Technology Roadmapping and Development

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A Quantitative Approach to the Management of Technology

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This book is dedicated to Lynn for her love and unending support

Foreword

If you want to spend a million dollars to develop a specific technology or system, you have a myriad of methodologies and tools at your disposal to help plan and execute your project. You might employ, for instance, design thinking, agile, waterfall, systems engineering, model-based design, TRIZ, axiomatic design, and any number of design and project management tools. If you want to spend a billion dollars on a portfolio of technologies, you are pretty much on your own. Not only is there a dearth of sound theoretical work on the subject of technology planning at scale, but the state of practice is remarkably primitive. If you want to spend a trillion dollars over the course of decades, you are in largely untrodden territory.

Turns out, we, as a species, are not very good at technology planning. The most celebrated technological feats—the Manhattan Project, the Apollo Program, and the iPhone—are renowned for their rapid execution and narrow focus. There have been long-term projects too—the pyramids and the cathedrals—but these took place in times of minimal technological change. Long-term, diverse technology portfolios do not have a good track record. For instance, the U.S. Department of Energy invested about as much as the Manhattan Project and Apollo Program combined (adjusted for inflation) over 35 years into the decarbonization of the US economy with few visible results.[1] NASA spent much of the decades of the 1980s, 1990s, and early 2000s with little to show for its sizable crewed space exploration budget largely due to poor planning.[2]

In my career, I had the opportunity to observe up close technology planning in the Pentagon and in the Silicon Valley venture ecosystem. I was also responsible for a $3 billion/year R&D portfolio at United Technologies and €1 billion in annual technology spending at Airbus (a journey on which this book's author joined me). While at DARPA, I led an unusual (even for DARPA) initiative called the 100 Year Starship, in which we studied how to organize a multi-decade investment in the

[1] The Manhattan Project, the Apollo Program, and Federal Energy Technology R&D Programs: A Comparative Analysis https://fas.org/sgp/crs/misc/RL34645.pdf

[2] In 2012, this led NASA to undertake an ambitious technology roadmapping effort described in Chap. 8.

broad set of technologies needed to travel to the nearest star. While interstellar travel may seem far-fetched and whimsical as a use case for technology planning, the resources and time scales involved are not so different from those needed to decarbonize the world economy, for instance. I had a few battle scars and takeaways from these experiences.

First, the approach to technology planning is usually qualitative and lacking in rigor. This is especially apparent when you compare it to the increasingly sophisticated analysis, modeling, and experimentation used in actually executing technology projects and combining multiple technologies to build systems and products. Almost every organization professes to practice roadmapping to inform its technology planning. Most of these roadmaps are—in a term of art I learned from former DARPA head Regina Dugan—"swooshy." They comprise a fat arrow (a "swoosh"), going from the lower left (bad) to the upper right (good), along an x-axis that loosely corresponds to the passage of time and a y-axis that vaguely represents some unitless measure of progress, with a series of projects enumerated along the swoosh. This kind of roadmap has minimal descriptive value (it is essentially a list of projects) and no prescriptive value whatsoever to help make decisions about which projects should be undertaken, when, and why. Instead, these decisions are made largely through a combination of intuition, opinion, politics, quid pro quos, and fads.

What this conceals, of course, is the fact that every organization operates with constraints, including a finite R&D budget to invest in its technology portfolio. In whatever manner decisions are made, they represent a ranking of possible projects, with some getting funded and others cut. A real roadmap makes this process explicit, which can be uncomfortable. It exposes the tradeoffs being made. It pits near-term revenues versus long-term growth and risk versus returns. It forces the choice between low-risk, incremental improvements to existing products and high-risk technology bets with potentially revolutionary but uncertain outcomes.

Second, time horizons for technology planning are typically very short: one or two years. This is a byproduct of annual budget cycles, which are ubiquitous both in industry and government. Each budget cycle provides an opportunity to re-plan, particularly as new stakeholders come with different opinions and new priorities. So even if there is a longer-term plan, there is frequent opportunity to deviate from it. While this can be helpful in adapting to lessons learned and changing circumstances, it is generally counterproductive to making progress toward long-term goals. The Pentagon attempts to counteract this through a 5-year planning process. Many companies likewise create multi-year plans. However, since both Congress and corporate boards typically approve budgets on an annual basis, the longer-term planning process is largely a pro forma exercise.

