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Financial Resources and Technology to Transition to 450mm Semiconductor Wafer Foundries

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Abstract

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E.M.B.A., Northwestern University – Chulalongkorn University, 2000

B.S.E.E., Arizona State University, 1990

E.T., DeVry University, 1978

Dissertation Submitted in Partial Fulfillment

of the Requirements for the Degree of

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Abstract

Future 450mm semiconductor wafer foundries are expected to produce billions of low cost, leading-edge processors, memories, and wireless sensors for Internet of Everything applications in smart cities, smart grids, and smart infrastructures. The problem has been a lack of wise investment decision making using traditional semiconductor industry models. The purpose of this study was to design decision-making models to conserve financial resources from conception to commercialization using real options to optimize production capacity, to defer an investment, and to abandon the project. The study consisted of 4 research questions that compared net present value from real option closed-form equations and binomial lattice models using the Black-Scholes option pricing theory. Three had focused on sensitivity parameters. Moore's second law was applied to find the total foundry cost. Data were collected using snowball sampling and face-to-face surveys. Original survey data from 46 Americans in the U.S.A. were compared to 46 Europeans in Germany. Data were analyzed with a paired-difference test and the Box-Behnken design was employed to create prediction models to support each hypothesis. Data from the real option models and survey findings indicate American 450mm foundries will likely capture greater value and will choose the differentiation strategy to produce premium chips, whereas higher capacity, cost leadership European foundries will produce commodity chips. Positive social change and global quality of life improvements are expected to occur by 2020 when semiconductors will be needed for the $14 trillion Internet of Everything market to create safe self-driving vehicles, autonomous robots, smart homes, novel medical electronics, wearable computers with streaming augmented reality information, and digital wallets for cashless societies.

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Dedication

This work is dedicated to my wife, Kazuko, for constantly supporting my academic advancements despite some hardships. This work is also dedicated to my daughters Maria, Mariko, and Kaori; hopefully they too will someday understand.

This work transpired with thoughts of my father, William Pastore, a valiant U.S. Marine. My last memories of him were in the vast beauty of Arlington National Cemetery on May 28, 2009, as the motorcade proceeded down Eisenhower Drive past Section 60, where soldiers with valor from Afghanistan and Iraq were buried. Along the tree-lined Bradley Drive, the motorcade arrived at Section 64 where a detachment of Marines in crisp uniforms were awaiting a war hero. Marines under the direction of the Gunnery Sergeant carried William Pastore with the American flag draped over the coffin past a large tree to grave 64-5943 within a beautiful open clearing. Close by, a lone bugler played taps as the Marines folded the American flag with extreme precision. Farther away, the rifle detachment saluted William with three volleys, after which the Catholic military Chaplin recited from the Bible. The Marine Corps Gunnery Sergeant presented the triangular Stars and Stripes and the spent rounds to me with Kazuko at my side. Nearby was the 9/11 Pentagon Group Burial marker. In the distance, there was the Washington Monument at the left and the Pentagon to the right. As this paper transpired, I had similar memories of my uncle, my father’s older brother, Robert Pastor, also a U.S. Marine in World War II and a leader of several Elks Lodges. He had just recently passed away. Finally, my mother, Ellen Pastore, a skillful artist, had passed away a little more than a year ago.

Acknowledgments

Thanks to my Professor Dr. Jeff Prinster, a retired USMC Lieutenant Colonel, for his generous support. Thanks for the many enjoyable conversations and lessons you gave during the 2006 Walden University residency at Universidad Europea de Madrid in Spain. Dr. Prinster encouraged me on my data collection quest in Europe with the mantra, “Lock and Load!! Attack with Passion!! Onward and Upward!! Semper Fidelis!!”

Thanks to Professor Dr. William Brent, a retired USN Lieutenant Commander, for overseeing my real option work and for being my mentor spanning from KAM 1 to KAM 7. Thanks to Professor Dr. Aqueil Ahmad for his support and classes at the 2008 Walden University residency at Universidad Andrés Bello-Republica in Santiago, Chile.

Thanks to Dave Burgess, Hewlett Packard (HP Labs), for being my semiconductor failure analysis mentor. Thanks to Roy Currence, for being a great friend and mentor, for providing an internship at Xerox, a great Sr. engineering project, and for encouragement throughout my academic and professional career. Thanks to Dr. Glenn Possley, President of Alphatec Submicron (a 200mm wafer fab), for making life better for my family in Thailand, for many conversations about constructing Thailand’s first 200mm wafer foundry, and for snowball sampling support. Thanks to Robert DiChiara, a Boeing Research and Technology Technical Fellow, for many hours of discussions, support, and problem solving with response surface methods, Taguchi methods, design of experiment software, and Apple computers. Thanks to Randy Brandt, a Boeing Research and Technology Associate Technical Fellow, for his support and Mathcad conversations. Thanks to Tom Webb, for his trust, recognition, and generous support at Boeing.

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Chapter 1: Introduction to the Study

For the last several years, leaders in the semiconductor industry have recognized that efficiency improvements for semiconductor manufacturing have failed to create significant competitive advantages. Jones (2009) reported that the industry campaign known as *300mm Prime* has failed to increase manufacturing efficiency in 300mm wafer foundries with a 50% cycle time reduction and a 30% cost reduction (pp. 14-15). Jones stated that cost simulations to manufacture an Intel microprocessor in 300mm wafer foundries will be $6.28 by 2015, whereas the cost to manufacture in 450mm wafer foundries will be $4.64 (p. 14). Chang, Chien, Wang, and Wu (2007) performed an economic analysis and foresaw the race to build 450mm semiconductor wafer foundries will provide greater efficiency with an economy of scale by 2.25 times with a 30% cost reduction (pp. 2-3). For these reasons, the semiconductor industry has been transitioning from 300mm semiconductor foundries to giant 450mm wafer foundries to build competitive advantages that may eventually benefit societies around the globe.

Davis (2012), the president of the Semiconductor Equipment and Materials International (SEMI) consortium, said that many governments around the world have recognized that 450mm wafer fabs will be crucial in achieving a "national competitiveness strategy" (p. 33). Davis reported that SEMI has met with more than 50 state and federal government officials such as congressional leaders to promote American 450mm wafer foundries since they are being recognized as national assets. In addition, Cestari (2013) reported "the next big opportunity" will be 450mm wafer foundries like the one currently under construction in New York; this will likely demonstrate America is not only an innovator of advanced technology but also a manufacturer of high-quality products with lower production costs (p. 12). With the construction of the G450C consortium's 450mm wafer fab in New York, Singer (2012) described job creation opportunities to design and build wafer-processing tools for this giant foundry (p. 5). Officials in Europe have recognized the same opportunities and competitive advantages. Meredith (2012) reported that IMEC announced construction of a 450mm wafer foundry in Belgium with investment funding from the European Commission (pp. 6-7). The January 2014 SEMI EU 10/100/20 Fact-sheet quoted Neelie Kroes, the European Commission Vice-President, as saying, "I want to double our chip production to around 20% of global production. It's a realistic goal if we channel our investments properly" (p. 3).

There was a need to conduct this research study since studies on wise investment decision making models to conserve limited financial resources for 450mm semiconductor wafer foundries do not exist in the literature. Wise investment decisions made by management building giant 450mm wafer foundries will likely proliferate abundant low cost technology products, which are expected to drive technology for the Internet of Everything and will likely contribute to global social change. Major sections in this chapter describe the problem and purpose statements, research questions, defined terms, the theoretical framework, nature of the study, significance and social change implications, scope and limitations, assumptions, and a summary.

Background of the Study

Looking ahead in the 21st century, Ahuja (2012) said that the recent market for consumer electronics represents the "Golden era of electronics" and the start of the next economic growth engine to escape the 2008 global recession (p. 3). The semiconductor industry's lead consortium, the International Technology Roadmap for Semiconductors (ITRS), in their 2011 executive summary, outlined a plan to transition from 300mm (12-inch) wafers to 450mm (18-inch) wafers with the construction of giant 450mm wafer processing foundries. In Appendix B, a 2007 video shows a $3 billion investment with the construction and operation of Intel's Fab 32, a 300mm wafer foundry (Perera, 2009). In comparison, future 450mm wafer fabs will be significantly larger.

