothesized force structures and their associated risks under a wide range of uncertainty conditions.
- We described a debiasing procedure to diminish the effect of bias on the predictions and evaluations about different hypothetical force structures. Expert knowledge is effective as the bases for this procedure (e.g. Camerer 1981).
- A salient feature of our paradigm is the ability to design distinct robust force structures. **Robustness** means that the fleet's performance is highly immune to uncertainty even when the uncontrollable uncertainty variables are not removed.
- Another conceptual and practical innovation is the consideration of the sociotechnical system that designed and will implement the force structure, as a production system. The fundamental desirable attributes, for a production system, like a factory, are repeatability and reproducibility. We applied the Gage R&R measures on our sociotechnical systems that produce decisions as intellectual artefacts for enactment. The concepts apply. The way we address this problem ushers a new domain of research. The Gage R&R method for sociotechnical systems is a rich new area for research.
- We stepped through our systematic process for executive decisions to test efficacy at five levels.
- Overall, the results reported in this chapter are evidence for the claim of efficacy of our methodology. We conclude that there is strong support for the efficacy of our methodology.

Readiness level	Our systematic process	Efficacy
X-RL1 Characterize problem space	Sense making—uncomplicate cognitive load	☑
	Frame problem/opportunity. specify boundary conditions	☑
	Specify goals and objectives	☑
	Specify essential variables Managerially controllable variables Managerially uncontrollable variables	☑
X-RL2 Engineer solution space	Specify subspaces of solution space Alternatives space and uncertainty space	☑
	Specify entire solution space	☑
	Specify base line and uncertainty regimes Do-nothing case and choice-decision Estimate base line and dispel bias	☑
X-RL3 Explore operations space	Specify Sample orthogonal array Do-nothing case and choice decision-alternative	 ☑ ☑
	Predict outcomes	☑
	Design and implement robust alternative Design and implement any what-if alternative	☑ ☑
X-RL4 Evaluate performance space	Evaluate performance: analyze 3R Robustness, repeatability, reproducibility Reflect	☑ ▣ ☑
X-RL5 Enact commitment space	Decisive executive Approval of plan Commit funds, equipment, organizations	☐ ☐ ☐

☑ indicates support is demonstrated
▣ indicates tentative support is demonstrated
☐ indicates not completed in this example

Appendix 9.1 The Free-Rider Problem

In the vernacular, free-riding is used to describe the behavior of a person or a party who intentionally chooses to reap benefits from another person, party or organization without contributing to the cost or effort it takes to produce the benefit (e.g. Hardin 2013). The concept appears clear, but there is more to it than meets the eye. The examples below illustrate some of the nuances. The issue is about *fair riding*, not free riding.

Example 1 A king asked his subjects to bring milk and pour it into a big pot, to which he will also contribute and then distribute among the poor. When the large pot was examined, it was watery. Many villagers brought water hoping to dilute the milk from other people. They were free riding—hoping others would bring milk so they could bring water and hoping no-one would notice, while appearing as a contributor. They prefer to do very little and let others contribute, hope it goes unnoticed and benefit from the overall effort. For economists, two factors characterize the problem.

- *Non-excludability*—Once provided, you can't stop anyone using it.
- *Non-rivalry*—consumption doesn't reduce amount available to others.

This story is colourful, but it does not address the question of how much milk should be contributed as a function of the farmer's income. Nor that the farmer that diluted his milk had a herd of dogs that protected the cows of neighbouring farms from vicious predators. (http://www.economicshelp.org/blog/glossary/free-rider-problem/. Downloaded Jan. 2, 2017)

Example 2 A beekeeper keeps bees to produce honey. An ancillary benefit effect is an externality—her bees will pollinate flowers in surrounding properties, benefiting owners of those properties at no cost. Nor is there any practical means by which the beekeeper can produce her honey without conferring this benefit on her neighbors. Thus, the "good" provided to surrounding property owners is *nonexcludable*. This situation involves no detriment to anyone, let alone *any violation of rights*. The beekeeper chooses to buy the bees because she expects to be better off by virtue of her actions. Moreover, as an unintended consequence of her purchase, surrounding property owners also find themselves enjoying a benefit from the bees, at no cost to them. This may seem like a fortuitous event—even something to be celebrated.

If the beekeeper possessed some means to prevent surrounding property owners from benefiting from her bees, without detracting from her own enjoyment, then she would be able to negotiate with them to pay her for the benefit. Since she would then derive an additional benefit from her bees—the payment—she would have an incentive to keep *even more* bees, benefiting both herself and her neighbors to an even greater extent. This ceases to be a *zero-sum* game. Rather, under certain assumptions, it turns out that there is some level of payment at which the surrounding property owners would be indifferent between the excludable and the no excludable situation, whereas the beekeeper would be demonstrably better off, i.e., there would be a Pareto-efficient gain. (https://mises.org/library/solving-problem-free-riding. Downloaded Jan. 2, 2017. Minor editing by Vtang)

Note:

1. "The beekeeper is ALSO a free-rider. Her bees are dependent upon the flowering plants on his neighbors' property for the pollen and nectar they need to survive. And any attempt on her part at coercion of payment can be swiftly met with the spreading of pesticides by the land owners, or they could plant noxious weeds that would contaminate her bees' honey, making it unpalatable or even toxic." (source: "not so crazy" blogger).
2. In the South China Seas, light houses and weather reports are provided *gratis*, by the Chinese authorities from the newly constructed islands. They are free goods benefiting all ships navigating those waters. A free ride is given each year, to nations and enterprises accounting for $5.3 trillion of trade which passes

through the South China Sea of which U.S. trade accounts for $1.2 trillion of this total. (http://www.cfr.org/asia-and-pacific/armed-clash-south-china-sea/p27883). 80% of China's of its crude oil imports flow through the South China Sea. (Fensom, A. 2016. $5 Trillion Meltdown: What If China Shuts Down the South China Sea? *National Interest*. Downloaded Jan. 2, 2017.) http://nationalinterest.org/blog/5-trillion-meltdown-what-if-china-shuts-down-the-south-china-16996).

Example 3 Figures 9.3, 9.6, and 9.7 are less examples of "free riding", but illustrative examples of "unfair riding". The unfairness is very evident and impressive. The US taxpayer is contributing a significant amount to the security of the world. NATO countries by mutual agreement are required to spend 2% of their GDP on defense. Of the countries that have joined since 2004 only Estonia and Poland are meeting those requirements. Of the remaining members only US, France, and Greece have to pay the agreed GDP share for defense. Therefore, the issue is not "free" riding but "unfair" riding. Resolution of this question is outside the scope of this chapter and it is one for the member nations to reach an n-party Nash Equilibrium.[1]

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[1] http://www.economist.com/blogs/graphicdetail/2017/02/daily-chart-11

Appendix 9.2 The L_{32} Data Set: Worse Uncertainty Regime

Worse uncertainty regime

Experiments	SSBN	SSN	SSGN	CVN	DDG51	LCS/FF	LPD	LHA	CLF	other	fleet size	Σcost $B	R index							average	std. dev
													A	B	C	D	E	F	G		
base	2	2	2	3	2	2	3	3	3	3	321	$605.03									
# 1	1	1	1	1	1	1	1	1	1	1	269	$476.00	0	0	0	0	0	0	1		
# 2	1	1	2	2	2	2	2	2	2	2	301	$550.62	2	4	3	3	2	3	4		
# 3	1	1	3	3	3	3	3	3	3	3	327	$595.30	5	7	5	6	6	6	7		
# 4	1	1	4	4	4	4	4	4	4	4	361	$679.08	6	8	7	8	8	8	9		
# 5	1	2	1	1	2	2	3	3	4	4	318	$539.03	3	4	3	3	2	3	4		
# 6	1	2	2	2	1	1	4	4	3	3	313	$589.05	4	3	5	5	4	5	6		
# 7	1	2	3	3	4	4	1	1	2	2	334	$609.44	5	5	6	3	6	5	7		
# 8	1	2	4	4	3	3	2	2	1	1	325	$655.92	5	6	6	5	6	6	8		
# 9	1	3	1	2	3	4	1	2	3	4	334	$590.90	5	5	5	3	3	5	6		
# 10	1	3	2	1	4	3	2	1	4	3	349	$602.75	6	4	6	5	3	6	6		
# 11	1	3	3	4	1	2	3	4	1	2	321	$674.28	6	4	7	4	4	6	7		
# 12	1	3	4	3	2	1	4	3	2	1	327	$653.59	7	4	7	5	6	7	8		
# 13	1	4	1	2	3	3	3	4	2	1	344	$646.75	7	6	5	6	4	6	8		
# 14	1	4	2	1	4	4	4	3	1	2	360	$651.69	6	5	7	6	4	7	7		
# 15	1	4	3	4	1	1	1	2	4	3	326	$675.34	6	4	7	3	4	5	6		
# 16	1	4	4	3	2	2	2	1	3	4	343	$664.97	7	5	7	4	6	6	6		
# 17	2	1	1	4	1	4	2	3	2	3	308	$591.68	3	5	3	4	4	5	6		
# 18	2	1	2	3	2	3	1	4	1	4	312	$582.56	2	5	3	4	3	4	7		
# 19	2	1	3	2	3	2	4	1	4	1	323	$589.62	3	4	4	4	4	6	5		
# 20	2	1	4	1	4	1	3	2	3	2	323	$576.94	3	4	3	4	5	5	7		

# 21	2	2	1	4	2	3	4	1	3	2	325	$626.11	5	5	4	4	4	5	6		
# 22	2	2	2	3	1	4	3	2	4	1	318	$597.79	5	4	5	3	3	6	6		
# 23	2	2	3	2	4	1	2	3	1	4	330	$616.66	6	5	5	5	4	5	6		
# 24	2	2	4	1	3	2	1	4	2	3	325	$595.08	6	3	5	5	4	6	7		
# 25	2	3	1	3	3	1	2	4	4	2	334	$635.49	7	6	5	5	4	6	7		
# 26	2	3	2	4	4	2	1	3	3	1	342	$688.22	8	6	6	5	6	6	7		
# 27	2	3	3	1	1	3	4	2	2	4	333	$608.25	6	3	6	4	3	5	5		
# 28	2	3	4	2	2	4	3	1	1	3	337	$638.44	7	5	7	4	5	6	7		
# 29	2	4	1	3	4	2	4	2	1	3	345	$674.77	7	6	7	7	5	6	7		
# 3 0	2	4	2	4	3	1	3	1	2	4	347	$702.94	8	5	7	5	6	5	7		
# 31	2	4	3	1	2	4	2	4	3	1	347	$651.08	7	5	6	4	5	6	8		
# 32	2	4	4	2	1	3	1	3	4	2	336	$658.35	7	6	7	3	5	6	7		

Appendix 9.3 ANOVA Statistics for Worse Uncertainty Regime

ANOVA Table for DMU *R*-Index for Worse Uncertainty Regime

Analysis of Variance for Means—worse uncertainty regime

Source	DF	Seq SS	Adj SS	Adj MS	F	P
SSBN	1	0.3200	0.3200	0.32000	7.05	0.077
SSN	3	12.9456	12.9456	4.31521	95.07	0.002
SSGN	3	9.3241	9.3241	3.10804	68.47	0.003
CVN	3	9.7492	9.7492	3.24974	71.59	0.003
DDG	3	10.0274	10.0274	3.34247	73.64	0.003
LCS/FF	3	3.3376	3.3376	1.11253	24.51	0.013
LPD	3	4.6070	4.6070	1.53567	33.83	0.008
LHA	3	4.3360	4.3360	1.44535	31.84	0.009
CLF	3	0.6548	0.6548	0.21827	4.81	0.115
OTHER	3	0.6685	0.6685	0.22283	4.91	0.112
Residual Error	3	0.1362	0.1362	0.04539		
Total	31	56.1065				