Third, there is a frequent failure to recognize the exponential nature of technological progress. In part, this is because the planning intervals are so short that changes in technology look locally linear. It is also because humans are notoriously bad at conceptualizing exponentials. By the time the exponential becomes perceptible, it is usually too late. History is littered with carcasses of companies that failed to spot exponential technological change. Spotting it is no guarantee of success, however. Exponentials are notoriously sensitive to initial conditions, so it is important to recognize the limits and uncertainties in technology forecasting.

In fact, there is an almost universal failure to take into account and plan for uncertainty in technology planning. This includes technological uncertainty—the risk that a technology may or may not pan out as planned—as well as volatility in budgets, requirements, and priorities. The conventional approach to dealing with uncertainty is with margins—adding reserves to account of lower performance, greater weight, or growth in schedule and budget that commonly plagues technology projects. But there are other potent tools that are seldom employed and almost never in a systematic manner across a technology portfolio. One such tool is diversity—pursuing multiple technological paths that are unlikely to suffer from the same failures. Another is optionality—investing in future flexibility to change course. Both require a quantitative framework for modeling uncertainty and its impact on the value and cost of a technology portfolio.

The genesis of this book harks back to one late-summer day in 2016. Prof. de Weck and I met in a Silicon Valley café and I had a proposal. A few months earlier, I was asked by Airbus CEO, Tom Enders, to become the company's Chief Technology Officer. Tom was just entering his second term as CEO and had an ambitious agenda. He wanted to streamline Airbus' governance, undertake a digital transformation of the company's operations and services, and be faster and bolder at technological innovation. Tom understood that the visibly exponential pace of development of digital, electronic, and electrical technologies was much faster than the aerospace industry was used to—and that Airbus had to catch up.

I translated Tom's mandate into three priorities for the Airbus technology organization. First, rationalize, streamline, and focus the roughly €1 billion in annual research and technology (R&T) spending. Second, introduce frequent and ambitious flight demonstrators as a way of bringing together clusters of technologies, accelerating their development, and providing early validation of their maturity. And third, to significantly accelerate the speed with which Airbus developed and manufactured new airplanes and other systems. The efficiencies from the first would also have to pay for the latter two!

This was my proposal to Prof. de Weck that day in Silicon Valley—would he come to Toulouse, France, the heart of Aerospace Valley, and help sort this out? More specifically, would he lead the creation of a rigorous technology planning and roadmapping capability for the company that would help deliver on future flight demonstrators and products? He was perfect for the role. We had known each other for over a decade, with Prof. de Weck providing valuable guidance to DARPA in the agency's quest to improve the design process for complex military systems. He was an eminent academic who spent much of his MIT career thinking deeply about the interaction between technology and its surrounding social and societal systems. He cut his teeth in industry on the McDonnell Douglas F/A-18 program and knew how to navigate large, complex organizations. And he was originally Swiss, and therefore could plead neutrality between the French and German factions at Airbus, which, while much subsided since its early years as a government-owned consortium, still figured prominently in decision-making.

Airbus presented an opportunity to take the latest theoretical work from multiple fields (strategic planning, portfolio theory, formal modeling, etc.), mold it into a technology planning and roadmapping process, and prove it out in the messy reality of corporate planning and budgeting at one of the world's great aerospace companies. Prof. de Weck and I discussed at some length the features of a successful technology planning process and agreed that it should address the four major shortfalls I outlined above:

- It should be objective, as well as both descriptive (where we are and where others are) and prescriptive (where we could go and where we should go).
- It should explicitly link the technology portfolio to the company's long-term product and service strategy, and one should inform the other.
- It should accurately reflect the pace of technological progress with quantitative figures of merit both for internal projects as well as for the external technology ecosystem.
- It should quantify uncertainty and capture the value, cost, and risk associated with each technology and the portfolio as a whole.

In the two years that Prof. de Weck spent at Airbus as Senior Vice President of Technology Planning and Roadmapping, most (though not all) of the items on this list went from an aspiration to a pressure-tested methodology, enabled by a robust set of tools and processes, and operationalized by a well-trained and well-respected cadre of technology roadmap owners. And it has endured. Today, the methodology is well on its way to becoming part of Airbus' cultural fabric. Nothing about this approach, however, is unique to aviation or aerospace. Any technologically driven field such as automotive, consumer electronics, energy, medical devices, and mining—just to name a few—can benefit from a similar journey.