Clark (2013) reported that Intel was constructing two 450mm wafer fab complexes; the first was Fab D1X in Hillsboro, Oregon and the second was Fab 42 in Chandler, Arizona. Furthermore, Rogoway (2013) reported that the first D1X construction phase began in 2010 at a cost of $3 billion. The second D1X construction phase began in 2013 at a cost of $2 billion. Fab D1X, after completion, will cover an area of 2.2 million square feet and will operate as a pilot fab for 450mm wafer processing. In addition to Fab D1X, Anderson (2013) reported that Intel was constructing Fab 42, a $5.2 billion fab construction project in Chandler, Arizona. Swartz (2011) reported on President Barack Obama's tour of Intel (p. 1B). The President was told Fab 42 would cost at least $10 billion, and the complexity would be equivalent to building a 1-million-square-foot nuclear reactor. Moreover, Chang, Clare, and Hung (2012) reported that the Taiwanese government had granted TSMC permission to build a 450mm wafer foundry in central Taiwan at the expected cost of 8 to 10 billion dollars. The contenders in this race are Intel (America), IMEC (Belgium), TSMC (Taiwan), and Samsung (South Korea).

An extensive literature review revealed a deficiency in business valuations for 450mm wafer-foundry projects. With the objective to continue the advancement of innovative semiconductors based on nanotechnology, the 2011 ITRS executive summary stated, “There is a need to model and design next generation factories for a wide spectrum of flexibility. Such future factories must have the ability and flexibility to be implemented through early development phases and into production” (p. 30). ITRS stated that the industry economic model (IEM) was originally developed in the 1990s to transition from 200mm to 300mm wafer fabs and was revised for 450mm wafer foundries to forecast capacity and demand (pp. 14, 88). Despite the revision, the IEM model does not support fab management with wise investment decision making. Ford and Garvin (2010) recommended staged real options for architectural, construction, and engineering projects to account for the value realized from contingency options for high-risk projects (pp. 55-56). For advanced technology projects with capital intensive investments and high uncertainties, Chevalier-Roignant and Trigeorgis (2011) proposed a real option valuation comprised of a series of investment outlays (pp. 163-168).

Financial valuations of 450mm wafer foundries may have been conducted, most likely to maintain competitive advantage; that information has not been disclosed. This study is needed because there is a lack of literature on financial models that support wise investment decision making by fab management to plan, build, and operate future 450mm wafer fabs. Knowledge of total investment cost, individual investment costs, investment timing, how to optimize capacity, the impact of delayed investments, and when to abandon the project is presented. This information is expected to provide management with the ability to conserve financial resources, to reduce cost, to obtain greater economy of scale, and to realize greater efficiency and national competitiveness. In summary, this study demonstrates the development of four real option models with a sensitivity analysis and presents timing and individual investment information to support wise decision making for fab management.

Financial Valuation

In this study, I describe the development of three-stage 450mm wafer-foundry models that were comprised of four real options to expand capacity, to constrict capacity, to defer the Extreme Ultraviolet (EUV) lithography investment, and to abandon the project. EUV lithography technology represents a revolutionary tool that is expected to expose wafers to a light source with a 13.5 nanometer wavelength to manufacture leading edge semiconductors. Figure 1 illustrates a timeline with growth opportunities as indicated by the three investment stages, X_1 to X_3, followed by the commercialization stage with the generation of future free cash flows that span from S_1 to Sn.

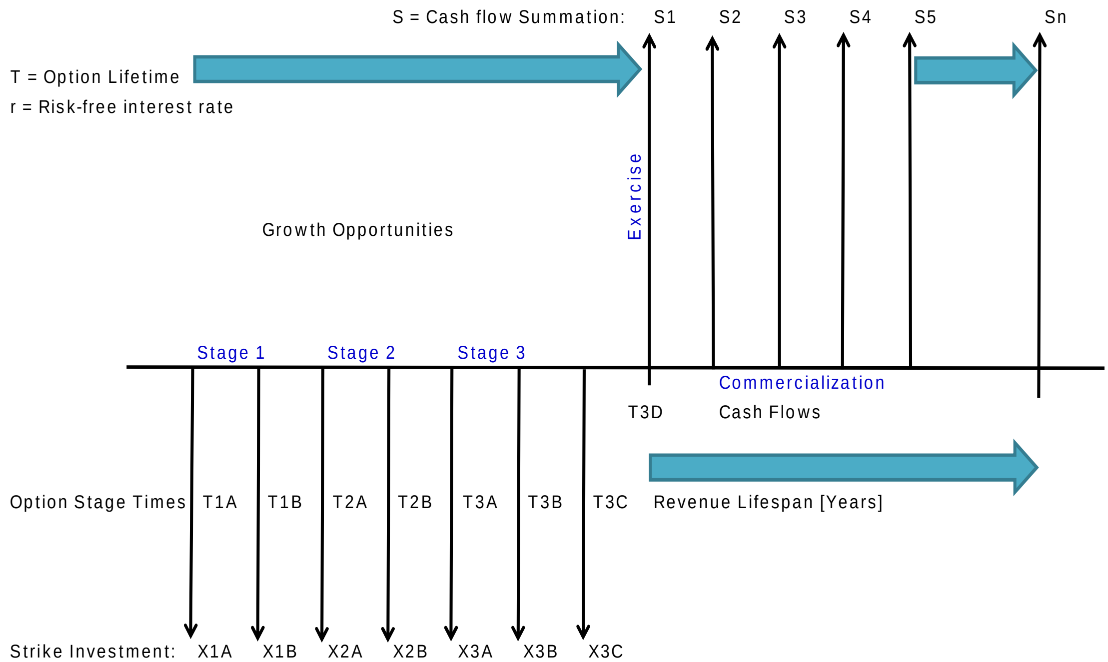

Figure 1. Real option cash flow diagram to determine net present value (NPV).

Problem Statement

Despite the fact that the IEM was revised, the 2011 ITRS executive summary identified the research problem as a need for flexible financial models for next generation foundries that span from R&D to commercialization (pp. 14, 30). However, the IEM model currently lacks real option capabilities to make wise investment decisions. Singer (2013) provided consensus by quoting the European Commission Vice-President Neelie Kroes, who recognized the current problem as a lack of wise investment tools (p. 3). In summary, wise investment models based on real options with sensitivity analyses to build and operate future 450mm wafer foundries do not exist in the literature.

Purpose of this Study

The purpose of this quantitative study was to develop wise investment decision making models using real options to expand capacity, to contract capacity, to defer the EUV investment, and to abandon the project with a goal to compare net present value (NPV) for American 450mm wafer foundries versus those to be built in Europe. The following independent variables were applied using closed-form equations and binomial lattice models: the underlying value (S), the strike cost (X), volatility (σ), lifetime (T), and the risk free interest rate (r). The Black-Scholes equations were applied to calculate the dependent variables: the call value (C), the put value (P) and five sensitivity parameters delta (Δ), gamma (Γ), rho (ρ), theta (θ), and vega (ν). Hypothesis testing was performed prior to developing inferential models using response surface methods to make NPV and business strategy predictions.

Research Questions

RQ1: Based on a real option to expand capacity with a 450mm wafer-foundry project in America, will the NPV be less than or equal to one in Europe?

RQ2: Based on a real option to contract capacity with a 450mm wafer-foundry project in America, will the NPV be less than or equal to one in Europe?

RQ3: In case EUV lithography is not ready for the Stage 2 pilot 450mm wafer foundry, with the real option to defer the EUV investment X_{2A}, will the NPV for a fab in America be less than or equal to one in Europe?

RQ4: Based on a real option to abandon production ramp-up in a 450mm wafer foundry at time T_{3A}, will NPV in America be less than or equal to one in Europe?

RQ5: Will the sensitivity parameter delta (Δ) be less than or equal for a 450mm wafer foundry in America compared to one in Europe?

RQ6: Will the sensitivity parameter vega (ν) be less than or equal for a 450mm wafer foundry in America compared to one in Europe?

RQ7: Will the sensitivity parameter theta (θ) be less than or equal for a 450mm wafer foundry in America compared to one in Europe?