Appendix 9.4 Main Effect Tables for Means and Standard Deviation for Worse Uncertainty Regimes

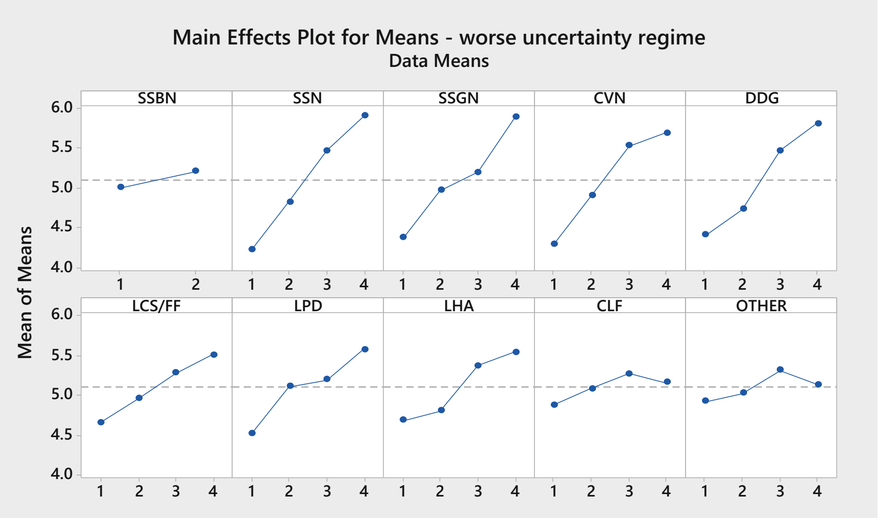
Response Table for Means—worse uncertainty regime

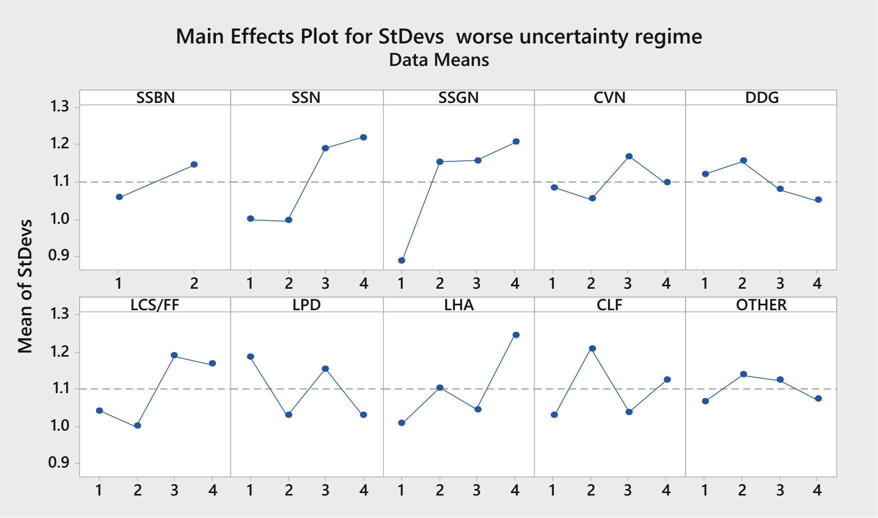
Level	SSBN	SSN	SSGN	CVN	DDG	LCS/FF	LPD	LHA	CLF	OTHER
1	4.999	4.221	4.368	4.293	4.405	4.657	4.520	4.679	4.880	4.923
2	5.199	4.816	4.959	4.893	4.723	4.952	5.105	4.798	5.082	5.027
3		5.462	5.195	5.523	5.463	5.279	5.191	5.375	5.271	5.314
4		5.896	5.875	5.688	5.805	5.509	5.580	5.545	5.163	5.132
Delta	0.200	1.675	1.507	1.395	1.400	0.852	1.061	0.866	0.391	0.391
Rank	10	1	2	4	3	7	5	6	8	9

Response Table for Standard Deviations—worse uncertainty regime

Level	SSBN	SSN	SSGN	CVN	DDG	LCS/FF	LPD	LHA	CLF	OTHER
1	1.0559	0.9984	0.8860	1.0825	1.1189	1.0417	1.1851	1.0066	1.0285	1.0673
2	1.1438	0.9941	1.1521	1.0533	1.1544	0.9993	1.0288	1.1026	1.2100	1.1377
3		1.1890	1.1561	1.1675	1.0772	1.1903	1.1552	1.0442	1.0374	1.1228
4		1.2180	1.2051	1.0961	1.0489	1.1682	1.0303	1.2460	1.1235	1.0715
Delta	0.0879	0.2240	0.3191	0.1143	0.1055	0.1910	0.1563	0.2394	0.1816	0.0704
Rank	9	3	1	7	8	4	6	2	5	10

Appendix 9.5 Plots of Response Tables for Means and Standard Deviation for Worse Uncertainty Regimes





Appendix 9.6 UNCLOS: Pros and Cons Overview

UNCLOS, the United Nations Convention on the Law of the Sea, is an organization of more than 160 member states, that **defines** the extent to which nations can use resources of the seas.[2,3] The US has not ratified this treaty, although it frequently invokes it to persuade nations to abide by it. Mazaar (2017) of RAND writes—"... [international] stability depends on leading members abiding and being seen to abide—by key norms of behavior. When the leader of an order consistently appears to others to interpret the rules as it sees fit, the legitimacy of the system is undermined and other countries come to believe that order offends, rather than sustains their dignity." In this appendix, we present some samples that argue two sides of this argument. The issues are complex, messy, and wicked (e.g. Beckman 2010; Freeman 2017; Goves and Chang 2014; Republic of China 2016; Duterte's Pivot 2016).

- "If we're truly concerned about China's actions in the South China Sea ... the Senate should help strengthen our case by approving the Law of the Sea convention, as our military leaders have urged," Barak Obama.[4] Many agree, e.g. Mirasola 2015, Majumbar 2016.

  Steven Groves, research fellow the Heritage Foundation says that Obama's argument is "completely ridiculous."[5]

  Perhaps these are the reasons why the US is silent on Japan's Okinotorishima rocks 1050 nautical miles south of Tokyo. It is an exaggeration to call them islands. It is built on stilts supporting a manmade platform,. This legal fact did not prevent Japan's Chief Cabinet Secretary Yoshihide Suga to assert the position that Okinotorishima is an island under international law and consequently entitled to a 200-nautical-mile exclusive economic zone.[6]
- The U.S. "could say a lot more, and probably much more convincingly" if it were a party to the treaty, says. "As it stands, they have to talk about more abstract terms like 'accepted rules' of international law and 'rules-based order,'" Andrew Chubb, University of Western Australia.[7]
- Others disagree. "Why-the-law-of-the-sea-treaty-is-still-a-bad-idea" (undated) *The Heritage Foundation*. Downloaded 24 Dec. 2016. http://heritageaction.com/stoplost/why-the-law-of-the-sea-treaty-is-still-a-bad-idea/

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Appendix 9.7 China's Intentions and Goals. Some Implication to the US

Appendix 9.7.1 Overview China's Intentions and Goals

This appendix summarizes our understanding of China's intentions. It describes examples of what we have called uncontrollable variables in Sect. 9.2.4.2. All the content of this appendix is in the public domain. Much is the work of scholars. We begin with a brief summary from a scholarly book published by RAND (Swaine et al. 2000). They succinctly summarize Chinese national strategy over the past 1000 years.

- "Protect the heartland through border defense". Formerly by building a wall, the today approach to this is through anti-access (Cliff et al. 2007).
- "Periodic expansion and contraction of regime boundaries as a function of state power, but eventual unification, in spite of periods of fragmentation and civil wars". Less through outright military conquest, but biased to using acculturation of Sinic culture and values. Chinese history is more of a "civilization state" than a nation state (Jacques 2009). Morgenthau (1960) notes "... that for a thousand years China has not tried to expand its influence and power westward and southward by military conquest and annexation. It has, rather, relied upon the natural attraction of Chinese civilization." However, two recent centuries of colonial humiliation has diminished this "natural attraction" and is driving China to strengthen national defense and adopt a more assertive strategy.
- "Reliance on non-coercive security strategies when weak, avoidance of force when perceived as unnecessary or costly". They are deeply influenced by SunTzu who wrote "The best strategy is to win without violence. (SunTzu's 2012)." When weak, build strength, and wait for the time when you will be taken seriously. China is now in the indomitable nation building period. They have patience and very long memories (Savic 2016).

The following are our opinions on China's current policy and strategic priorities.

- Emphasize economic development. Without it, government legitimacy will be severely questioned by its citizens. Hence China's singular focus on GDP growth. So far it is working, >700 million have been lifted out of poverty since 1978.[8] According to *The Economist*, China has had a "20-fold increase in economic output since the late 1970s".[9] A very large middle class is still more than a decade away and is ambitiously targeted for 2030.[10]
- Frame and implement massive international projects, which do not include making enemies. On the contrary, the apparent strategy is to bind nations inextricably with China through economic development, e.g. One Belt One Road (OBOR), Asia Infrastructure Investment Bank (AIIB), Kra Canal, trans-continental high-speed rail across China, Russia and Europe, a similar proposal made to Brazil and Peru, military armaments exports with lenient and exceptional technology transfers. And it is proving its abilities to execute.[11,12,13] And

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[8] "Since ...1978, China has ... and has lifted more than 800 million people out of poverty." (http://www.worldbank.org/en/country/china/overview. Sep 14, 2016).

[9] *Disorder Under Heaven*. 2017. The Economist, April 22.

[10] http://www.cnbc.com/2016/11/02/china-will-be-middle-income-by-2030with-spending-on-cars-luxuries-health-to-rise.html

[11] http://www.economist.com/news/china/21714383-and-theres-lot-more-come-it-waste-money-china-has-built-worlds-largest

[12] http://inhabitat.com/china-is-spending-over-500-billion-to-expand-high-speed-rail/

[13] http://indianexpress.com/article/business/business-others/china-to-increase-high-speed-rail-network-to-30000-km-by-2020/

when China perceives it is being excluded from multilateral organizations or being encircled, it will build its own, AIIB is a good example.
- Exercise flexibility on territorial issues, and will negotiate. China-expert Taylor Fravel's (2005, 2008, 2010a) research shows that since 1949, China has been involved in 23 territorial disputes with its neighbors on land and sea. Seventeen have been settled through compromises, which have resulted in less than 50% of the land areas going to China. Moreover, China has used force only against its most military capable neighbors. Possibly China is not as aggressive as portrayed by some of its detractors.