Ultimately, it was the freedom and encouragement to write a book based on the experience that convinced Prof. de Weck to come to Toulouse. It would become a book documenting what is certainly the most rigorous technology planning and roadmapping process ever implemented at scale and battle-tested in a complex, corporate environment. It would be a book to teach and inspire a generation of practitioners and theorists to improve the way in which we plan and manage technology development for the long term. This is that book.

Los Angeles, CA, USA Paul Eremenko
December 2021

Preface

I am writing these words at the Massachusetts Institute of Technology (MIT), which has been my professional home for the last 25 years. In this book I focus on the last word in the name of our institution: *Technology*. We all know what it is. And yet, when asked to describe it succinctly, many of us struggle.

This is a somewhat startling admission.

When asking students, professionals, or the general public for a definition of what is "technology" (without using the word itself) we hear a bewildering variety of answers. This has been compounded in recent years by the use of the short form "*tech*" to refer among other things to a set of electronic devices we carry around with us. Sometimes "*tech*" simply seems to refer to all technologies as a collective.

It may be useful to go back to the founding of MIT in 1861 to see what was meant by technology back then. The inscription inside Lobby 7, now the main entrance to MIT, has always held a special meaning for me. I see it nearly every day on the way to my office and I often crane my neck to read it again and again, even though I have seen it many times. The text reflects the original intent of William Barton Rogers, the founder of MIT, and it is also reflected in the Institute's charter.

> *Established for Advancement and Development of Science its Application to Industry the Arts Agriculture and Commerce. Charter MDCCCLXI*

Thus, "*tech*" is about the development, advancement, and beneficial application of scientific principles in industry and in other domains such as the arts, agriculture, and commercial enterprises. We will take a similarly broad view here. Interestingly, MIT itself as an institution was referred to simply as "*Tech*" or "*Technology*" in its early years.

Why This Book?

Since my early childhood growing up in Switzerland I have always been fascinated with technology. I would look up at the sky in the Alps through my first telescope, and observe the Moon and planets at night, and I would follow the helicopters resupplying mountain huts and rescuing mountaineers during both day and night. I would disassemble my mechanical alarm clock to better understand how it worked. What material was this device made of? How did it work? What was its internal mechanism? Could it be made better?

In the late 1980s, I studied engineering at ETH Zurich and decided to specialize in the area of *production* and *technology management*. Right after university I was fortunate to be asked to develop and implement a technology transfer plan for the Swiss F/A-18 aircraft program which is what brought me to the USA in 1994. Little did I know that over 25 years later I would still be living in the USA and that my profession would be to think about technological systems and how they evolve over time.

This book was written over a period of three years in 2019–2021, but it is in reality the culmination of two decades of research and application of technology in a variety of sectors. The final impetus for it came when I took a leave of absence from MIT to serve as Senior Vice President for Technology Planning and Roadmapping at Airbus in Toulouse, France, as described in the foreword by Paul Eremenko. Much of what I learned during this time is in this book.

The book provides a review of the principles, methods, and tools of technology management, including technology scouting, technology roadmapping, strategic planning, R&D project execution, intellectual property management, knowledge management, technology transfer, and financial technology valuation. In 22 chapters we explain the underlying theory and empirical evidence for technology evolution over time and present a rich set of examples and practical exercises from a number of domains such as transportation, communications, and medicine. The linkage between these topics is shown using what we call the Advanced Technology Roadmap Architecture (ATRA). Each chapter's position in the ATRA framework is shown using a graphical map at the start of each chapter. Technology roadmapping is presented as the central process that holds everything together (Chap. 8).

Readers of this book will learn how to develop a comprehensive technology roadmap on a topic of their own choice. This is also the foundation of my popular MIT class *16.887-EM.427 Technology Roadmapping and Development* which was first offered in 2019, and an on-line version of the class available to practitioners via MIT Professional Education. Technology roadmapping is presented as the core activity in technology management. Every year my students develop a number of technology roadmaps which are subsequently published and are freely accessible over the Internet[1].