Research Hypotheses

H_A1: With a real option to expand capacity for a 450mm wafer foundry-project in America, the NPV will be greater compared to one in Europe.

H_A2: With a real option to contract capacity for a 450mm wafer-foundry project in America, the NPV will be greater compared to one in Europe.

H_A3: In case EUV lithography is not ready for the Stage 2 pilot 450mm wafer foundry, with the real option to defer the EUV investment X_{2A}, the NPV will be greater for a fab in America compared to one in Europe.

H_A4: With a real option to abandon production ramp-up for a 450mm wafer foundry at time T_{3A}, NPV will be greater for a fab in America compared to one in Europe.

H_A5: The sensitivity parameter delta (Δ) will be greater for a 450mm wafer foundry in America compared to one in Europe.

H_A6: The sensitivity parameter vega (ν) will be greater for a 450mm wafer foundry in America compared to one in Europe.

H_A7: The sensitivity parameter theta (θ) will be greater for a 450mm wafer foundry in America compared to one in Europe.

Definition of Terms

American option: This option can be exercised any time prior to the expiration. This option has a higher value in comparison to European options as stated by Black and Scholes (1973, pp. 637, 647).

Black-Scholes option pricing model: This valuation model emulates a European real option, which consists of the following independent variables: the underlying value (S), investment strike cost (X), volatility (σ), option lifetime (T), and the risk free interest rate (r). This model was applied to calculate dependent variables: the call value (C), put value (P), and the five sensitivity parameters, delta (Δ), gamma (Γ), vega (ν), theta (θ), and rho (ρ). Luenberger (1998) provided an overview of the Black-Scholes option pricing model which is based on several partial differential equations (pp. 351-381).

Call option value (C): Value is captured from the freedom but not the obligation to invest in an asset prior to the expiration. A European call option is “in the money” when the underlying asset value (S) exceeds the strike investment cost (X) such that the call value $C = \text{Max}\,[S - X, 0]$ as described by Kodukula and Papudesu (2006, pp. 3-4).

Delta (Δ): This is a sensitivity parameter describing the rate of change for the call value C with respect to the underlying asset value S. Passarelli (2012) stated that the delta parameter can be applied to estimate the statistical probability or the option profitability of expiring “in the money” (p. 28).

European option: This option, according to Black and Scholes (1973), can be exercised only at a specified expiration or maturity date (p. 637). The Black-Scholes theory emulates the operation of a European option (p. 640).

Extreme ultraviolet lithography (EUV or EUVL): This term refers to the revolutionary lithography tool that is currently under development to pattern 450mm wafers. The capital investment cost for pilot EUV lithography tools was designated as X_{2A} while X_{3A} designates production EUV lithography tools. Palmer (2012) provided an overview of EUV lithography.

Fab: This abbreviated name stands for a semiconductor fabrication foundry or factory. The terms fab, foundry, and factory all have the same meaning. The capital investment outlay for fab construction was designated as X_{1A}.

Gamma (Γ): This sensitivity parameter is the rate of change for delta Δ with respect to the underlying asset value S. Passarelli (2012) stated gamma is a second derivative that measures the sensitive inflection changes of delta while the option is performing "at the money" threshold (p. 35). Passarelli (2012) explained that the gamma-theta relationship improves investment strategy insight (p. 96).

Greeks: These are the Black-Scholes sensitivity parameters comprised of delta (Δ), gamma (Γ), theta (θ), rho (ρ), and vega (ν); each of these dependent variables provide performance insight on value drivers, as explained by Mun (2006, p. 227). The authors Madhumathi and Parthasarathy (2010), Passarelli (2012), and Luenberger (1998) demonstrated these sensitivity parameters in various applications.

Internet of Everything (IoE): This is the future application of cheap and abundant semiconductors to connect people, places, machines, self-driving vehicles, autonomous robots, smart buildings, smart grids, wearable computers, and digital wallets to the Internet. Jalali (2013) foresaw 50 billion Internet connections by 2020 (pp. 210-213).

Lifetime (T): This is the project lifetime or expiration of the project. For a successful project, the lifetime ends with the start of commercialization and the generation of free cash flows. Kodukula and Papudesu (2006) stated that uncertainty makes an accurate project time frame difficult to determine (p. 93).

Nanotechnology: Baik et al. (2011) stated that nanotechnology consists of manmade materials fabricated with a physical size between one and 100 nanometers (nm) (pp. 2709, 2711). Abraham, Brand, Naik, Schuegraf, and Thakur (2013) forecasted 10nm manufacturing by 2016, 7nm by 2018, 5nm by 2020, and 3.5nm by 2022 (p. 67).

Option to abandon: This real option provides management with a contingency to abandon the project for salvage in case the project fails to develop the process recipe by a deadline or other catastrophic event. Kodukula and Papudesu (2006) demonstrated binomial lattice expressions to abandon the project (pp. 102-108).

Option to contract: Due to poor project performance or a pessimistic forecast, this real option gives management the opportunity to conserve cash by reducing production capacity and operations with tools, employees, and processes. Kodukula and Papudesu (2006) demonstrated the binomial lattice expressions to contract capacity (pp. 116-121).

Option to defer: Based on an important outcome, this real option gives management the opportunity to invest or to defer an investment. Kodukula and Papudesu (2006) demonstrated the binomial lattice expressions for a defer option (pp. 126-130).

Option to expand: Due to a favorable forecast, this real option gives management the opportunity to increase production capacity with greater investments to expand operations with tools, employees, and processes. Kodukula and Papudesu (2006) demonstrated the binomial lattice expressions to expand capacity (pp. 110-116).

Put option value (*P*): Value is captured from the freedom but not the obligation to sell an asset prior to the expiration. A European put option is "in the money" when the strike investment cost (*X*) exceeds the underlying asset value (*S*) such that put value $P = \text{Max}\,[X - S, 0]$ as described by Kodukula and Papudesu (2006, pp. 3-4).

Real options: Unlike financial options, real options are used in high-risk projects to expand capacity, contract capacity, to defer investments, or to abandon a project. Mun (2010) stated that "real options can be used to hedge the downside risk and take advantage of the upside uncertainties" (p. 11). Ayanso and Herath (2010) recommended compound real options with three stages to value nanotechnology projects (pp. 191-200).

Response surface methodology (RSM): Box and Draper (1987) said that RSM is a statistical modeling technique based on least-square approximation methods, matrix theory, and ANOVA parameters to optimize a model with multivariate variables (pp. 1, 114-123). Baysal, Nelson, and Staum (2008) have applied RSM to solve financial options based on the Black-Scholes model.

Rho (ρ): This is the sensitivity parameter for the rate of change for call value, *C*, with respect to the risk-free interest rate, *r*. Passarelli (2012) stated that rho displays a positive correlation with interest and is influenced by option lifetime, *T*, and the investment cost, *X* (pp. 135-138).

Risk-free interest (r): This is the interest rate applied to the project. Kodukula and Papudesu (2006) indicated this risk-free interest rate can be determined by using the U. S. Treasury rate (p. 94).

Strike cost (X): This is the total cost of the project and involves a series of investments. Kodukula and Papudesu (2006) described investments for plant construction, product development, patents, and product marketing (pp. 92-93).

Theta (θ): This is the sensitivity parameter for the rate of change for the call value, *C*, with respect to the project lifetime. Passarelli (2012) stated that call value increases with higher volatility (pp. 38-41). Madhumathi and Parthasarathy (2010) stated that theta has a negative value and the value of the real option decreases as the project matures over time (p. 16).

Underlying value (S): This is the underlying asset value for the project, and it is determined by forecasting cash flows. Kodukula and Papudesu (2006) explained how to construct binomial lattices to determine the underlying present value based on a series of investments over the project lifetime (pp. 85-86).

Vega (ν): This is the sensitivity parameter that measures the change in call value, *C*, with respect to the implied volatility, as explained by Passarelli (2012, pp. 42-51).

Volatility (σ): This parameter represents project uncertainty of underlying asset cash flows over the project's lifetime. Kodukula and Papudesu (2006) provided three methods to calculate volatility from future cash flows (pp. 91-92).