China has declared that the South China Seas are part of China's core interests (罗援 2014, Fravel 2010b, 2011, Erikson and Goldstein 2009). In fact China reclaimed these islands with the cooperation and assistance of the US Navy after WWII, its wartime ally.[14] This was in accordance to the 1943 Cairo Conference and the 1945 Potsdam Conference. It is my belief China is prepared to temporize, put territorial "claims" aside and opt for joint economic development to extract resources. For example, China and the Philippines will drill for oil in disputed waters (Dela Cruz 2017). Unless provoked by hostile foreign interventions or military action, it will avoid military action. U.S. Ambassador Freeman (2017) states:

> "… in accordance with the Cairo and Potsdam Declarations and with American help, the armed forces of the Republic of China in Nanking [Nanjing] accepted the surrender of the Japanese garrisons in Taiwan, including the Paracel and Spratly Islands. Nanjing then declared both archipelagoes to be part of the Guandong Province. In 1946 it established garrisons on both Woody (now Yongxing/永興) Island in the Paracels and Taiping Islands in the Spratlys."
>
> "The US Navy facilitated China' replacement of Japan's military presence in both island groups in 1945 because it considered that they were either part of Taiwan, as Japan had declared or—in the words of the Cairo Declaration—among other 'territories Japan stolen from the Chinese' to 'be restored to the Republic of China'."
>
> "No country with claims to the Spratly's interferes with shipping or peacetime naval transit in the south China Sea. Nor does any party in the region have an interest in threatening commerce transiting it. The South China Sea is every littoral nation's jugular. China and the other countries on the South China Sea have a greater stake in assuring freedom of navigation in and through it than the United States does."

Moreover, "Shipping [is] Unaffected by South China Sea Tensions".[15]

The DiaoYu Islands in the East China Sea (Japan calls Senkaku) are also part of China's core interests. On the question of territorial sovereignty China's position has hardened (e.g. Kristof 2010; Smith 2013; 罗援 2014). This hardening was triggered by Japan's changing the status quo through "purchase" of the DiaoYu Islands from a "private business" for $26.1 M (Smith 2013). To the Chinese, this is a hijack motivated by weakness (Handel 2003). It inflamed Chinese public opinion by announcing it on September 18, anniversary of Japan's start of military aggression

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[14] http://www.mepc.org/articles-commentary/speeches/china-and-other-claimants-south-china-sea?print Downloaded Jan 2 2016.

[15] *The Maritime Executive*. Downloaded January 2 2016. http://www.maritime-executive.com/article/shipping-unaffected-by-south-china-sea-tensions

in Peking, which officially ignited WWII in China (Fravel 2012). In a cunning effort to further obfuscate the issue, Japan is proposing a name change to the islands (Ishigaki 2017). In 1978 China and Japan had a tacit understanding established by President Deng XiaoPing of China and Japanese Prime Minister Tanaka when they negotiated the peace treaty between these two nations. They agreed to shelve the issue to a "wiser and more intelligent generation" to resolve the dispute (https://www.youtube.com/watch?v=e6sCVtEoazs) (e.g. Lo 2013).

- Right now China's stated operational principle is: "Assertiveness, but not belligerence." China correctly considers peaceful relations with the US as most important (華春瑩 2016). Its military is very realistic about its capabilities. Following a Chinese visit to the Pentagon and important US military commands, a Chinese general observed that "we are 20 years behind".[16] China has publicly stated "China has neither intention nor capability to challenge the US, let alone to replace US as world's dominant power"(Qu 2015). Nor does it intend to repeat the pre-1914 error of the German Kaiser (Murray 2010). Given its priorities on economic development and eradicating poverty, it does not follow that China wants to play the Delian leader in a Peloponnesian type conflict. Chinese general and professor at their National Defense University states categorically that China welcomes strong competition because "we are getting lazy" and that "to make small improvements you need friends, but for big improvements you need tough adversaries" (金一南 2017).

China military doctrine is: predicated on the rule that "We will not be provoked into firing the first bullet. But should the enemy fire first, we will make sure they incapable of firing the second."

- A "Never Again" mentality, as in Israel, is seared into the Chinese mind (e.g. Mitzen 2006). It is an integral part of China's national identity and their *Zeitgeist* of this century. It is part of the national belief system that China's misery and humiliations of the past two centuries began with foreign navies. Starting with the Opium Wars, the Japanese in 1895 and again during WWII. There is no need to discuss these topics. Its history and judgments are known to all. For example, two quotes:

> First quote. "The use of opium is not a curse, but a benefit to the hard-working Chinese". 1858 Press release from Jardine, Matheson & Co (Hanes and Sanello 2002).
>
> Second quote. "[our] flag is become a pirate flag, to protect an infamous traffic." William Gladstone. 1842. (Hannes and Sanello 2002).

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[16] https://www.youtube.com/watch?v=qnPWUz5hpEg (interestingly this link was closed on January 29 2017.

Photograph 1 Signs posted in extraterritorial parks for Europeans, Americans, and Japanese. Circa 1900–1945

Photograph 2 John Rabe, **German** citizen. He saved thousands of lives during the 1937 Nanjing Massacre. This is a a memorial in his honor in Nanjing, China

Photograph 3 **American** Robert Wilson MD. Working with John Rabe, he provided medical help to thousands of victims during the Nanjing Massacre. He also deserves a memorial. Sources. All photographs are from Google Images. Downloaded 25 April 2017. https://www.google.com/search?safe=active&site=&tbm=isch&source=hp&biw=1468&bih=706&q=john+rabe+nanking&oq=john+rabe&gs_l=img.1.6.0l10.1721661.1729772.0.1734985.9.9.0.0.0.0.347.1397.0j8j0j1.9.0....0...1ac.1.64.img..0.9.1381...0i7i30k1.UU4YtsSKYVE#spf=1. https://www.google.com/search?safe=active&site=&tbm=isch&source=hp&biw=1468&bih=706&q=nanjing+massacre&oq=nanjing+massacre&gs_l=img.3..0l10.2489.7195.0.8325.16.10.0.6.6.0.212.1476.0j9j1.10.0....0...1ac.1.64.img..0.16.1664.wBWbjStS7Qc#spf=1

The first photograph is a typical sign that used to be posted at the entrance of many extraterritorial parks in major cities in China. A privilege gained by foreign powers in China by coercive force of arms.

The next photographs are that of John Rabe, a German businessman, who saved thousands of lives during the Nanjing Massacre (Chang 2012). The Nanjing Massacre makes Thucydides' grisly account of the Thracian massacre at Mycallesus read like a Sunday stroll (Thucydides 1980). There are no words to describe Rabe's humanity and heroism. His tombstone has been moved from Berlin to Nanjing where it sits in a place of honor and veneration. The other photograph is that of Robert Wilson MD, an American missionary who chose to stay behind in Nanjing to provide medical help to hundreds of men, women and children. His heroism is prominently documented and displayed in the Nanjing Massacre Museum. He worked closely with John Rabe (Chang 2012). Bix (2000) writes that "during the entire period [Nanjing massacre] he [Hirohito] energetically spurred his generals and admirals on to greater victories in the national project to induce Chinese self-'reflection.'

- Finally, the Chinese have very long memories. This is the result of many factors. One is its continuous national history not as much as a nation-state in the European sense, but more as a civilization-state (Jacques 2009). A civilization that takes its history very seriously. Sima Qian (45–85 BC) established an honored tradition of recording history that continues to this day. His work is more a record of events. It is didactic moral history, which has influenced Chinese culture for two millennia. Why does Sima Qian have such an impact on the Chinese? He chose the judicial punishment of castration rather than edit what the emperor considered politically correct. Kissinger (1999, 141) notes:

> Asked when a certain event occurred, the American will cite a date; the Chinese will refer to a dynasty. Of the fourteen Chinese dynasties, seventeen have lasted longer than the entire history of the United States, and three were in place just as long. . .Chinese historical references tend to mystify all but the most expert Americans. Our references to our own history tend to be viewed by the Chinese as primarily illustrating an insufficient national experience hardly warranting an informed judgement.

This Chinese mentality makes them unforgiving about what they deem national humiliations. They tend to be more charitable to Europeans and Americans. European extraterritoriality in China has been abolished. Hong Kong, Macau have been returned to China without armed conflict. **Only** the U.S. rather than enjoy the funds, of imposed treaty reparations, from the 1900 Boxer Uprising, returned part of the funds to China to build universities. China's most prestigious engineering university, Ching Hua, is one of them. It is also the alma mater of China's president Xi JinPin and of its former president Hu Jintao.

Appendix 9.7.2 What It Means to the US

It is impossible to discuss this subject in an Appendix. Its scope and scale is very large. Many China experts have written extensively on this subject. We will highlight their key points. They are necessary to appreciate the subject of this Appendix.

- Many consider China's rise with a sense of alarm (Mearsheimere 2010), but also "Most important, China is a disruptive power but not a revolutionary one. Its size, wealth, and assertive foreign policy lead it to demand significant changes to existing institutions, but it does not seek to overturn the current international order wholesale" (Feigenbaum 2017).
- "China, however, sees itself not as a rising power but as a returning one, predominant in its region for two millennia and temporarily displaced by colonial exploiters taking advantage of Chinese domestic strife and decay. It views the prospect of a strong China. . . not as an unnatural challenge to the world order but rather as a return to normality." . . .. "It would be unusual if the world's second-largest economy did not translate its economic power into increased military capacity" (Kissinger 2012).
- China is a country undergoing a chrysalistic transformation. "The model of government that emerges will likely be a synthesis of modern ideas and traditional Chinese political and cultural concepts . . . " (Kissinger 2012).

- "It would be unusual if the world's second-largest economy did not translate its economic power into increased military capacity" (Kissinger 1999, 2012).
- " . . . China is less the result of its increased military strength than of the United States own declining competitive position, driven by factors such as obsolete infrastructure, inadequate attention to research and development, and a seemingly dysfunctional governmental process. The United States should address these issues with ingenuity and determination instead of blaming a putative adversary."... "It should not adopt confrontation as a strategy of choice" (Kissinger 2012). . "... the United States cannot abandon its role as the international order's chief sponsor (Cronin et al. 2012). Although it will longer be a hegemon presiding over a unified system, it will still be a crucial factor—a catalyst for solutions and managing partner of a mixed order, each of whose members sees itself as the equal of others . . . US leadership will remain critical to global stability" (Mazaaar 2017).

We are entering an age of ***heterogemony.*** The Thucysides trope does not apply in this epoch. Rather than a single monolithic hegemon, power is networked and distributed among interacting distinct hegemonic complexes. Spheres of hegemonic influences seem to emerging. For example, monetary, network security, terrorism, space, ecommerce, social media, and so on. Power is no longer monolithic and unidimensional, but multi-dimensional. Specifically, we think we need an Eastphalia of naval powers, not a repeat of the Washington Naval Conference of yore. New thinking is called for (Antoniades 2008; Bagby 1994; Herbert 1996; Ikenberry 2014; Ikenberry et al. 1988; Kissinger 2002, 2015; Williams 2004; Murphy 2014). The US must take the lead.

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Appendix 9.8 WWII Legacy: *Quo Usque Tandem Abutere*[17]

Long Memories of History: Japan Neo-Militarists and Right-Wing Tarnishing US Efforts

Neo-militarism and right-wing Japanese officials are not doing the U.S. any favors. They erode U.S.'s moral high ground and tarnishes our image as a champion of human rights.