There are several reasons that make this book pertinent at this time:

[1] To view these technology roadmaps, use the following link: http://roadmaps.mit.edu

- Exponential progress of technology in many areas is now apparent. However, quantification of technological progress needs to be done carefully and with real data. Few texts address this issue head-on.
- Roadmaps are a central boundary object in technology-based organizations. While there has been much emphasis on innovation in general, there is not a large literature on how to explicitly connect strategy, technology, and finance. The emphasis on roadmapping in this book explains how these concepts link together.
- The impact of technologies and the products, missions, and systems in which they are infused on their surrounding ecosystems and industrial clusters is addressed in several chapters. To put it simply, firms should not reinvent the wheel by investing in technologies and intellectual property (IP) that already exist. Conversely, technologies themselves shape innovation ecosystems around the globe in ways that were unimaginable a century ago.

The following individuals may find this book interesting and useful:

- Chief technology officers and chief innovation officers
- Technology executives and engineering managers
- Students in engineering, management, and technology
- Researchers in technology and innovation management
- Educators
- Financial market analysts
- Technology enthusiast and historians of technology
- Venture capitalists

This book is organized into different parts and chapters within the ATRA framework as follows:

Descriptive Part (Chaps. 1, 2, 3, 4, 5,7, 19, 20, 21, 22)

This part describes *what we mean by technology*, how technological progress can be quantified, and what are the key elements of a technology roadmap. We also look at the history of technology in broad strokes and consider the relationship between nature and human-made (artificial) technologies. This boundary was once considered to be very sharp, but is becoming increasingly blurred with advances in biotechnology.

Prescriptive Part (Chaps. 8,10, 11, 12, 14, 15, 16, 17)

This part develops a *systematic approach* and methodology for technology roadmapping specifically, and technology management more generally. We review different ways of implementing and linking to each other the most important technology management functions including technology scouting, technology roadmapping, and the management of intellectual property (IP).

Case Studies (Chaps. 6, 9, 13, 18)

In this part of the book we take an in-depth look at several case studies of technology development over time. These cases look primarily at cyber-physical systems, that is, those containing complex hardware and software such as automobiles, aircraft, and deep space communications, but not exclusively so. One of our case studies looks at the progress in DNA sequencing, which is one of the foundations of modern biotechnology.

These cases and the book overall show that technological progress is not smooth and "automatic." Rather, it is a deliberate and stepwise continual process, driven by powerful forces such as the desire for human survival, scientific curiosity, as well as competition and collaboration between firms and nations. Technology must be carefully managed, since it may sow the seeds of our eventual destruction as a species, or it may propel humanity to new levels of capability and yet unimagined future possibilities.

Cambridge, MA, USA Olivier L. de Weck
February 2022

Acknowledgments

There are many individuals to thank without whom this book would not have seen the light of day. First, my professors and colleagues who initially got me interested in the topic of technological systems in Switzerland in the late 1980s and early 1990s. These include Professors Pavel Hora, Hugo Tschirky, and Armin Seiler at ETH Zürich and Dr. Claus Utz and Dr. Elisabeth Stocker at F+W Emmen (which today is part of the company named RUAG).

One of the foundations of thinking about technology in a rigorous way is systems architecture. I want to acknowledge the influence and mentorship I have received from Prof. Edward Crawley at MIT over the years on this subject. Prof. Dov Dori from the Technion introduced me to Object Process Methodology (OPM) – which is used extensively in this book – and our collaboration on applying OPM to technology management has grown into a real friendship.