Theoretical Framework

The seven research questions were solved with a theoretical framework based on the Black-Scholes option theory, which originated from the seminal work of Black and Scholes (1973). The Black-Scholes pricing model was originally developed for financial options to find value. Years later, the contributors Merton and Scholes were recognized by a Nobel Prize in economics. Other theorists have extended the Black-Scholes model to improve various real options and compound real options. In Chapter 2, I describe the theoretical framework, the development of real options, and Greek sensitivity parameters using two constructs consisting of closed-form Black-Scholes equations and binomial lattices to emulate four real options to compare NPV for American and European 450mm wafer-processing fabs.

The theoretical framework included Moore’s second law, as presented by Rupp and Selberherr (2011), to develop survey question Q19, which is a time-dependent exponential growth equation to determine the total strike price (*X*), this represents the total wafer-foundry cost. The competitive real option gaming strategy theories by Smit and Trigeorgis (2004) and Chevalier-Roignant and Trigeorgis (2011) strengthen the theoretical framework with justification for the cost leadership and differentiation business strategies.

Nature of the Study

This study was designed with the quantitative method because it provides a postpositivist worldview and a reductionist approach, which encouraged me to narrow in on a topic with one reality, to identify specific variables for causality problems, and to investigate the phenomenon of interest. The five independent variables examined in this study were the underlying asset value (*S*), investment cost (*X*), volatility (σ), the risk free interest rate (*r*), and lifetime (*T*). The dependent variables included the call value (*C*), put value (*P*), and the five sensitivity parameters: delta (Δ), vega (ν), theta (θ), gamma (Γ), and rho (ρ). With the objective to solve seven research questions, a survey instrument comprised of closed-ended questions was constructed prior to collecting data from participants in America and Europe. Descriptive statistics were performed on collected survey data, and the results are presented in several tables. Hypothesis testing was conducted, followed by making inferences using response surface methods, as discussed in Chapter 3.

Significance and Social Change Implications

As wise investment decision making models to plan, build, and operate future 450mm wafer foundries do not exist in the literature, this study is significant because real option models with sensitivity parameters were demonstrated. Real option models were developed for managers to make wise investment decisions with a goal to conserve limited financial resources. Real options developed in this study provide information such as the investment costs, investment timing, how to optimize capacity, the impact of investment delay, and a contingency in case of project failure. Data collected from randomly selected participants in America and Europe was utilized in real option models, and the NPV and strategy findings are expected to fill a deficiency in scholarly literature.

This study may be the first to demonstrate real options to compare NPV for American 450mm wafer foundries versus those to be built in Europe. This study may be the first to solve sensitivity parameters delta, vega, and theta and to improve decision making with optimal solutions obtained from the response surface method specifically with the Box-Behnken design. This study presents a new finance approach to develop predictive models as an alternative to Monte Carlo simulations. The Box-Behnken design can provide second-order inferential models, contour plots, and three-dimensional response surface plots, and financial information.

In this study, I validated Moore's second law, maximized NPV, utilized a business gaming strategy theory, and demonstrated conservation of limited financial resources for 450mm wafer foundries that could support stable operations to supply billions of advanced semiconductor products by 2019. These semiconductor products will likely drive the Internet of Everything around the globe starting in 2020 with connected smart cities, smart infrastructures, smart grids, and smart buildings. Significant positive social change is expected to occur when low cost leading edge semiconductors will be needed to provide quick decisions from big data analytic platforms connected to billions of intelligent bi-direction sensors throughout smart grid networks, cashless society networks, smart infrastructures to support self-driving autonomous vehicles, to stream on-demand information into wearable computers with augmented reality displays, to improve healthcare, and to support communication networks for autonomous robots.

Scope and Limitations

The research problem was solved with the creation of flexible real option models that can emulate 450mm wafer fab operations from R&D to commercialization to expand capacity, to contract capacity, to defer the EUV investment, and to abandon the project.

Two real options excluded from this study were rainbow options, which consider different volatilities, and switch options, which allow managers to investigate value from different products, such as switching from 22nm transistors to advanced 14nm transistors.

Figure 2 illustrates the global semiconductor industry, and the arrow points to the scope, the 450mm wafer foundry. In regard to boundaries, in this study, I included participants who were potential stakeholders for future 450mm wafer fabs in America and Europe. In this study, I excluded participants from the back-end package, IC test companies, and product distributors in the global marketplace. External validity and the ability to make accurate generalizations were improved by collecting data from two different populations. With the goal to reduce bias and to counter threats to internal validity, in this study, I applied a process of random selection to survey participants. In Europe, one limitation may have been an English communication problem, which may have been a source of confusion with the survey instrument. Two constructs were developed to counter the threat to construct validity. The first construct was developed using closed-form Black-Scholes equations and the second construct was built using binomial lattices. A potential source of bias that could have influenced the outcome was the selection of participants who may have had less knowledge of 450mm wafer foundries than previously expected. This threat was limited when a few introductory questions were asked to ensure participants were knowledgeable about this topic. Threats to statistical conclusions were mitigated by checking assumptions to determine if they were valid. Responses to each survey question were analyzed with descriptive statistics to characterize the data and to ensure the data represented a normal distribution.

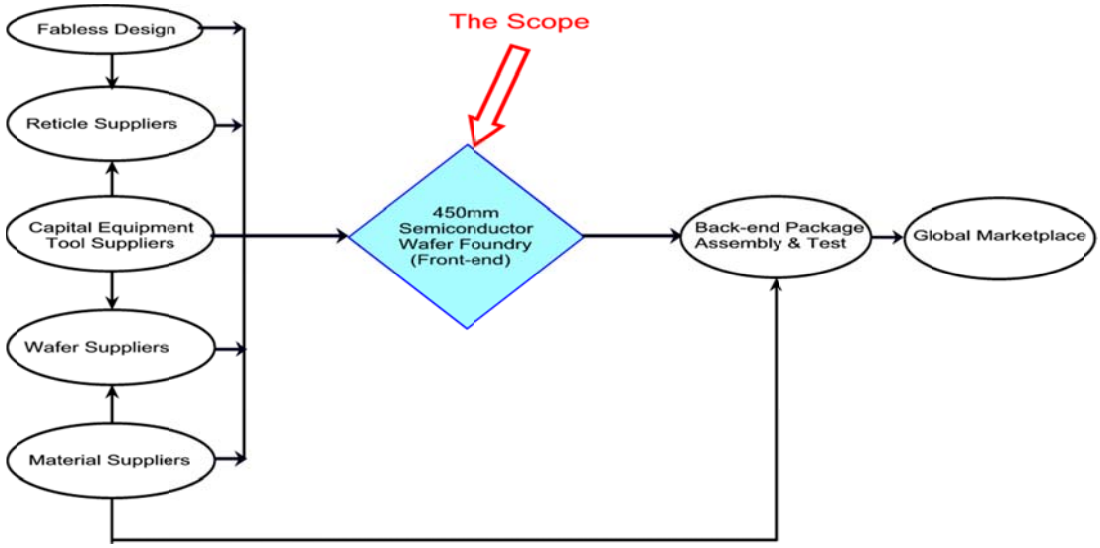

Figure 2. The global semiconductor industry and the scope.

Assumptions

Several assumptions were made. Solutions for each research question were clarified by employing the same assumptions outlined by Black and Scholes (1973, pp. 640-641). It was assumed that the independent variables volatility (σ) and the risk free interest rate (r) were constant throughout this study; in reality, they fluctuate. Assumptions were made that the euro-dollar exchange rate did not vary and there were no dividends. Given the five independent variables from the Black-Scholes theory, an assumption was made that there were no interactions between the five independent variables. Moreover, an assumption was made that a causal relationship existed such that the dependent call value, put value, and Greek sensitivity parameters depended on the independent variables. To simplify the investigation of production capacity using the real options in research questions RQ1 and RQ2, an assumption was made that production rate capacity would follow a linear function. With a goal to compare NPV for the seven research questions, the assumption was made that a no growth conservative perpetuity would be simple to calculate and would not distort the NPV values obtained from the four real options.

The assumption was made that the sample size of $n = 46$ was sufficient to establish a normal distribution to improve reliability and to make generalizations about a population. For the survey instrument, an assumption was made that each participant answered every question to the best of his or her ability, that each question was correctly interpreted, and that the independent variables were correctly measured. In the context of external validity, an assumption was made that the independent variables obtained from the participants were equivalent regardless of different people, location, and time.