- Class **A** War Criminals memorials in Yasukini are inflammatory to Japan's neighbors.
- US tolerance is difficult to understand. Imagine Angela Merkel going to a Himmler or Goering memorial service. It is unthinkable any German leader would even think of such a thing. National honor and moral decency forbids it.
- Japanese government's refusal to acknowledge their heinous practice and their appalling official objections Korean memorials to "comfort women" are morally offensive. "Comfort women" were females from China, Korea, Philippines, Singapore, etc. that were coerced into Japanese military brothels to "comfort" Japanese soldiers. (See archival references in this Appendix).

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[17] The immortal first line from Cicero's speech to the Roman Senate (Beard 2015).

- Japan's debate on the number of deceased in the Nanjing is likewise incomprehensible. Imagine Angela Merkel debating the number of Jews that perished in gas chambers as being exaggerated.
- Most egregious is their response about Unit 731 which experimented on live humans in China. Harries and Harries (1991, 230) write "As the war progressed, . . .the Japanese Army stretched far beyond, murder, rape, looting and wanton destruction of property. The war . . . assumed genocidal proportions; medical and biological warfare experiments on civilians and prisoners of war." But the Japanese Education Ministry declares that "To write about reconsideration of the war is un-necessary since present-day pupils had nothing to do with it" (Behr 1989, 397). Imagine Willy Brandt making such an outrageous comment.
- Japanese leaders are *actually retracting* apologies for actions Japan had accepted guilt for in the past (Zarakol 2010).
- Japan's actions are inconsistent with our emphasis of common decency, human rights and the values we propagate to the next generation.
- Japan's government actions only serve to reinforce the construction of the modern Korean and Chinese unfavorable perceptions of Japan's national identity. Part of which includes a deepening dislike and distrust of Japan in general and especially its right-wing militarists. This is regrettable. Statesmanship favors building amity and goodwill.

It is hard to imagine what universal moral principles of human rights and humane treatment of civilians in war zones are being upheld by these Kabuki Kuroko government policies. Max Weber taught the world the meaning of *Gesinnungsethik* and *Verantwortunggesethik* (Weber 2004). The goal is to achieve both without violating either one. Violating both simultaneously is not a moral standard worthy of contemplating. Kissinger (1994, 1999) understands this well and has been able to guide US foreign policy with consummate virtuosity. Nelson Mandela and Willy Brandt understood this and set examples for all time. Brandt's *Warschauer Kniefall* enabled all Germans to hold their high. (http://www.japantimes.co.jp/news/2015/08/13/national/history/70-years-wwii-neighbor-states-hold-germany-high-heap-scorn-axis-ally-japan/#.WRBukOQkt9A). The Japanese government's actions appear to serve neither *Gesinnungsethik n*or *Verantwortunggesethik.*

Willy Brandt and Nelson Mandela Offer Historic Lessons of Moral Leadership
Willy Brandt set an example of moral rectitude. Nelson Mandela set an example on how to face truth, reconcile injustice of the past, and build trust.

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Not all Japanese are unrepentant right-wing militarists about the atrocities perpetrated. The government should bear responsibility

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Archives on "Comfort Women"

被遗忘的"慰安妇"被遗忘的"慰安妇" Forgotten "Comfort Women"

Published on Jul 28, 2013. https://www.youtube.com/watch?v=K5mavGJhqoc

日本二战老兵现身说法 士兵脱裤子排队蹂躏慰安妇 Japanese Soldiers' Behavior with "Comfort Women"

Published on Aug 27, 2015 https://www.youtube.com/watch?v=DQU899YvfUE

真实历史画面首次曝光, Historical pictures for the first time exposure about "Comfort Women"

Issue date: September 2015。 https://www.youtube.com/watch?v=cHt52PYenME

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Appendix 9.9 Wag the Dog Tragedies: Implications to the US

"Wag the Dog" is an uniquely expressive and colorful American expression. Merriam Webster Dictionary[18] defines the term as:

> a situation in which an important or powerful person, organization, [nation], etc., is being controlled by someone or something that is [weak] much less important or powerful.

It is a highly effective strategy, but used by the weak. And which has brought very tragic results in the past. Consider the examples below. Who is wagging whom?

- World War I illustrates the tragedy that wag-the-dog can bring.

Bagby (1994) writes: "Kaiser Wilhelm made a crucial mistake in guaranteeing Serbia's security and allowed himself to be overtaken by war paranoia". Serbia the tail was wagging Austria-Hungary and Germany. Tuchman in her celebrated book *The Guns of August* narrates the sequence of events in a gripping narrative (Tuchman 2014, 79).

> "Some damned foolish thing in the Balkans". Bismarck had predicted, would ignite the next war. The assassination of the Austrian heir apparent, Archduke Franz Ferdinand, by Serbian nationalists on June 28. 1914, satisfied his condition. Austria-Hungary, with the bellicose frivolity of senile empires, determined the use to use the occasion to absorb Serbia . . . On July 25 Germany assured Austria that she could count on Germany's "faithful support" . . .

- Another example from WWI illustrates how the wag-the-dog strategy is put to play.

Around 1910, the British were already anticipating hostilities in the continent. At that time, Harold Wilson held the office of Director of Military Operation of the British Army. Fluent in French, he struck a strong friendship with Ferdinand Foch then commandant of the École Supérieure de la Guerre in France. MacMillan (2013, 402) writes the following conversation between them:

> Wilson: "What would you say was the smallest British military force that would be of any practical assistance to you in the event of a contest such as the one we have been considering?
>
> Foch: One single private soldier, and would take good care that he is killed."

"The French would do whatever it took to get Britain to commit itself. In 1909 they produced a carefully faked document . . . which purported to show Germany's invasion plans for Britain" MacMillan (2013, 402).

The outcome of this tragedy was 40 million dead by the end of the war. Germany lost 2.476,897 people, 3.8% of its population; Austria-Hungary 1.567,000 people or

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[18] https://www.merriam-webster.com/dictionary/the%20tail%20wagging%20the%20dog

3.05% of its population; and Serbia suffered 278,000 dead or 16.11% of its people.[19] Germany suffered the most. And the seeds of WWII were sown by all.

- The preeminent scholar of political science, Hans J. Morgenthau (Morgenthau 1960). writes: “Never Allow a Weak Ally to Make Decisions for You” Those that do “lose their freedom of action by identifying their own national interests completely with those of the weak ally. Secure in its support of its powerful friend, the weak ally can chose objectives and methods of its own foreign policy to suit itself” (Morgenthau 1960, 565). Morgenthau cites the example of Turkey wagging France and Great Britain during the events leading to Crimean War. Turkey in effect incited Great Britain and France into war confident of their support in the event of armed conflict against Russia.
- Fast forward to the current situation in the Pacific. The right-wing Japanese government “buys” the DiaoYu/Sennkaku Islands; thereby, violating the *status quo* and the tacit agreement between Chinese Premier Deng XiaoPing and Prime Minister Tanaka of Japan. Japan now declares that there was no such understanding. It stokes China bashing and gets Obama’s agreement to include the islands in their mutual defense treaty. The US is also reticent to near silence about Japan’s irredentist claims of the Korean Dokdo Islands, and Southern Kuril Islands, which according to the Potsdam Declaration, they have no rights to. The Declaration states that “Japanese sovereignty shall be limited to the islands of Honshu, Hokkaido, Kyushu, Shikoku . . .” DiaoYu is not among them. Abe visits the Yakuzuni in Tokyo where Class A war criminals are memorialized. We tolerate, wink and nod at these actions. The Japanese government approved the addition of *Mein Kampf* as a text book in Japan’s educational curriculum.[20] One wanders about the necessity of the legislative body of Japan to take this appalling action. Yet the silence from the US government and press is disheartening. The tail is wagging too fiercely. I fear that, for the follies of the right-wing neo-militarists, innocent Japanese people may have to reap the whirlwind yet again (Murphy 2014).
- As we go into press, a baffling and bizarre version of wag-the-dog is playing out in North Korea. Recent vitriolic attacks in the North Korean press against China are bewildering. They are even threatening China with “grave consequences”, declaring an ultimatum and reminding the Chinese leadership that "China should no longer try to test the limits of the DPRK’s patience.”[21] This is a case where the ***tail bites the dog.*** The result is that it is drawing China closer to the US. This is a positive development.

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[19] Centre Européen Robert Schuman. Downloaded 25 April 2017. http://www.centre-robert-schuman.org/userfiles/files/REPERES%20%E2%80%93%20module%201-1-1%20-%20explanatory%20notes%20%E2%80%93%20World%20War%20I%20casualties%20%E2%80%93%20EN.pdf

[20] http://www.japantimes.co.jp/news/2017/04/15/national/social-issues/japan-tolerates-use-hitlers-autobiography-schools/#.WQLVfeQkt9A

[21] http://www.cbsnews.com/news/north-korea-threatens-china-grave-consequences-nuclear-standoff/

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Part IV
Book Summary

Part IV is comprised of a single chapter:

Chapter 10—Summary: Executive Decision Synthesis Paradigm

Chapter 10
Summary: Executive Decision Synthesis Paradigm

Abstract We have two goals for this chapter. The first is to present a summary of the key ideas of our prescriptive decision paradigm. Second is to state the overarching concepts of our paradigm. These concepts are "like the skeleton, which, invisible to the naked eye, gives form and function to the body" (Morgenthau, *Politics among nations*. Alferd A. Knopf, 1960). These concepts are faintly visible throughout the book, but they form the skeleton of our book. We must be clear that we are making no claims about paradigm as theory. We are grounded on theory, but we are not building theory. Third, we will argue that we a rigorous paradigm. To demonstrate rigor, we submit our paradigm to tests of theory formulated by scholars. These tests of theory are the "eye of the needle" to demonstrate the paradigm's rigor, not to claim to theory. But nevertheless, we will thread the needle. We conclude that we have a rigorous prescriptive paradigm for robust executive decisions. The functionality and efficacy of our systematic process is verified by our simulations and case studies.

10.1 Introduction

This book began with a discussion about who is an executive, what is their span of control and the source of their power. We defined a decision as an artifact in the sciences of the artificial (Simon 1997, 2001), and the decision-enacting sociotechnical system as manufacturing production, a factory whose quality can be rigorously measured. We presented a systematic, step-by-step prescriptive paradigm to design robust executive decisions framed within a life-cycle management process spanning five spaces. We discussed the historical background and extant theories of decision theory and located our work in the prescriptive school. This chapter recapitulates our contributions and salient points about our paradigm. And finally, we argue that we have a rigorous and systematic prescriptive process executives can practice with confidence.

The chapter proceeds as follows. Consistent with the rubric of Summary, we begin by presenting a condensed list of the key concepts of our prescriptive paradigm (Sect. 10.2) These are the most salient and original ideas of our prescriptive paradigm. Foremost in the list of ideas is the *design of robust decisions*. Section 10.3 discusses how we answer the question about whether our methodology *works*. For any prescriptive methodology to be meaningful, it must *work*. We

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argued in Chap. 4 that a prescriptive sociotechnical methodology *works* if and only if its functionality and efficacy can be verified. We summarize the metrology and the measurement instrument we developed for the functionality and efficacy verification processes. This is an original contribution to the field of prescriptive decisions. In Sect. 10.4 we discuss another important question, does our paradigm produce good decisions? We discuss this by evaluating our paradigm using Howard's criteria for good decisions (Howard 2007) and Carroll and Johnson's criteria (1990) for good processes. We show that our methodology exceeds their criteria. Finally in Sect. 10.5 we evaluate our paradigm using tests of theory. We use these tests not to show we have a theory; rather, because these tests are so strict they serve as the "eye of the needle" for paradigm rigor. We conclude that the work in this book gives us confidence that we have a rigorous paradigm that works. Finally we conclude with the fundamental overarching concepts that underpin our work.