A significant portion of this book is based on a framework for technology management that was elaborated and put into practice at Airbus between 2016 and 2019. At Airbus, there are numerous individuals to thank for their support for what seemed initially to be an insurmountable task. These include Paul Eremenko, the Chief Technology Officer (CTO) who also contributed the foreword to this book, Tom Enders the CEO, members of the Engineering Technical Council (ETC), as well as members of the Research and Technology Council (RTC). My colleagues including Dr. Martin Latrille, Prof. Alessandro Golkar, Fabienne Robin, Jean-Claude Roussel, and Dr. Mathilde Pruvost worked with me to create a new organization called "Technology Planning and Roadmapping" (TPR) with about 60 technology roadmap owners and supporting staff. Specific technology thrusts were spearheaded by Thierry Chevalier in the area of digital design and manufacturing (DDM), Pascal Traverse in autonomy, the late Mark Rich in connectivity, as well as by Glenn Llewellyn in aircraft electrification. Matthieu Meaux and Sandro Salgueiro contributed to the details of the solar electric aircraft sample roadmap in Chap. 8. Marie Tricoire deserves mention for her outstanding administrative support. The passion for technology and planning for a better future were the fuel that carried us through many challenges and difficulties. Further thanks go to Grazia Vittadini, former CTO of Airbus, and Dr. Mark Bentall for continuing to implement the approach, even after my return to academia. Specific contributions to this book were made by Dr. Alistair Scott on the topic of intellectual property (Chap. 5), as well as Dr. Ardhendu Pathak in the chapters on technology scouting (Chap. 14) and knowledge management (Chap. 15).

Once back at MIT, the idea of creating a book and a new class on Technology Roadmapping and Development was greeted with enthusiasm by my department head Prof. Daniel Hastings, as well as by Prof. Steven Eppinger at the Sloan School of Management. The work of Prof. Christopher Magee in tracking technological progress over time was an inspiration and is referenced extensively in several chapters. Prof. Magee also provided a critical and in-depth review of the manuscript. I want to further thank Dr. Maha Haji, former postdoctoral associate at MIT and now a Professor of Mechanical and Aerospace Engineering at Cornell University, as well as my teaching assistants Alejandro "Alex" Trujillo, Johannes Norheim, and George Lordos for supporting the three first offerings of the Technology Roadmapping and Development class at MIT in 2019 and 2021. Dr. Haji in particular contributed substantially to Chap. 19 on industrial ecosystems. Additionally, we had about 80 students, many of them affiliated with the MIT System Design and Management (SDM) program, give valuable feedback on the content of the chapters and the logic and workability of the approach.

On specific topics I wish to acknowledge the contributions of Dr. Joe Coughlin and Dr. Chaiwoo Lee on the relationship between aging and technology (Chap. 21), as well as the specific situation of military intelligence and defense technologies that has been extensively studied by Dr. Tina Srivastava in her doctoral thesis and subsequent book (Chap. 20). Dr. Matt Silver, the CEO of Cambrian Innovation, had substantial inputs on Chap. 3 which discusses the relationship of technology with nature. The specific case studies were supported by experts in the field including Dr. Ernst Fricke, Vice President at BMW, on the automotive case (Chap. 6), Dr. Les Deutsch at the Jet Propulsion Laboratory (JPL) on the Deep Space Network (Chap. 13), and Dr. Rob Nicol at the Broad Institute on DNA sequencing (Chap. 18). Moreover, Chap. 12 on technology infusion analysis is largely based on a collaboration with Prof. Eun Suk Suh, formerly a system architect at Xerox Corporation, and now a full professor at Seoul National University (SNU). The work on technology portfolio optimization benefited from the contributions of Dr. Kaushik Sinha.

My thanks also go to Dr. Robert Phaal at the University of Cambridge for his detailed review of the manuscript, and the inspiration that his impressive body of work on roadmapping provided to this author.

Finally, my thanks go to the staff at Springer Nature for believing in this project and supporting its implementation. First and foremost, Michael Luby, who came to visit me at my MIT office in December of 2019 and is the senior editor for this book. Thanks also go to Brian Halm for excellent advice and coordination during the writing and editing process. I want to thank Cynthya Pushparaj and her team at Springer Nature for typesetting the manuscript and expertly producing this book in both physical and electronic format.

Contents

List of Abbreviations and Symbols

Symbols

⇨	Exercises in chapters that are meant for self-study
➽	Questions as a prompt for group discussion
[ ]	Units of measurement
✦	Definition
*	Quote

Abbreviations and Acronyms

ACH	Automated Clearing House
AGI	Artificial General Intelligence
AI	Artificial Intelligence
AOA	Angle of Attack
AR	Augmented Reality
ASCII	American Standard Code for Information Interchange
ASIP	Aircraft Structural Integrity Program
AUTOSAR	AUTomotive Open System ARchitecture
BCE	Before Common Era
BEV	Battery Electric Vehicle
BIT	Built-In Test
BLI	Boundary Layer Ingestion
BOF	Basic Oxygen Furnace (steel making)
BOM	Bill of Materials
BPR	Bypass Ratio
BPS	Biomass Production System
bp	Base Pairs
B/S	Balance Sheet