Summary

In Chapter 1, I described the semiconductor industry's failure to improve 300mm wafer-foundry efficiency, the need for 450mm wafer foundries to increase economy of scale by 2.25 times, and to reduce manufacturing cost by 30%. The problem statement described the need for wise investment decision making models for 450mm wafer foundries and a gap in the literature. The purpose of this quantitative study was to conserve limited financial resources with the development of wise decision making models using real options to expand or contract production capacity, to defer the EUV lithography investment, and to abandon the project in case of failure or an unexpected catastrophe. Operational terms were presented to clarify several meanings. The nature of the study described the development of seven research questions to compare NPV and to forecast future business strategy for American foundries versus those to be built in Europe. The theoretical framework was based on the Black-Scholes option pricing model, and it was applied to develop four real options using closed-form equations and binomial lattices to emulate 450mm wafer-foundry operations. I discussed sensitivity parameters and how the independent Black-Scholes variables change and influence option value. In the significance and social change section, I described a novel finance method to develop predictive models using the Bob-Behnken design as an alternative to Monte Carlo simulations. Assumptions, scope and limitations follow with a summary.

In Chapter 2, I describe the development of the research problem with a literature review, the development of four real options based on the theoretical framework, the Black-Scholes option pricing model, and the Greek sensitivity parameters. I describe technical aspects of 450mm wafer foundries, future semiconductors, and how they will likely contribute to positive social change. I conclude Chapter 2 with a review of research methods and a summary. In Chapter 3, I justified the quantitative methodology, and discussed the population setting and sampling techniques, the instrumentation process, the data collection and analysis, ethical protection of participant rights, and I conclude with a summary. In Chapter 4, I explain the data collection process and the quantitative process to solve seven research questions, I present the predictive results from four real option models, and I conclude with a summary. In Chapter 5, I interpret financial findings for American and European 450mm wafer foundries, state the implications of future semiconductor technology, describe positive social change, recommend topics for future research studies, and summarize with a conclusion.

Chapter 2: Literature Review

As explained in Chapter 1, the 2011 ITRS executive summary described a need for a financial model providing flexibility for next generation foundries that span from R&D to commercialization (pp. 14, 30). The literature review revealed that real option contingency models with sensitivity analyses for 450mm wafer foundries are not available in scholarly literature. The purpose of this quantitative study was to compare NPV for American 450mm wafer foundries versus European wafer foundries using real option models that span from the R&D phase to commercialization to expand capacity, to contract capacity, to defer the EUV lithography investment, or to abandon the project.

This study began with a literature review of recent peer-reviewed journal articles. I developed a critique and synthesized ideas to develop a theoretical framework, to identify gaps in the literature, and to explore key variables. The literature review is organized in five sections. Chapter 2 begins with an introduction; this is followed by source material in which I present an overview of heritage economic and financial models that have been previously used in the semiconductor industry. In the third section, the theoretical background focuses on the Black-Scholes framework to develop real options using closed-form equations and binomial lattice models. In the fourth section on background research, I explore recent journal articles describing the development of 450mm wafer foundries and the expected positive social change that most likely will occur from leading edge low cost semiconductor products. The fifth section is a review of research methodologies and applications by previous researchers.

In the last section, I summarize literature review highlights that focus on the research problem and the construction of real option models providing financial decision making for next generation foundries that span from R&D to commercialization. In the literature review, I also focus on the research purpose to compare NPV for American 450mm wafer fabs versus European wafer fabs with the development of real option models to expand capacity, to contract capacity, to defer the EUV investment, and to abandon the project. The two journal articles by Varma (2011) and Liu (2010) provided closed-form compound (call on a call) option equations to solve the third research question. The study by Baysal, Nelson, and Staum (2008) demonstrated the application of response surface methods (RSM) to solve a Black-Scholes put option; this article was useful to solve sensitivity problems for the last three research questions.

I applied several strategies during the literature review. The search began with the ProQuest Dissertations and Theses database to find dissertations on 450mm wafer fabs. This initial search produced only one dissertation by Golan (2008). Golan had focused on improving 300mm wafer foundries with the 300mm Prime program as a low cost alternative solution instead of developing 450mm wafer foundries. I implemented a second approach by attending the 2012 SEMICON West in San Francisco and the 2012 SEMICON Japan to refine the research topic. The third strategy was to use several peer-reviewed journal article databases. These databases included EBSCO Academic Search Complete, EBSCO Business Source Complete, Elsevier ScienceDirect, Emerald Management Journal, IEEE Xplore Digital Library, ProQuest ABI/INFORM Complete, ProQuest Central, and ProQuest Dissertations & Theses. Single words or a combination of words were used to locate peer-reviewed journal articles. Search terms included *450mm*, *abandon*, *American*, *binomial*, *Black-Scholes*, *call*, *capacity*, *compound*, *construction*, *cost-of-ownership*, *defer*, *European*, *EUV*, *fab*, *foundry*, *Geske*, *Greeks*, *IEM*, *Internet of Everything*, *lattice*, *lithography*, *options*, *puts*, *quantitative*, *real*, *response surface method*, *RSM*, *semiconductors*, and *valuation*.

Review of Source Material

In the first part of this literature review, I focus on heritage economic and finance models used by the semiconductor industry. The 2011 ITRS executive summary stated two economic models were updated: the first was the International SEMATECH's IEM model and the second was the strategic-range model developed by IC Knowledge to track demand for capital equipment tools (p. 14). Draina, Fandel, and Ferrell (2007) stated the IEM model was originally developed in the 1990s during the transition from 200mm to 300mm wafer foundries (pp. 53-54). The *Industry Economic Model Users Guide version 4.0.1* (2002) revealed the IEM was an Excel spreadsheet filled with historical product demand and accounting data such as fixed and variable costs, capital equipment, employees, product yield, wafer starts, maintenance expenses, depreciation, and other financial data to make forecasts (pp. 27, 37-46).

Similar to the IEM model, Iturralde and Nañez (1995) had developed a cost-of-ownership (CoC) model for wafer-processing tools using an Excel spreadsheet to forecast prices for tool acquisition, installation, qualification, service, maintenance, operations, yield loss, facilities support, consumables, depreciation, and decommissioning (pp. 170-171). Additionally, Jiménez, Mediavilla, and Temponi (2012) conducted a quantitative study on the 450mm wafer fab development to investigate the critical productivity parameters such as cost, schedule, return-on investment, and automated wafer-processing tool throughput (pp. 416-417). These researchers concluded that additional financial research on operational costs will likely be needed, and they recommended the need to obtain data from foundry tool suppliers (p. 417). In summary, the IEM model provides semiconductor management with market demand information based on passive database information. The literature review revealed a lack of finance models to conserve financial resources with wise investment decision making using flexible real options that can extend financial growth opportunities and limit project uncertainties.

Theoretical Background of the Study

The 2011 ITRS executive summary stated that to improve “cost efficiency” an integrated staged foundry model was needed to span from R&D, construction, production ramp up, and commercialization (p. 30). To develop an integrated staged foundry model, Ayanso and Herath (2010) recommended a three-stage real option model for large, complex nanotechnology projects with flexible decision making options to expand, delay, or to abandon the project from R&D to commercialization (pp. 193-197).

The theoretical foundation of the study was based on the Black-Scholes option pricing theory. This theory originated from Black and Scholes (1973), who stated, “almost all corporate liabilities can be viewed as a combination of options” (p. 637). The Black-Scholes theory makes several assumptions: its model emulates a European option and restricts exercising the option prior to maturity and it does not account for dividends (p. 640). Finally, the model assumes that the volatility (σ) and the risk free interest rate

(r) are constant and the underlying asset value (S) jumps with "random walks" (p. 640). Elegance and simplicity were the rationale for selecting the Black-Scholes theory to create flexible real options using two different types of constructs. The first constructs were developed using closed-form Black-Scholes equations. The second constructs were built using binomial lattices spanning 10 years.