10.2 Our Paradigm's Salient Ideas

- Robust executive decisions. Decision processes that are highly immune to uncontrollable conditions are said to be robust. Our prescriptive paradigm presents a systematic process to design decisions whose outputs are highly insensitive to uncontrollable and unpredictable conditions. This is a departure from conventional decision strategies that seek to maximize output without the property of high immunity to unpredictable conditions. Robustness reduces the downside risk of decision-making while still being able to capture upside opportunities.
- Our paradigm is grounded on the sciences of non-physical artefacts that are man-made. These are the Sciences of the Artificial and Bounded Rationality. Executive decisions are nonphysical artefacts. They are intellectual artefacts. Bounded rationality recognizes the limitations of time, data, computing power, and cognitive capacity. Therefore, the goal is to *satisfice* with robustness, not necessarily optimize or maximize in the absence of uncontrollable conditions.
- Executive decisions are non-physical man-made objects. Decisions are specifications designed for organizational action. They are blueprints for action that produce intended outcomes. Decisions are prescriptions created from design synthesis processes.
- Decision-making is an event. Executive decision management is a life-cycle process of five sociotechnical spaces. They are the Problem, Solution, Operations, Performance, and Commitment Spaces (Fig. 10.1).

Each space has at its core a fundamental sociotechnical system (Fig. 10.1)—the cognitive, design, production, measurement system, and the decisive executive, respectively. Each is intended to focus on a specific functional domain, i.e. sense making, decision synthesis, *gedanken* experiments, performance evaluation, and commitment to action, respectively.

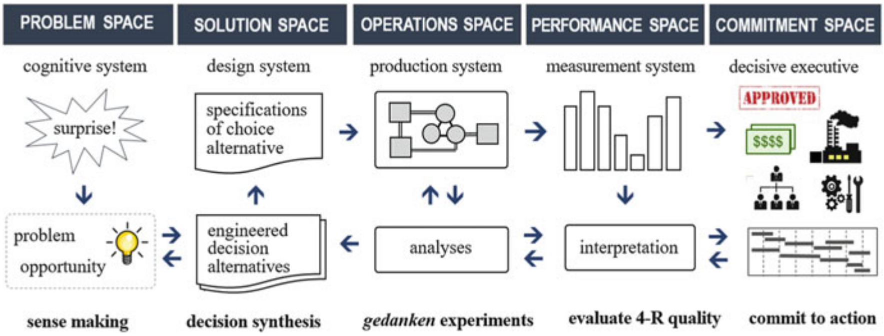

Fig. 10.1 The five spaces of the executive decision life cycle

Table 10.1 Systematic processes for the five spaces of executive decision's life cycle

Process spaces	Our systematic process
Characterize Problem space	• Sense making—uncomplicate cognitive load
	• Frame problem/opportunity and clarify boundary conditions
	• Specify goals and objectives
	• Specify essential variables – Managerially controllable variables – Managerially uncontrollable variables
Engineer Solution space	• Specify subspaces of solution space – Alternatives space and uncertainty space
	• Specify entire solution space
	• Specify base line and uncertainty regimes – Do-nothing case and choice-decision – Estimate base line and dispel bias
Explore Operations space	• Specify – Sample orthogonal array – Do-nothing case and choice decision-alternative
	• Predict outcomes
	• Design and implement robust alternative • Design and implement any what-if alternative
Evaluate Performance space	• Evaluate performance: analyze 4R • Robustness, repeatability, reproducibility • Reflect
Enact Commitment space	• Decisive executive • Approval of plan • Commit funds, equipment, organizations

- The sociotechnical system that enacts decision specifications is a ***production system***, like a factory that makes parts. In our case, the parts are decision specifications. As in every manufacturing and production system, its performance must be rigorously measured, *viz.* what is its production quality? Our paradigm adopts the Gage R&R manufacturing quality-measurement methodology for this purpose. The R&R stand for Repeatability and Reproducibility quality measures.

- Systematic Actionability is a fundamental goal of our prescriptive paradigm. To that end, we specified actionable prescriptive processes, within each space (Table 10.1).
- Unconstrained capability to explore any region of the solution space is a uniquely useful and practical capability of our prescriptive methodology. Exploration is accomplished using *gedanken* experiments. These experiments are not constrained to restricted local regions of the solution space under limited uncertainty conditions. Nor are the uncertainty conditions limited to small regions of the uncertainty space. The uncertainty space is made tractable by the specification of *uncertainty-regimes* that can span the entire uncertainty space.
- Powerful predictive capabilities are inherent in this paradigm. Unconstrained exploration is not very useful without the capability to predict outcomes of designed decision alternatives. Moreover, predictions without knowledge of their associated standard deviations would also make the prescriptive methodology very insipid. Our paradigm provides the ability to predict outcomes of any designed decision alternative including their associated standard deviations under any uncertainty regime. Our systematic processes make explorability very meaningful and practical. It enables us to design robust decision alternatives.
- In the final analysis the question is always: Does our paradigm work? This question cannot be answered as if we were discussing a light bulb. To address this question, we develop a metrology and a measuring instrument to calibrate the extent to which our paradigm will work. This another first in the field of executive decisions and the subject of the next Sect. 10.3.

10.3 Does Our Paradigm Work? A Metrology with Instruments

Whether complex systems, methodologies, or technologies "work" cannot be understood as a binary attribute. "Does it work?" cannot be framed, and addressed using the light-bulb on/off metaphor and posed as a false dichotomy. "It works" is a composite verdict of two orthogonal judgements about a designed decision and its specifications. One verdict is about *functionality*; the other is about *efficacy* (Fig. 10.2). Functionality and efficacy are necessary conditions. This is like the development of a drug in the pharmaceutical industry. Does a drug work? First it must be verified that it is functional in the laboratory of the pharmaceutical company. Namely, that it is functional. Second, that it must be verified that in the field of its efficacy*, viz.* that usage by customers is effective.

Functionality means that the prescriptive methodology is *ready-**to**-work*. This means that we, as creators of our executive-decision paradigm and its methods, can

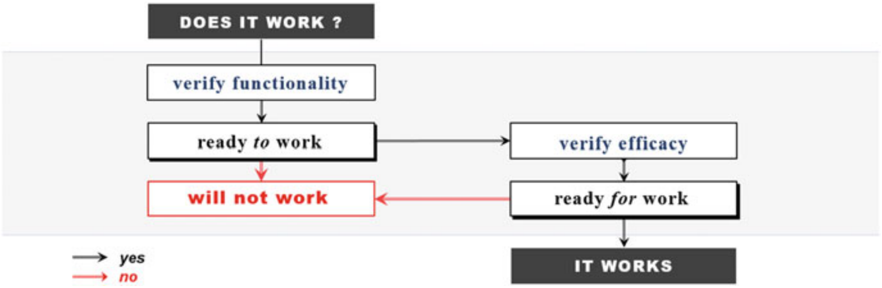

Fig. 10.2 Framing the concept of "It Works"

legitimately claim that our prescriptive methodology will perform as intended. For functionality, we must convince ourselves that our methodology meets our engineering design specifications. The onus is on us, as the original engineers and designers of this methodology. On the other hand, efficacy means that an executive, has made an independent verdict of effectiveness and made a commitment for usage. An executive has systematically acquired a body of information confirming or refuting the functionality and performance claimed by the artefact's creators. An executive is now convinced that our methodology is *ready-**for**-work*. This is a test of efficacy. In summary:

- Readiness is at the center of ready-**to**-work and ready-**for**-work. Our methodology "works" if and only if it is ready-to-work and ready-for-work.
- Functionality is necessary and sufficient to demonstrate our methodology is ready-to-work. The presumption is that it meets all design specifications, i.e. it will function as designed.
- Efficacy is necessary and sufficient demonstration that our methodology is ready-for-work for an executive. The presumption is that it is ready-to-work, and it is effective for an executive.

We now know the "what" of readiness. The "how" remains to be addressed, *viz.* "how" do you demonstrate readiness? What are the tools to measure the extent of readiness?

Measuring readiness is not like using a ruler, handling an ohmmeter, or simply standing on a weight scale in the bathroom. All of which can be accomplished in one undemanding move. In contrast, measuring readiness is a systematic and disciplined socio-technical process. It involves organizational procedures, skilled professionals, technical equipment, and a measurement system grounded on science, engineering, and logic. We need a **metrology** for readiness. *Regrettably, the science of metrology is absent in the field of executive decision theory and praxis.* We remedy this lacuna.

We define "metrology for readiness" as the science and practice of measuring the degree or extent of readiness of our methodology. Fundamental to any metrology is a discipline-neutral lingua franca for senior-executives and technical professionals to communicate goals, status, and progress. This exists, for example, for technology readiness (Tang and Otto 2009), but not for executive decision

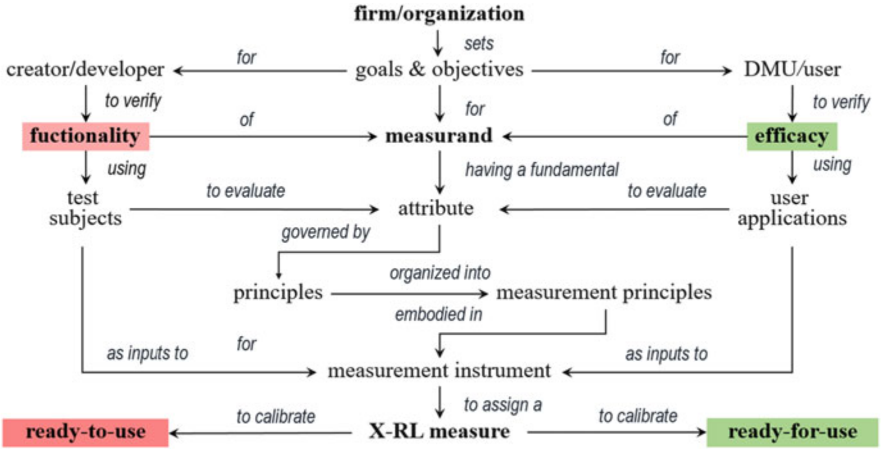

Fig. 10.3 Conceptual architecture of a readiness metrology

methodologies. Our metrology for readiness is a dynamic sociotechnical system. Its conceptual architecture is illustrated by Fig. 10.3 and the lingua franca in Table 10.2.