CAFE	Corporate Average Fuel Economy
Cal	One kilocalorie of energy
CAPEX	Capital Expenditures
CCS	Carbon Capture and Storage
CD	Compact Disk
CDF	Concurrent Design Facility
CE	Common Era
CEMO	Complex Electro-Mechanical-Optical
CFRP	Carbon Fiber Reinforced Polymer (material)
CONOPS	Concept of Operations
CLD	Causal Loop Diagrams
CPI	Cost Performance Index
CPM	Critical Path Method
CPU	Central Processing Unit
CRISPR	Clustered Regularly Interspaced Short Palindromic Repeats
CTO	Chief Technology Officer
DARPA	Defense Advanced Research Projects Agency
DDI	Digital Display Indicator
DMMH/FH	Direct Man Maintenance Hours per Flight Hour
DNA	Deoxyribonucleic acid
DOC	Diesel Oxidation Catalyst
DOD	Department of Defense
DRB	Design Record Books
DSM	Design Structure Matrix, or Dependency Structure Matrix
DSOC	Deep Space Optical Communications
DSN	Deep Space Network
EAF	Electric Arc Furnace
EBIT	Earnings Before Interest and Taxes
ECU	Electronic Control Unit
EDF	Electricité de France
EDL	Entry Descent and Landing
EEX	European Energy Exchange
EIS	Entry Into Service
EML2	Earth Moon Libration Point 2
EMR	Electronic Medical Records
EPA	Environmental Protection Agency
EPE	Enhanced Performance Engine
EV	Electric Vehicles
EVM	Earned Value Management
FAL	Final Assembly Line
FDI	Foreign Direct Investment
FFRDC	Federally Funded Research and Development Center
FMA	First Mover Advantage
FMS	Foreign Military Sales
FOM	Figure of Merit

FPGA	Field Programmable Gate Array
FPM	Functional Performance Metric
FTP	Federal Test Procedure
GI	Gastrointestinal
GNP	Gross National Product
GPU	Graphical Processing Unit
GSE	Ground Support Equipment
GUI	Graphical User Interface
HAPS	High Altitude Pseudo Satellites
HEV	Hybrid Electric Vehicle
HPC	High Performance Computing
HR	Human Resources
HSR	High Speed Rail (System)
HSS	High Strength Steel
ICE	Internal Combustion Engine
ICU	Intensive Care Unit
IOT	Internet of Things
IP	Intellectual Property
IRL	Integration Readiness Level
ISRU	In Situ Resource Utilization
IT	Information Technology
ITAR	International Traffic in Arms Regulations
ITU	International Telecommunications Union
ISO	International Organization for Standardization
JPL	Jet Propulsion Laboratory
JV	Joint Venture
JWST	James Webb Space Telescope
KM	Knowledge Management
KPI	Key Performance Indicator
kya	Thousands of years ago
LAN	Local Area Network
LDP	Low Drag Pylon
LEX	Leading Edge Extension
LH_2	Liquid Hydrogen
LHS	Left Hand Side
LIB	Lithium Ion Battery
LIB	Larger is Better
LLO	Low Lunar Orbit
LOM	Loss of Mission
LSP	Lunar South Pole
MaaS	Mobility as a Service
MBSE	Model-Based Systems Engineering
MDM	Multi-Domain Mapping Matrix
MFC	Microbial Fuel Cell
MOSFET	Metal–Oxide–Semiconductor Field-Effect Transistor