In the literature, many researchers have applied Black-Scholes to construct financial and real options. However, there were no studies in the literature that applied the Black-Scholes theory to emulate real options for 450mm wafer-foundry operations. Mun (2006) demonstrated flexible real options such as the option to expand capacity, to contract capacity, to defer investments, or to abandon a project (p. 93). Trigeorgis (1996) stated real options provide managers with the ability to carry out flexible decision making and to increase corporate value beyond the traditional discount cash flow method (pp. 1-9). Moreover, Smit and Trigeorgis (2004) stated flexible value creation begins when forecast information such as market demand prompts management to implement contingency options to preempt the competition by increasing or decreasing capacity, to divest, to wait, or to react to risks or opportunities (pp. 7, 93).

RQ1 began with the literature review of European call options to create a real option to expand production capacity. Damodaran (2002) showed the Black-Scholes European call option equation with five independent variables (S, r, T, X, and σ) to yield the dependent call option value, C (pp. 806-807). The first independent variable examined was the underlying asset value, which is the present value of all cash flows. This variable was designated as S. The second variable is the risk free interest rate, r. The third variable is the option lifetime, T, which represents the project completion date. Black and Scholes (1973) explained the option time frame is comprised of the maturity date minus the current date (pp. 639, 644). The fourth independent variable, X, signifies the investment cost, also known as the strike price, to develop the project. The last independent variable is the implied volatility, which is the variance of expected free cash flows and is represented by sigma, σ. Equation 1 shows the European option call value, C, as a function of the five independent variables, S, r, T, X, and σ.

$$C(S, r, T, X, \sigma) = \mathrm{S}N\left(d_1\right) - \mathrm{e}^{-\mathrm{r}\mathrm{T}}\,\mathrm{X}N\left(d_2\right) \tag{1}$$

This European call option as presented by Equation 1 employs the standard normal cumulative distribution function $N(d)$ as illustrated by Equation 2 on values d_1 and d_2 and is shown by Equations 3 and 4 to yield $N(d_1)$ and $N(d_2)$. Trigeorgis (1996) pointed out that the standard normal cumulative distribution is a univariate distribution function (p. 214). Furthermore, Wilson (2011) explained that Black-Scholes options can be developed with the normal cumulative distribution function using the Excel function =NORMSDIST (p. 591).

$$N(d) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{d} \mathrm{e}^{-\frac{x^2}{2}}\,dx \tag{2}$$

$$d_1 = \frac{\ln\left(\frac{S}{X}\right) + \left(r + \frac{\sigma^2}{2}\right)T}{\sigma\sqrt{T}} \tag{3}$$

$$d_2 = \frac{\ln\left(\frac{S}{X}\right) + \left(r - \frac{\sigma^2}{2}\right)T}{\sigma\sqrt{T}} = d_1 - \sigma\sqrt{T} \tag{4}$$

The implied volatility (σ) variable, as presented above in Equations 3 and 4, can be calculated from Equation 5. Kodukula and Papudesu (2006) recommended this volatility equation, which is obtained by taking the natural log of the ratio of the best-case and worst-case annual revenues and dividing it by four times the square root of the option lifetime, *T* (p. 92). Ghosh and Troutt (2012) applied the same volatility equation in their work (p. 543).

$$\sigma = \frac{\ln\left(\frac{\text{Sbest}}{\text{Sworst}}\right)}{4\sqrt{T}} \tag{5}$$

Barone-Adesi and Whaley (1987) stated the European call option can be extended to form an American call option, which adds an “early exercise premium” term to provide greater value (p. 305). A second method to create a real option to expand capacity was the development of a binomial lattice, as shown in Figure 3. Construction of this binomial lattice is discussed shortly.

For the second research question, RQ2, the literature review focused on the development of a European put option (*P*) to emulate a real option to reduce production capacity. The European put option applies the same five independent variables and the standard normal cumulative distribution function, *N*(*d*), to yield the put value, as illustrated by Equation 6.

$$P(S, r, T, X, \sigma) = e^{-rT} X N\left(-d_2\right) - S N\left(-d_1\right) \tag{6}$$

Greater value beyond the traditional European put option can be obtained from American put options. Barone-Adesi and Whaley (1987) stated the European put option can be extended to form an American put option that adds an "early exercise premium" term (pp. 307-308). In addition, Mun (2006) demonstrated the construction of a binomial lattice to emulate a contract option (pp. 170-175). Mun showed how to build a *choose option* with the integration of three options. The choose option improves investment decision making with the ability to expand capacity, to contract capacity, and to abandon a project instead of building three independent options since only one real option can occur during a single event (pp. 174-177). The choose option, as illustrated in Figure 3, is an essential binomial lattice for this study. This lattice model was constructed using several Microsoft Excel functions. After development of the binomial lattice choose option, the functionality of each option was validated in accordance with the examples provided by Mun (2006, pp. 174-177) and Kodukula and Papudesu (2006, pp. 121-125). The upper lattice shows the calculation of the underlying asset value (*S*) multiplied by the up and down probability factors at each node. The lower lattice was developed with the backward induction method. For each lattice node, the Excel maximum function (=MAX) was applied to select the highest option value from four option equations. Based on the results from the maximum function, compound logical IF statements (=IF) were developed to display one of four option flags. The option key shows the four flags, where the “A” flag represents the abandon option, the “C” flag represents the contract option, the “E” flag represents the expand option, and the “O” flag represents an open option to defer or to invest. With several example inputs, the choose option yielded a present value of $217.498 based on a 5-year project.

Inputs:		
PV Investment	180	180
Volatility [%]	33	0.33
Time [T: Years]	5	5
Risk-free Interest [rf %]	5	0.05
Contraction [%]	20	0.8
Contraction Savings	60	60
Stepping Time δt =	1	1
Expansion [%]	25	1.25
Expansion Cost	40	40
Abandon Salvage Value	120	120

u=	1.39097	Step Up
d=	0.71892	Step Down
p=	0.49453	Risk Neutral Probability

Present	Year 1	Year 2	Year 3	Year 4	Year 5
					Su^5
				Su^4	937.256
			Su^3	673.816	Su^4d
		Su^2	484.422	Su^3d	484.422
	Su	348.263	Su^2d	348.263	Su^3d^2
S	250.374	Sud	250.374	Su^2d^2	250.374
180	Sd	180	Sud^2	180	Su^2d^3
	129.406	Sd^2	129.406	Sud^3	129.406
		93.0332	Sd^3	93.0332	Sud^4
			66.8838	Sd^4	66.8838
				48.0844	Sd^5
					34.569

Options Key:
A = Abandon Option
C = Contract Option
E = Expand Option
O = Open Option

Present	Year 1	Year 2	Year 3	Year 4	Year 5
					Su^5 → **E**
				Su^4 → **O**	1131.57
			Su^3 → **O**	804.221	Su^4d → **E**
		Su^2 → **O**	569.334	Su^3d → **O**	565.528
	Su → **O**	405.543	Su^2d → **O**	397.279	Su^3d^2 → **E**
S → **O**	293.362	Sud → **O**	286.43	Su^2d^2 → **O**	272.968
217.498	Sd → **O**	213.366	Sud^2 → **C**	207.033	Su^2d^3 → **C**
	165.336	Sd^2 → **O**	163.525	Sud^3 → **O**	163.525
		135.116	Sd^3 → **O**	134.622	Sud^4 → **A**
			121.026	Sd^4 → **A**	120
				120	Sd^5 → **A**
					120

Figure 3. Binomial lattice for the combinational choose option.