- Measurement. Measurement is a process or experiment for obtaining one or more quantities about attributes of outcomes that can be ascribed to our executive-decision paradigm and its methods. The quantities are also called values. The attribute of interest is readiness.
- Measure. A measure is the assignment of a numerical value that represents the intensity of the *readiness* attribute of our methodology. Our methodology is the measurand.
- Measurand. The methodology that is the subject of measurements is not a simple "dumb" artefact like a resistor. The resistor is *passive*. Complex measurands, like a car engine being measured for power, requires fuel to make the engine run in order to take measurements. The combination of engine and the fuel form a *system measurand*. The measurement unit is newton-meters, for example. Our methodology together with an experimental test case qualifies as a system measurand.
- Measurement Unit. Measurement unit is a defined scalar quantity that will be used as a basis for comparison. Our measurement for readiness is an ordinal number, *readiness level-n*, $n \epsilon \{1,2,3,4,5\}$. Level-1 is the lowest readiness level for least ready. Level-5 is the highest for most ready.
- Measuring instrument. A measurement instrument is an artefact used for making measurements, alone or in conjunction with supplementary artefact(s). A ruler is a simple instrument. The twin Laser Interferometer Gravitational-wave Observatory (LIGO) detectors form a system instrument. Instruments can be physical, non-physical or a mixture of both.
- Measurement procedure. A measurement procedure is intended for *people* to implement. The procedure is a documented recipe that is in sufficient detail to

Table 10.2 Readiness level specifications for executive decisions

Process Phases	Our systematic process	
X-RL1 Characterize **Problem space**	Sense making—uncomplicate cognitive load	☑
	Frame problem/opportunity and clarify boundary conditions	☑
	Specify goals and objectives	☑
	Specify essential variables Managerially controllable variables Managerially uncontrollable variables	☑
X-RL2 Engineer **Solution space**	Specify subspaces of solution space Alternatives space and uncertainty space	☑
	Specify entire solution space	☑
	Specify base line and uncertainty regimes Do-nothing case and choice-decision Estimate base line and dispel bias	☑
X-RL3 Explore **Operations space**	Specify Sample orthogonal array Do-nothing case and choice decision-alternative	☑
	Predict outcomes	☑
	Design and implement robust alternative	☑
	Design and implement any what-if alternative	
X-RL4 Evaluate **Performance space**	Evaluate performance: analyze 4R	☑
	Robustness, repeatability, reproducibility	☑
	Reflect	
X-RL5 Enact **Commitment space**	Decisive executive	☑
	Approval of plan	☑
	Commit funds, equipment, organizations	☑

☑ Indicates required for Readiness

enable a measurement that is attributable to the extent of readiness of an executive-decision paradigm and its methods.

- Measurement principle. A measurement principle is a phenomenon that serves as the basis for a measurement. For example, concentration of hydrogen ions by increments of 10 in a liquid solution determine the pH value. Factors of 10 make a qualitative change in the acidity of a solution. Principles are made operational and discernible by methods within an instrument.
- Measurement method. An *instrument* implements, by design, a logical organization of operations during a measurement according to measurement principles to obtain a readiness *measure* for an executive-decision paradigm and its methods. A measurement method is intrinsic to the instrument. In contrast, a measurement procedure is extrinsic, it is intended for people to implement.
- Measurement system. We define the measurement system as the sociotechnical composite comprised of the organization, their knowledge, data bases, formal and informal procedures, and instruments, all together, as a measurement system (Figs. 10.3 and 10.4).

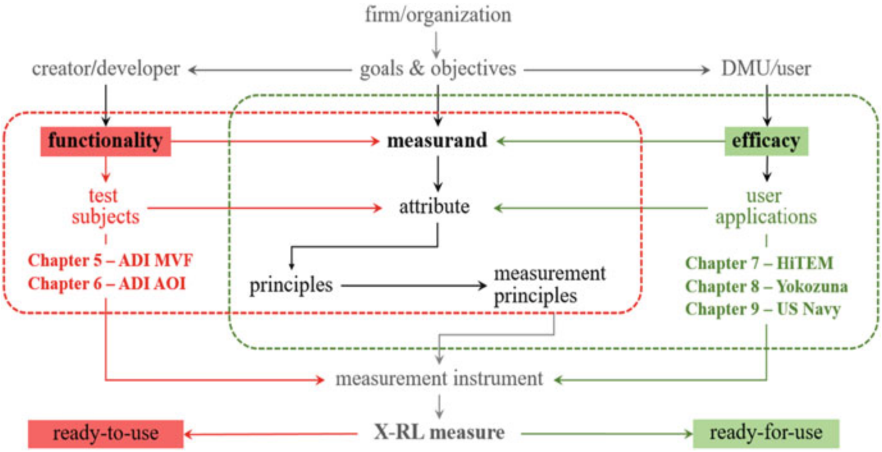

Fig. 10.4 Verifying functionality and efficacy using our metrology framework

We verified functionality in Chaps. 5 and 6. We used simulations of a real company by implementing the tasks within the box outlined by the red dashed lines. We verified **efficacy** in Chaps. 7, 8, and 9 with real world executives by implementing the tasks within the green dashed lines. The instrument used to calibrate readiness is our X-RL checklist of progressively increasing readiness, Table 10.2. Findings from Chaps. 5, 6, 7, 8, and 9 support our claim of functionality and efficacy for our prescriptive paradigm.

10.4 Does the Paradigm Produce Good Decisions?

Regarding what is a “good” decision, there are many opinions. In Sect. 2.7, we reviewed three authoritative views on that subject. The first is based on the well-known four axioms of von Neumann and Morgenstern’s (vNM). Second view are Howards’ criteria six of a good decision (Howard 2007). Third are Carroll and Johnson’s criteria regarding a good decision process and its outcomes (Sect. 2.7.4). In this section, we will review our paradigm against Howard’s criteria and then use Carroll and Johnson’s criteria. We will also do so using our 4-R criteria. We will summarize our findings and close this section.

10.4.1 Review Using Howard’s Criteria

Howard’s six criteria of a good decision analysis process are:

- A committed decision-maker. By definition a decision is determining of what to do and what not to do with a resolute commitment to action.

- A right frame. Framing is the process of specifying the boundaries of a decision situation. What is to be included and what is going to be excluded from consideration. An articulated frame shapes a decision maker's conception of the acts, outcomes, and contingencies associated with a particular choice to be made (Kahneman and Tversky 2000).
- Right alternatives. Their development is the most "creative part of the decision analysis procedure" (Howard and Matheson 2004, 27; Simon 1997). A creative alternative is one that might resolve a conundrum, remedy defects, and improve future prospects.
- Right information. Information is a body of facts and/or knowledge that arm an executive to make more meaningful, accurate, and complete evaluations of decision alternatives. The goal is to improve judgment.
- Clear Preferences. Every alternative is more or less attractive, preferred or undesirable, to an executive by applying consistent rules.
- Right decision procedures. Having the right decision procedure means having a process like our systematic paradigm, the canonical paradigm, or a process like Howard's Decision Analysis process (Howard 2007). The goal is having disciplined and effective processes between a DMU and organizational units (Spetzler 2007).

We evaluate our prescriptive paradigm relative to Howard's criteria. The summary of our evaluation is shown in Table 10.3.

Howard's criteria concentrate on the tasks leading to the event of decision-making. The criteria are constructed around four questions: who decides? How do you decide? What do you know? And what do you want? Howard then specifies desirable attributes about who, how, and the two what's. For example, who decides? Answer: a committed decision maker. How to decide? Answer: right decision procedures. And so on. The question that is left implicit is: So what? Namely is the outcome as desired and expected? Consistent with strong normative character of Howard's decision analysis process, the implicit assumption is that a rigorous process that is predicated on the vNM axioms with the right information is

Table 10.3 Review of our paradigm relative to Howard's Criteria

Howard's criteria	Selected particulars of our prescriptive systematic process	
Committed decision maker	Decisiveness is a requirement for our executive decision maker	●
A right frame	Sense making, framing, clear goals and objectives part of our paradigm	●
Right alternatives	Design of robust solutions alternatives are part of our actionable processes	●
Right information	DMU debiased *gedanken* experiment data	●
Clear inferences	Robust solution identified by outcomes and standard deviation	●
Right decision procedures	Decision design synthesis, ANOVA, Gage R&R, strong predictive power	●

● Indicates Howard's criterion is met

by definition a good logical decision. He writes that “there is no better alternative in the pursuit of good outcome than to make good decisions” which is by his standards the “right decision procedures” (Howard 2007, 33). Good process is a good decision.

10.4.2 Review Using Carroll and Johnson’s Criteria

Carroll and Johnson (1990) specify six criteria to evaluate a decision and its processes. They are:

- Discovery. “Having the power to uncover new phenomena, surprise the researcher, and lead to new creative insights.”
- Understanding. Having valid constructs that uncover mechanisms. “Providing a cause-and-effect analysis that uncovers the mechanisms or processes by which decisions are made” i.e. uncovering working principles.
- Prediction. Ability to make predictions based on rules of logic, and mathematics. “Having logical or mathematical rules that predict the judgement and decisions that will be made. The rules need not represent the actual decision processes.”
- Prescriptive control. Capability to modify the process including better prescriptions and hypothetical what-if and other conditions. “Providing opportunities and techniques for changing the decision process, as in prescribing better decision rules or testing potential manipulations.”
- Confound control. Creating controlled situations. “Creating controlled situations so as to rule out other explanations of the results (Known as confounds).”
- Ease of use. Efficient and economic use of time and resources. “Taking less time and resources for the same progress to the other goals.” This means that it must be efficient.

Table 10.4 highlights of the evaluation of our systematic process using Carroll and Johnson’s criteria.

Carroll and Johnson’s (1990) criteria have a strong emphasis on the quality of the process (e.g. confound control, prescriptive control, ease of use), the impact of outcomes (e.g. discovery, understanding), predictive capability, and new insights (e.g. discovery and understanding). Their criteria have strong decision life cycle perspective.

10.4.3 Review of Our Approach

10.4.3.1 Introduction

There is a lot of dogma on the issue of what are good decisions (Sect. 2.7). Given the sociotechnical complexity, messy, and wicked nature of **executive** situations, we assert that robust decisions that satisfice a decisive executive are good decisions.

Table 10.4 Review of our paradigm relative to Carroll and Johnson's Criteria

Carroll and Johnson's criteria	Selected particulars of our prescriptive systematic process	
Discovery	Executive decisions can be studied using *gedanken* experiments and DOE	●
	Decisions' production quality can be measured with Gage R&R	
Understanding	*Ex post* phenomenological system behavior can be determined	●
	Essential variables are the controllable and uncontrollable variables	
	Determine the gage, repeatability and reproducibility of production system	
	Model behavior of the sociotechnical system under any uncertainty regime	
Prediction	Can predict the outcomes and standard dev of any designed alternative	●
	Prediction of a decision alternative can be under any uncertainty regime	
Prescriptive control	Vary uncertainty conditions at will to explore decision alternatives	●
	Vary the intensity of any controllable and uncontrollable variable	
	Configure any mix of variables to predict out comes and standard deviation	
Confound control	The % contribution of variables revealed by ANOVA statistics	●
	The importance of interactions can be determined for appropriate analysis	
	Effect of any uncertainty condition or any variable condition is predictable	
Ease of use	Orthogonal array sampling is enormously efficient	●

● Indicates Carroll and Johnson's criterion is met

The aphorism about the proof of the pudding applies. The chef may offer an opinion, but the fact he chose the right recipe from Julia Child, has the right ingredients, and so on are all relevant. Moreover, the chef has undoubtedly sampled his work and judged it to be good. But the aphorism asserts other important determinants of a good pudding that need to be considered.