MOT	Management of Technology
MRO	Maintenance Repair and Overhaul
mya	Millions of years ago
M&A	Mergers and Acquisitions
NAE	National Academy of Engineering
NAICS	North American Industry Classification System
NDA	Non-Disclosure Agreement
NE	Nash Equilibrium
NEDC	New European Driving Cycle
NIH	National Institutes of Health
NIH	Not-Invented Here Effect
NIST	National Institute for Standards and Technology
NOx	Oxides of Nitrogen
NPV	Net Present Value
NRC	National Research Council
NRC	Non-Recurring Cost
NRE	Non-Recurring Engineering
NREL	National Renewable Energy Laboratory
NZF	Non-Zero Fraction
OEM	Original Equipment Manufacturer
OP	Operational Program
OPD	Object Process Diagram
OPEX	Operating Expenditures
OPL	Object Process Language
OPM	Object Process Methodology
PCB	Printed Circuit Board
PCT	Patent Cooperation Treaty
PDP	Product Development Process
PEV	Plug-in Electric Vehicle
PHC	Patent Holding Company
PI	Program Increment
PRC	People’s Republic of China
P/L	Profit and Loss Statement
PM	Particulate Matter
PSTN	Public Switched Telephone Network
PV	Photovoltaics, also known as solar cells
RFID	Radio Frequency Identification
RHS	Right Hand Side
RMO	Roadmap Owner
RNA	Ribonucleic Acid
ROI	Return on Investment
RT	Remote Terminal
RVI	Relative Value Index
R&D	Research and Development
SAM	Surface to Air Missile

SARS	Severe Acute Respiratory Syndrome
SETI	Search for Extraterrestrial Intelligence
SI	Système International (international unit system)
SLAM	Simultaneous Localization and Mapping
SME	Subject Matter Expert
SOW	Statement of Work
SPI	Schedule Performance Index
SPL	Sound Pressure Level
SPO	Single Pilot Operations
SSTO	Single Stage To Orbit
STEM	Science Technology Engineering Mathematics
SUV	Sports Utility Vehicle
SWIFT	Society for Worldwide Interbank Financial Telecommunication
SysML	Systems Modeling Language
TAA	Technical Assistance Agreement
TAM	Technology Acceptance Model
TCP/IP	Transmission Control Protocol/Internet Protocol
TDP	Technical Data Package
TGV	Train à Grande Vitesse
TIA	Technology Infusion Analysis
TPS	Toyota Production System
TRD	Technology Roadmapping and Development
TRIZ	Theory of the Resolution of Invention-Related Tasks
TRL	Technology Readiness Level
TSTO	Two Stage to Orbit
UAV	Unmanned Aerial Vehicle
USPTO	United States Patent and Trademark Office
VFR	Visual Flight Rules
VLSI	Very Large-Scale Integration
VMT	Vehicle Miles Traveled
VR	Virtual Reality
WBS	Work Breakdown Structure
WIPO	World Intellectual Property Office
WRU	Weapons Replaceable Unit
WWI	World War I
WWII	World War II
WWW	World Wide Web

Mathematical Symbols

B	Bandwidth [Hz]
c	Speed of light in vacuum [m/s]
C/N	Signal-to-Noise Ratio [-]

D	Diameter [m]
E	Energy [J]
E[ΔNPV]	Expected Marginal Net Present Value
σ[ΔNPV]	Standard Deviation of the Expected Marginal Net Present Value
D_T ,D_i	Total demand for the market segment, and demand for ith product
g_C	Critical value for the attribute
g_I	Ideal value for the attribute
g_o	Market segment average value for the attribute
h	Height [m]
K	Market average price elasticity (units / $)
l	Length [m]
m	Mass [kg]
N	Number of competitors in the market segment
N_e	Number of elements in the DSM
$NEC_{\Delta DSM}$	Number of non-empty cells in the ΔDSM
NEC_{DSM}	Number of non-empty cells in the DSM
$N1$	Number of elements in the DSM
$N2$	Number of elements in the ΔDSM
P_i	Price of the ith product
R_{max}	Maximum data rate [bps]
TIA	Technology Infusion Analysis
T_{DSM}	Number of hours required to build a DSM model
v	Velocity [m/s]
V, V_i	Value of the product, Value of the ith product
V_o	Average product value for the market segment
$v(g)$	Normalized value for attribute g
T_{DSM}	Number of work hours required to build a DSM model
N_e	Number of elements in the DSM
Q	Economic output measured as GNP (gross national product) in $
Q_H	Heat [J]
K	Capital actively in use in units of $
L	Labor force employed in units of man-hours[1]
t	Time in years
w	Width [m]
σ_w	Yield strength [MPa]

[1] Both capital K and labor L account for active workers and capital assets in use. This means that unemployment and idle machinery have to be corrected for.