A real option to defer an investment was developed for RQ3 using a European call on a call (CC) option. Varma (2011) described the application of a European compound call on a call option to develop an option to defer an investment (pp. 13-14). This compound call equation applied by Varma was similar to the Geske equation presented by Trigeorgis (1996, p. 214). Moreover, Trigeorgis (1996) presented an elegant form of Geske's compound call on a call option equation (pp. 220-221). Liu (2010) also described the same Geske equations (pp. 442-444). In addition, Liu demonstrated the application of the compound call on a call equation with a numerical example (p. 453). Wolfram's Mathematica 8.0 software was applied using Liu's example, and the same Geske values were obtained. As a result, this exercise validated Liu's work and provided proof of concept for RQ3. The European compound call on a call option equation developed by Geske and the variables presented by Trigeorgis and Liu were substituted with 450mm wafer fab model variables to develop Equation 7.

$$\begin{aligned} \mathrm{CC} = &\left[\mathrm{S}\beta\left(d_3, d_4, p_2\right) - \mathrm{X}e^{-r\left(\mathrm{T}_{3\,\mathrm{D}} - \mathrm{T}_{2\,\mathrm{A}}\right)} \beta\left(d_6, d_5, p_2\right) \right] \\ &- \mathrm{X}_{2\,\mathrm{A}} e^{-r\left(\mathrm{T}_{2\,\mathrm{A}} - \mathrm{T}_{1\,\mathrm{A}}\right)} N\left(d_6\right) \end{aligned} \tag{7}$$

Trigeorgis (1996) demonstrated the compound European call on a call option equation that utilizes the bivariate cumulative normal distribution function, β(*a*, *b*, *p*) (p. 214). Wilson (2011) explained that variable *a* represents the number of successes, *b* represents the number of trials, and *p* represents the probability of success (p. 516). Wilson explained that the bivariate function can be implemented with the Excel function =BINOMSDIST (pp. 515-522). Equation 8 shows the bivariate cumulative normal distribution function where p_2 is the probability for Stage 2 success in the fab.

$$\beta(a, b, \mathrm{p}_2) = \int_{-\infty}^{a} \int_{-\infty}^{b} \frac{e^{\left(-\frac{x^2 - 2(\mathrm{p}_2)(x)(y) + y^2}{2\left(1-\mathrm{p}_2^{\,2}\right)}\right)}}{2\pi\sqrt{1-\mathrm{p}_2^{\,2}}}\, \mathrm{d}x\, \mathrm{d}y \tag{8}$$

Trigeorgis (1996) indicated that the bivariate normal cumulative distribution function should be applied twice, while the univariate normal cumulative distribution function is used once (p. 220). This technique was applied to Equation 7 on values d_3, d_4, d_5, and d_6. The *d* values as presented by Trigeorgis and Liu were substituted with 450mm wafer fab model variables as shown in Equations 9 through 12.

$$d_3 = \frac{\ln\left(\frac{\mathrm{S}}{\mathrm{X}_{2\,\mathrm{A}}}\right)\left(\mathrm{r} + \frac{\sigma^2}{2}\right)\left(\mathrm{T}_{2\,\mathrm{A}} - \mathrm{T}_{1\,\mathrm{A}}\right)}{\sigma\sqrt{\mathrm{T}_{2\,\mathrm{A}} - \mathrm{T}_{1\,\mathrm{A}}}} \tag{9}$$

$$d_4 = \frac{\ln\left(\frac{\mathrm{S}}{\mathrm{X}}\right)\left(\mathrm{r} + \frac{\sigma^2}{2}\right)\left(\mathrm{T}_{3\,\mathrm{D}} - \mathrm{T}_{2\,\mathrm{A}}\right)}{\sigma\sqrt{\mathrm{T}_{3\,\mathrm{D}} - \mathrm{T}_{2\,\mathrm{A}}}} \tag{10}$$

$$d_5 = d_4 - \sigma \sqrt{T_{3\,D} - T_{2\,A}} \tag{11}$$

$$d_6 = d_3 - \sigma \sqrt{T_{2\,A} - T_{1\,A}} \tag{12}$$

The literature review continued with research question RQ4 with the goal to build a real option to abandon the project. Schwartz (2004) explained that the abandon options are necessary for management decision making because high risk projects can be prone to development failure, a catastrophic event, consuming greater capital than expected, or market demand may lack cash flow intensity or duration (pp. 23-31). Damodaran (2002) demonstrated a real option to abandon a project using an American put option (pp. 811-813). Mun (2006) described several abandon options using European put options, American put options, and binomial lattice models (pp. 163-167, 386-395). Mun (2006) indicated abandon options require knowledge of the enterprise salvage value (p. 164). Trigeorgis (1996) introduced Geske's European call on a put (CP) option (p. 224). Variables for the 450mm wafer-foundry model were substituted into the compound CP option equation as illustrated by Equations 13 through 17. Backer, Casimon, Engelen, Van Wouwe, and Yordanov (2011) presented a pharmaceutical compound real option with six sequential investment growth stages, each with an optional path to abandon the project (pp. 1203-1209). Jang and Lee (2010) compared the value obtained from an eight-stage compound real option with a subsequent string of options to expand or abandon a project (pp. 95, 100-103).

$$\mathrm{CP} = \left[\mathrm{S}\nu\beta\left(-d_7, d_8, p_3\right) - \mathrm{S}\beta\left(-d_9, d_{10}, p_3\right) \right] - \mathrm{X}_{3\,\mathrm{A}} e^{-r\left(\mathrm{T}_{3\,\mathrm{A}} - \mathrm{T}_{1\,\mathrm{A}}\right)} N\left(d_7\right) \tag{13}$$

$$d_7 = d_9 - \sigma\sqrt{\mathrm{T}_{3\,\mathrm{A}} - \mathrm{T}_{1\,\mathrm{A}}} \tag{14}$$

$$d_8 = d_{10} - \sigma\sqrt{\mathrm{T}_{3\,\mathrm{D}} - \mathrm{T}_{3\,\mathrm{A}}} \tag{15}$$

$$d_9 = \frac{\ln\left(\frac{\mathrm{S}}{\mathrm{X}_{3\,\mathrm{A}}}\right)\left(\mathrm{r} + \frac{\sigma^2}{2}\right)\left(\mathrm{T}_{3\,\mathrm{A}} - \mathrm{T}_{1\,\mathrm{A}}\right)}{\sigma\sqrt{\mathrm{T}_{3\,\mathrm{A}} - \mathrm{T}_{1\,\mathrm{A}}}} \tag{16}$$

$$d_{10} = \frac{\ln\left(\frac{\mathrm{S}}{\mathrm{X}}\right)\left(\mathrm{r} + \frac{\sigma^2}{2}\right)\left(\mathrm{T}_{3\,\mathrm{D}} - \mathrm{T}_{3\,\mathrm{A}}\right)}{\sigma\sqrt{\mathrm{T}_{3\,\mathrm{D}} - \mathrm{T}_{2\,\mathrm{A}}}} \tag{17}$$

Compound options using the binomial lattices were constructed and were validated with the examples presented by Mun (2006, pp. 184-186) and Kodukula and Papudesu (2006, pp. 146-156). The 10 year compound option, as illustrated in Figure 4, was the second essential building block for this study. Two lattices are shown. The upper binomial lattice shows the product of each node after multiplying up or down probabilities with the previous underlying asset (*S*) value. The lower lattice applied the backward induction method, where the Stage 3 investments were calculated first at the far right. The final option value was calculated at the far left. In this study, I integrated both lattices into a single lattice which yielded an NPV option value of $149.4529.

Probability		
u=	1.491825	Step Up
d=	0.67032	Step Down
p=	0.463724	Risk Neutral Probability

Present	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
										Year 10
									Year 9	Su^10
								Year 8	Su^9	29100.81
							Year 7	Su^8	19506.9	Su^9d
						Year 6	Su^7	13075.8	Su^8d	13075.84
					Year 5	Su^6	8765	Su^7d	8765	Su^8d^2
				Year 4	Su^5	5875	Su^6d	5875.35	Su^7d^2	5875.353
			Year 3	Su^4	3938	Su^5d	3938.4	Su^6d^2	3938.37	Su^7d^3
		Year 2	Su^3	2640	Su^4d	2640	Su^5d^2	2639.97	Su^6d^3	2639.966
	Year 1	Su^2	1769.6	Su^3d	1770	Su^4d^2	1769.6	Su^5d^3	1769.62	Su^6d^4
Present	Su	1186	Su^2d	1186.2	Su^3d^2	1186	Su^4d^3	1186.21	Su^5d^4	1186.213
S	795	Sud	795.14	Su^2d^2	795.1	Su^3d^3	795.14	Su^4d^4	795.143	Su^5d^5
533	Sd	533	Sud^2	533	Su^2d^3	533	Su^3d^4	533	Su^4d^5	533
	357	Sd^2	357.28	Sud^3	357.3	Su^2d^4	357.28	Su^3d^5	357.281	Su^4d^6
		239.5	Sd^3	239.49	Sud^4	239.5	Su^2d^5	239.492	Su^3d^6	239.4923
			160.54	Sd^4	160.5	Sud^5	160.54	Su^2d^6	160.537	Su^3d^7
				107.61	Sd^5	107.6	Sud^6	107.611	Su^2d^7	107.6108
					72.13	Sd^6	72.134	Sud^7	72.1337	Su^2d^8
						48.35	Sd^7	48.3527	Sud^8	48.35267
							32.412	Sd^8	32.4118	Sud^9
								21.7263	Sd^9	21.72625
									14.5635	Sd^10
										9.762236