The judgement of *good executive decisions* must include a verdict from the executives who are responsible and accountable for the decisions they make and for the outcomes they produce. The executives who must evaluate a decision-maker's performance also contribute to this verdict. This is realistic and practical. They are the ones who have their careers, promotions. bonuses, and kid's college tuitions at risk. ***They, who have been given the power to command, must be able to explain their decisions to whom they must answer to***. And so on up the chain of command. The judgements are unlikely to be based entirely on outcomes or exclusively on process. Research shows that presenting strong arguments, to justify a decision and an outcome, is an effective managerial practice (Keren and de Bruin 2003). Thus we concur with the statement that "there is no unequivocal answer to the question how to judge decision goodness" (Keren and de Bruin 2003). The answer is situational, not categorical. By no means, are we advocating a "do nothing" approach to the question of a good decision. Research must continue to add to the cumulative knowledge about good decisions.

Howard's approach, Carroll and Johnson's reveal different emphasis—Howard more on the rigor leading to the event of decision-making, whereas Carrol and Johnson more on the process and the learning that can be accrued from outcomes. Our paradigm is a life-cycle prescriptive methodology. We can segment it into temporal phases. We start by marking the time when the decision is taken, i.e. when the executive commits to a decision specification and assigns resources to its implementation. Call this the *zero-hour*. We have the following time periods—*ex ante* (before zero-hour), *ex inter* (during zero-hour), and *ex post* (after zero-hour). In our paradigm, we consider:

- ***ex ante***. The process must consider the actions before zero-hour. For example, Howard's criteria for a decisive executive (Sect. 10.4.1) and design for Robustness (Sects. 2.7.5 and 1.3.2.5) are examples of actions taken *ex ante*. We address this by specifying XRL1, X-RL2, and X-RL3.
- ***ex inter***. The sociotechnical system must have a decisive executive who can commit at the moment of decision, zero-hour (Sect. 1.5.3 and Appendix 1.5). At the moment of decision, the executive must commit. We address with X-RL4 and X-RL5 requirements and prescriptions.
- ***ex post***. Every decision involves an outcome, it follows that it is necessary to evaluate the quality of the outcome and of the sociotechnical system that produced it. The implementing sociotechnical system is a manufacturing production system of decisions as intellectual artefacts. Repeatability and reproducibility (Sects. 2.7.5 and 1.3.2.6) are the quality measures of such a production system. Measurements are meaningless without reflecting and learning from them; therefore this is a requirement. We address with X-RL4 requirements and prescriptions.

Pushing our pudding aphorism further, we assert that our X-RL instrument and its set of actionable prescriptions are directed at the chef and the consumer of the pudding.

10.4.3.2 First Principles and Epistemic Rules

Prescriptive methodologies must not only be useful but also meaningful. Regrettably, many are of the "buy low, sell high" variety. They sound good, but are not sound. Prescriptions should not be just based on data and empirical patterns. The entire prescriptive body must be coherent as a conceptual structure, based on first-principles (Sect. 1.6). We impose four epistemic rules to test our principles:

- **Rule 1. Research Rule**. The principles must have a research base. Scholarly work that investigates these principles and closely related subjects must exist in the literature.
- **Rule 2. Falsibility Rule**. The Popper falsibility criterion must apply (Popper 1959). Science is distinct from non-science by the fact that only falsifiable claims can be considered scientific. We impose this rule because we seek to bring rigor to our prescriptive paradigm. In our case, we use Bacharach's (1999) tests of falsibility (Sect. 10.5).
- **Rule 3. Accretion Rule**. The principles must advance the research and the practice of executive-decision for complex, messy and wicked situations. Science and praxis advances through the accretion of valid and effective knowledge and the elimination of invalid information from anecdotal customs and processes.
- **Rule 4. Sciences-of-the-Artificial Rule**. Our principles must be consistent with the fundamental premises of the Sciences of the Artificial. Sciences of the Artificial dealing with manmade artefacts under bounded rationality (Simon 1997, 2001).

Our six principles follow (Sect. 1.6.2).

Principle 1. Abstraction *Reduce cognitive load, attack complexity by abstractions.*

This principle is grounded on the cognitive sciences. Reduce the cognitive load imposed on the DMU with representations that are not complicated. Whereas complexity is an inherent property of systems, complicatedness is the degree to which people make complexity cognitively unmanageable. Einstein famously said: "Make things as simple as possible, but not simpler." Complexities need not be exhaustively revealed, in their glorious detail, to those who have to deal with it. Abstraction will facilitate cognition for meaningful sense-making, decision design, and enactment. Abstracting is seeing the underlying simplicity of complexity (Simon 1997, 2001). To abstract, one must suppress non-essential features so that its essential structure and working principles are revealed, in their most parsimonious and insightful forms (Sect. 3.2). Abstraction is also necessary for implementing sociotechnical systems to attenuate operational cognitive load required.

Principle 2. Actionability *Ground abstraction on managerially controllable variables that directly influence intended outcomes.*

This principle is targeted at the frequently voiced criticism that abstractions are difficult to operationalize. Our Actionability principle is grounded on elegant engineering design-practice. Focus on the essential variables (Sect. 3.3.2). Elegant engineering design uses effective working principles using a parsimonious set of variables, to determine the behavior and the artefact to produce the intended outcomes. Good design represents an **uncomplicated** mental model of the decision situation and its specifications for action. In Sect. 1.4.3, we discussed the logic and significance of an uncomplicated system image for those faced with complex and messy situations. Concentrate on decision specifications that will satisfice. Simon (1997; 112) argues that for functional artifacts, the keys are "… an understanding of what are the key variables that shape system equilibrium and what policy variable can effect that equilibrium". In our paradigm, we argue the necessity of including uncontrollable variables and explicitly integrating them into the prescriptive paradigm. The entire spectrum of uncertainty is thus addressed with our actionability principle.

Principle 3. Robustness *Design decisions so that they are highly immune to uncertainty conditions even when uncontrollable conditions cannot be removed. This is robust design.*

Uncertainty is part of the universe. This means that many variables are managerially uncontrollable. Robustness is the property of a system that is high immune to the pernicious effects of uncontrollable variables even when they cannot be removed. Thus, systems and decisions must be designed for robustness. Robustness is achieved by identifying the essential uncontrollable variables and including them in the design of the decisions. Robust engineering methods for physical products are proven to be highly effective. We adopt this strategy for the design of executive decisions.

Principle 4. Unconstrained Explorability *Unconstrain actionability by enabling exploration of the entire solution space under the entire space of uncertainty conditions.*

The first idea to solve a problem is unlikely to be the most worthy. Explorations for alternative and potentially superior ideas must be permitted without constraints. Any hypothetical "what if" decision alternative must be permitted to be explored under any uncertainty condition. Actionability and Robustness are highly desirable, but not very useful if the decision can only be explored in a narrow region of the solution space and only under a very limited set of controlled conditions. A useful methodology must remove these constraints. This capability of unconstrained explorability is required for any executive decision alterative.

Principle 5. Production Quality Is R&R *Production quality is robustness, repeatability and reproducibility.*

Principles 1, 2, 3, and 4 deal with the definition, design, and exploration of design alternatives. This principle deals with the production system for executing decision specifications. The focus is on the quality of the decision-manufacturing system. This principle is grounded on performance evaluations and improvements based on measurement data of the sociotechnical system's operations. We want to know the quality of the system and pinpoint sources of production defects. Are the defects due to the measurement tools, the artefact, the people in the measurement process, or a mix of these factors? If so to what extent is each of these factors contributing to the defects? Consistently predictable outcomes must be the result of r*epeatable* and *reproducible processes*. These criteria are useful to analyze the quality of results and to identify sources of defects in the processes.

Principle 6. Decisiveness *An executive cannot be irresolute. Executives by definition must decisively formulate a plan, lead organizations to execute and commit irrevocable resources for implementation.*

Decisiveness is the ability to cross the Rubicon. Tom Furey, IBM senior executive and friend, was fond of saying that he'd rather be wrong than indecisive. Doing nothing, at the moment of decision, merely extends the state of uncertainty and prolongs ignorance. Even doing the wrong thing will produce new information that confirms or refutes. Doing something becomes a learning opportunity. An executive must be decisive, take a decision when it is required, not sooner, not later. Neither jumping the gun nor procrastinating, but acting with firmness and determination in the face of uncontrollable uncertainties. Commit irrevocable funds and equipment, lead organizations to enact, and engage existing a new critical skills to implement the plan. Timidity, indecisiveness and reluctance to make a decision are sure signs of one who should not be in a position of command. Decisiveness is a necessary condition, but insufficient for effective and efficient decisions. Finally decisiveness also means having principles for knowing when to say *yes* and when to say *no*.

10.5 We Have a Rigorous Paradigm

10.5.1 Definition of Prescriptive Paradigm

This book is about a prescriptive paradigm for executive-management decisions. The vast majority of the book has concentrated on the prescriptive parts. We began with an overview of our prescriptive methodology, followed with a review of the literature to place it in context. Then we discussed our approach to show that the methodology "works". And finally we used five cases to show functionality and efficacy. But what is a prescriptive paradigm? We define it as follows:

> A **prescriptive paradigm** is a set of systematically actionable processes, based on first-principles and epistemic rules, to produce robust outcomes under uncertainty for complex, messy, and wicked sociotechnical problems.

10.5.2 Tests of Paradigm Rigor

In this section we will test our paradigm against criteria of a theory. *We do not claim, nor do we desire to claim that our prescriptive paradigm is a theory*. But the tests of theory are meaningful to test the rigor of our prescriptive paradigm. They are the "eye of the needle", which will thread with the work of scholars and our finding in this book. We will apply three tests. Baharach's test of theory, Sutton and Staw (1995) test of what is *not* theory, and finally, Shepherd and Suddaby (2016) tests for theory and theory building.

Bacharach (1999) in a widely referenced paper discusses in detail the necessary components of a good theory and the evaluation criteria for a candidate theory

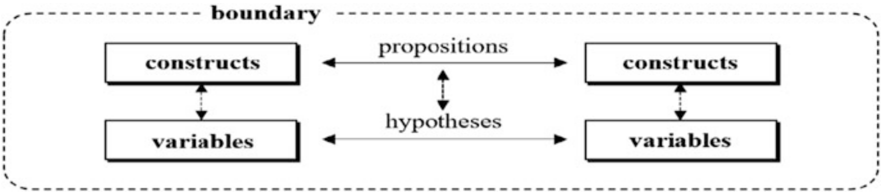

Fig. 10.5 Verifying functionality and efficacy using our metrology framework

(Fig. 10.5). We will use his test, not for theory testing, but to show that we have a rigorous paradigm. According to Bacharach (1999) theory is "statement of relationships between units observed or approximated in the empirical world" … "Observed units mean variables, which are operationalized empirically by measurement (*op. cit.* 498)". A variable is "an observable entity which is capable of assuming two or more values" … "Constructs can be applied or even defined on the basis of the observables [variables]." … "may be viewed as a broad mental configuration of a given phenomenon (*op. cit.* 500)". Finally "theoretical systems take the form of propositions and proposition-derived hypotheses. While both propositions and hypotheses are merely statements of relationships, propositions are the more abstract constructs and all-encompassing of the two … Hypotheses are the more concrete and operations statements of these broad relationships and are therefore built from specific variables (*op. cit* . 500).

Bacharach's criteria are listed in Table 10.5. Our prescriptive methodology satisfices all the criteria. We eschew elaborate explanations. The concepts were addressed in Chaps. 1 through 4, and demonstrated in Chaps. 5 through 9 using detailed case studies.

It can be said that Bacharach's criteria have been satisfied by our simulations in Chaps. 5 and 6, and by our *in situ* case studies in Chaps. 7, 8, and 9.

However Sutton and Staw (1995) argue that the presence of empirical data, lists of variables and constructs, hypotheses, diagrams and models are not sufficient to claim a theory. Wolpin (2013) cogently argues the point. They argue that a "why" must be able to tie all of the above into a coherent conceptual whole. Our interpretation of this statement comes from physics. Tycho Brahe spent a lifetime accumulating data about planetary trajectories. But he did not have a theory. Johannes Kepler made brilliant observations from the data. They are called Kepler's law of planetary motion. But he did not have a theory either. The "why" remained unanswered. It was Isaac Newton that provided the "why" with his inverse square law of gravitational attraction. A stupendous theory was born. Similarly, management was anecdotal and descriptive until Frederick Taylor's time-and-motion studies. Taylor invented a quantitative measurement system for production. Manufacturing has not been the same since. Taylorism was the geneses of management science and production management. This thinking has evolved to administrative theory and social science in organizations (e.g. Thompson 2004). Achterbergh and Vriens (2009) persuasively argue that organizations are social systems conducting experiments. Our thesis is that systematic *gedanken*

Table 10.5 Our prescriptive paradigm satisfies Bacharach's criteria

Criteria	Our prescriptive paradigm
Variables	• Managerially controllable variables • Managerially uncontrollable variables • Social processes • Technical processes
Constructs	• Decision = f (controllable variables, uncontrollable variables) • *Gedanken* experiments = set of organized • Orthogonal array is a set organized of orthogonal decisions • Uncertainty regimes = {n-tuple of uncontrollable variables} • Decision alternatives = {m-tuples of controllable variables} • Solution space = {n-tuple uncontrollable variables} × {m-tuples controllable variables} • DMU is sociotechnical system to address decisions
Hypotheses	• Decisions are an intellectual artefacts • Organizations are sociotechnical systems • Decision are specifications for action for sociotechnical systems to execute • Decision enacting organizations are manufacturing production systems • Decisions are designed intellectual artefacts • *Gedanken* experiments = f (controllable variables, uncontrollable variables) • Solution space = orthogonal array × uncertainty regimes • Uncertainty space can be represented by a progression of uncertainty regimes • A decision *works* if it is both ready-*for*-work and ready-*to*-work – i.e. the decision specification is functional and it is effective
Propositions	• Robust decisions are designed • Robustness can be predicted and measured • Quality of the manufacturing system is measurable using Gage R&R • Unconstrained exploration of solution space is possible • Unconstrained exploration of uncertainty space is possible • DOE (Design of Experiments) of *gedanken* experiments suffices for predictions – Predict robustness, outcomes, and standard dev. of any decision alternative • Prescriptive paradigm's capability is determined by readiness
Boundary	• Empowered decisive executives • Empowered decisive executives • Span of control—middle, up and down • Complex, messy and wicked problems

experiments for robust executive-decision management is functional and efficacious. Bacharach's (1999) criteria are an important test of rigor.

Another test for rigor are Shepherd and Suddaby's (2016) requirements for a theory and theory building. They assert that a good theory is like a good story. It requires five elements: (i) conflict, (ii) character, (iii) setting, (iv) sequence, and (v) plot and arc. We have all those elements in our executive decision life cycle of five spaces. But they have a long list of criteria under each of those elements that must be satisfied. We select seven of the most important (Table 10.6). A challenge is that the criteria are not orthogonal. Nevertheless, we construct our Table 10.6 structured as follows. Each row identifies a key theory building **element**. Under

Table 10.6 Selected key Shepherd and Suddaby criteria for theory building

Element	Notes
Paradox	**"Conflict of two statements"** . . .**individually make sense "but together are contradictory triggers**. . .**" to theorizing and paradox resolution** • Complex, messy wicked sociotech. systems representation is difficult – We reduce this complexity to using only two kinds of variables – Decisions are a Cartesian product of n-tuples of these two variables • Uncertainty is intractable space a managerially and modeling – We define uncertainty regimes that can span the entire uncertainty space • Outcome goals and uncertainty can be risky, but robustness will produce outcomes that are highly insensitive to uncertainty even when those conditions are not removed
Labeling constructs	**"Identifying and naming a core construct(s) helps to separate the phenomenon of interest from the mass of noise** . . .**"** • Decision $= f$ (controllable variables, uncontrollable variables) • *Gedanken* experiments = set of organized • Orthogonal array is a set organized of orthogonal decisions • Uncertainty regimes = {n-tuple of uncontrollable variables} • Decision alternatives = {m-tuples of controllable variables} • Solution space = {n-tuple uncontrollable variables} × {m-tuples controllable variables} • DMU is sociotechnical system to address decisions
Ontology	**"Shifting the way"** . . . **conceptualization to "a new perspective from which to theorize but also requires a corresponding shift in epistomology"** • We reconceptualize . . . – Decisions as specifications for action – Decisions as the output of engineering design of a nonphysical artefact – Decision organizations and their sociotechnical systems as a factory – Decision analysis as *gedanken* experiments using DOE • A paradigm "works" if and only if it is functional and efficacious • We declared our first-principles and epistemic rules (Sect. 10.4.3.2)
Thought experiments	**"Posing problem statements, making conjectures** . . . **trialing conjectures, and selecting and retaining those that show promise** . . .**"** • It is difficult to discern from their description how it differs from thinking, analyzing alternatives and conjecturing. We think that a defining feature of *gedanken* experiments is that physical apparatus is not required • We think of thought experiments as systematic *gedanken* experiments from which epistemic rules and first principles can be applied to gain new and surprising insights. For example, Einstein's elevator *gedanken* experiment, Galileo's *gedanken* experiment • We present a systematic process to construct structured classes of *gedanken* from which robust decisions can be constructed, their outcomes predicted, and the influence of uncertainty on them quantified
Metaphors	**"Analogically connecting and blending concepts** . . . **between domains"** • We adopt the concepts from . . . – Engineering design synthesis concept for physical objects to decisions which are non-physical objects – The ideas of physical experiments to non-physical *gedanken* experiments • Concept that a prescriptive paradigm "works" from the pharmaceutical industry.

(continued)

Table 10.6 (continued)

Element	Notes
	It must be first functional, then it must be verified for efficacy. Concept of readiness from technology management and develop an analogous metrology, measurements, and instruments
Original and useful	**"Reveal something** . . . **we did not know"** • We can design and construct robust decisions, without having to . . . – *Ex ante* represent analytically the decision enacting system *ex ante* decision making – Represent analytically the uncertainty space *ex ante* decision making • We can predict the outcomes and risk over the entire spaces of any potential solutions over the entire space of uncertainty therefore, exploration of solutions over uncertainty is unconstrained • Using DOE with *gedanken* experiments we can predict outcomes and risk over the entire space of uncertainty for any design executive decision • Data collection is massively efficient. Using 243 experiments, in Chap. 9, we cover $1.374{,}389 \times 10^{12}$ possibilities. And we can predict any outcome under any uncertainty regime in this massive space • We can measure the quality of the decision enacting sociotechnical system • We developed a metrology to measure functionality and efficacy
Empirical surprise	**"Reveal data and findings** . . . **not otherwise expected, which requires theorizing for an explanation"** • We find that the predictive power of our methodology is good is supported by the case studies • We find that the sociotechnical system behavior of the organizations are quasi-linear in which the factor interactions are generally small • We find that the case study data supports the view of the decision enacting sociotechnical system is a factory whose quality is measurable • A small number of factors are very effective to model and study very large complex, messy and wicked decision situation under very complex uncertainty conditions

notes, there are two rows**.** The top half is a definition from Shepherd and Suddaby. The bottom half is comprised of bulleted examples from our prescriptive paradigm. We do not attempt to be exhaustively complete with our examples for Table 10.6. Previous sections of this chapter have already addressed many of our key ideas and claims.

10.5.3 Our Paradigm's Core Concepts

Bacharach (1999), Sutton and Staw (1995) and Shepherd and Suddaby (2016) all present demanding criteria that must be met by claims to theory or theory building. The criteria are many and their interrelationships are complex. Applying our first-principle of abstraction, we can distill their criteria to an uncomplicated question:

Can you distill your work to a fundamental idea? We said that Tycho Brahe's work, Kepler's Laws were not theory until Newton's simple idea, but genius concept of universal gravitation expressed by his inverse law was articulated. Similarly all the empirical data, experiments and their false caloric explanations about heat and temperature did not rise to a theory until simple overriding ideas could explain the "why's" of what was observed and measured. The uncomplicated ideas were heat is energy and energy is conserved.

What are the simple, uncomplicated ideas of our prescriptive paradigm? They are:

- Executive decisions can be designed so that they are robust.
- Executive decisions can be designed because they are manmade artefacts. Intellectual artefacts.
- Sociotechnical systems executing executive decisions are production systems like a factory.
- The Sciences of the Artificial serve are the governing principles.
- Sociotechnical rationality serve as the organizing and operating principles. **QED—quod erat demonstrandum**

10.6 Chapter Summary

- Salient ideas of our prescriptive executive-decision paradigm are:
  - Robust executive decisions,
  - Paradigm's grounding on the Sciences of the Artificial,
  - Decisions are manmade intellectual artefacts.
  - Executive-decision management is a life-cycle process of five spaces.
  - Decision enacting sociotechnical organization is a manufacturing production system.
  - Our paradigm is systematically prescriptive.
  - Unconstrained explorability of the entire solution space under any uncertainty regime.
  - Ability to predict outcomes and standard deviations of any designed alternative.
  - Our paradigm works because we can measure its functionality and efficacy. To this end, we developed a metrology and measuring instrument based on the notion of readiness.
- On the question whether our paradigm is a good process to produce good decision:
  - We tested against Howard's criteria and find that it satisfices his criteria.
  - We tested against Carroll and Johnson's criteria and find that it satisfices their criteria.

  - We argue that we have a functional and efficacious paradigm, based on first principles and epistemic rules, for robust executives decisions that satisfice.
  - Epistemic rules are: research rule, falsibility rule, accretion rule, sciences of the artificial rule. Executive decision first-principles are: abstraction, actionability, robustness, unconstrained explorability, Gage R&R for production quality of sociotechnical systems, and a decisive executive.
  - We can say that our prescriptive executive-decision paradigm is useful and helps executives make intelligent robust decisions.

- We have a rigorous paradigm
  - We tested our paradigm against Bacharach's (1999) theory evaluation criteria.
  - We tested our paradigm against Sutton and Staw (1995) criteria of non-theory.
  - We tested our paradigm against Shepherd and Suddaby (2016) tests of theory and theory building.

- The core concepts of our paradigm are:
  - Executive decisions can be designed so that they are robust.
  - Executive decisions can be designed because they are manmade intellectual artefacts.
  - Sociotechnical systems executing executive decisions are production systems, i.e. a factory.
  - The Sciences of the Artificial serve as governing principles.
  - Sociotechnical rationality serve as organizing and operating principles.

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