Inputs:		
PV Underlying Asset (S)	533	
Stage 1 Investment Cost (X1)	100	
Stage 2 Investment Cost (X2)	220	
Stage 3 Investment Cost (X3)	500	
Volatility [%]	40	0.4
Stage 1 Time, T1 [Years]	1	
Stage 2 Time, T2 [Years]	3	
Stage 3 Time, T3 [Years]	5	
Risk-free Interest [rf %]	5	0.05
Stepping Time δt [Year]	1	1
Contraction [%]	0	0
Contraction Savings	0	0
Expansion [%]	0	0
Expansion Cost	0	0
Abandon Salvage Value	100	100

Present	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
										Year 10
									Year 9	Su^10→ **O**
								Year 8	Su^9 → **O**	28880.81
							Year 7	Su^8 → **O**	19297.6	Su^9d→ **O**
						Year 6	Su^7→ **O**	12876.8	Su^8d → **O**	12855.84
					Year 5	Su^6 → **O**	8575.6	Su^7d→ **O**	8555.73	Su^8d^2→ **O**
				Year 4	Su^5 → **I3**	5695	Su^6d→ **O**	5676.29	Su^7d^2→ **O**	5655.353
			Year 3	Su^4→ **O**	3438	Su^5d – **O**	3749	Su^6d^2→ **O**	3729.1	Su^7d^3→ **O**
		Year 2	Su^3 → **I2**	2164.4	Su^4d – **I3**	2460	Su^5d^2→ **O**	2440.9	Su^6d^3→ **O**	2419.966
	Year 1	Su^2 → **O**	1097.2	Su^3d → **O**	1270	Su^4d^2– **O**	1580.3	Su^5d^3→ **O**	1560.35	Su^6d^4→ **O**
Present	Su→ **I1**	578.8	Su^2d → **I2**	710.6	Su^3d^2→ **I3**	1012	Su^4d^3→ **O**	987.149	Su^5d^4→ **O**	966.2133
S → **O**	223	Sud → **O**	185.89	Su^2d^2 → **O**	295.1	Su^3d^3→ **O**	616.47	Su^4d^4– **O**	585.872	Su^5d^5→ **O**
149.4529	Sd → **A**	133	Sud^2 → **A**	181.2	Su^2d^3→ **A**	386.8	Su^3d^4→ **O**	354.886	Su^4d^5→ **O**	313
	100	Sd^2 → **A**	100	Sud^3 → **A**	100	Su^2d^4– **O**	225.11	Su^3d^5→ **O**	189.079	Su^4d^6→ **A**
		100	Sd^3 → **A**	100	Sud^4 – **A**	155.6	Su^2d^5→ **O**	134.416	Su^3d^6→ **A**	100
			100	Sd^4 → **A**	100	Sud^5→ **A**	110.3	Su^2d^6→ **A**	100	Su^3d^7→ **A**
				100	Sd^5 → **A**	100	Sud^6→ **A**	100	Su^2d^7→ **A**	100
					100	Sd^6→ **A**	100	Sud^7→ **A**	100	Su^2d^8→ **A**
						100	Sd^7→ **A**	100	Sud^8→ **A**	100
							100	Sd^8→ **A**	100	Sud^9→ **A**
								100	Sd^9→ **A**	100
									100	Sd^10→ **A**
										100

Options Key:
A = Abandon Option
C = Contract Option
E = Expand Option
I1 = Invest at Stage 1
I2 = Invest at Stage 2
I3 = Invest at Stage 3
O = Open Option

Figure 4. Binomial lattice for a three-stage compound option.

Black-Scholes Sensitivity Parameters

Mun (2006) stated the Black-Scholes sensitivity parameters, known as the Greeks, are comprised of delta (Δ), gamma (Γ), theta (θ), rho (ρ) and vega (ν) (p. 227). These sensitivity parameters provide comprehensive insights into how the independent variables change as well as sustaining robustness. These Greek sensitivity parameters provide performance insights on value drivers that can be applied to investigate the best-, optimal-, and worst-case scenarios. Kodukula and Papudesu (2006) recommended a sensitivity analysis using the Greek parameters to gain deeper insight into the dynamics within the Black-Scholes model (pp. 96, 99). Madhumathi and Parthasarathy (2010) presented a case study on a large construction project that utilized Greek sensitivity parameters and three-dimensional graphic plots to investigate land prices and interest-rate volatility (pp. 7-21). Emery, Guo, and Su (2008) investigated the Black-Scholes Greek sensitivity parameter theta to gain a better perspective on risk management (pp. 60, 70).

Limon and Morris (2010) gained deeper insights into the dynamics of the independent variables with the wavelet transform, a numerical matrix method to solve the Black-Scholes delta and gamma parameters (pp. 404-413). This numerical application failed, as excessive oscillations were obtained for the gamma profile. Albeverio, Popovici, and Steblovskaya (2006) extended the Black-Scholes model to analyze a basket of securities using Monte Carlo simulations with a million runs to generate three-dimensional plots with the objective to reduce distortion and to improve response accuracy (pp. 69-88). The disadvantage of these Monte Carlo simulations was the excessive computations to find solutions. Carver and Ennis (2011) described the benefit of investigating Greek sensitivity parameter gamma versus the option strike price and explained that this information may be useful to develop investment strategies (pp. 220-230). Finally, Baysal, Nelson, and Staum (2008) demonstrated the application of response surface methods (RSM) to solve a financial put option using the Black-Scholes option pricing model (pp. 631, 633).

Originating from the Black-Scholes call equation, Mun (2006) derived partial derivatives for each Greek parameter (pp. 227-231). The Greek sensitivity parameter delta (Δ) is the first derivative that provides the rate of change for call option value, C, with respect to the underlying cash flow value, S, as shown by Equation 18. Rho (ρ) is the rate change for the call value, C, with respect to the risk free interest rate, r, as presented in Equation 19. Vega (ν) is the rate of change for the call value, C, with respect to the implied volatility, σ, as presented in Equation 20. The calculation of vega depends on the standard normal probability density function $n(d_1)$, as illustrated by Equation 21. The second derivative, gamma (Γ), is the rate of change of delta (Δ) with respect to the underlying value, S, as illustrated by Equation 22. Like vega, gamma is calculated using the standard normal probability density function. The final dependent sensitivity parameter, theta (θ), is the rate of change for call option value, C, with respect to the real option lifetime, as shown by Equation 23. The calculation of theta involves the use of the standard normal cumulative distribution function and the standard normal probability distribution function. Finally, the authors Luenberger (1998, pp. 355-379), Emery, Guo, and Su (2008, pp. 61-62), and Madhumathi and Parthasarathy (2010, pp. 10-18) demonstrated how to apply these Greek parameters.

$$\Delta = \frac{dC}{dS} = N\left(d_1\right) \tag{18}$$

$$\rho = \frac{dC}{dr} = e^{-rT}\, XTN\left(d_2\right) \tag{19}$$

$$\nu = \frac{dC}{d\sigma} = Xe^{-rT} n\left(d_2\right)\sqrt{T} \tag{20}$$

$$n\left(d_1\right) = \frac{e^{-\frac{\left(d_1\right)^2}{2}}}{\sqrt{2\pi}} \tag{21}$$

$$\Gamma = \frac{d\Delta}{dS} = \frac{d^2C}{dS^2} = \frac{n\left(d_1\right)}{S\sigma\sqrt{T}} \tag{22}$$

$$\theta = -\frac{dC}{dT} = -\frac{S\sigma\, n\left(d_1\right)}{2\sqrt{T}} - rXe^{-rT} N\left(d_2\right) \tag{23}$$

Background Research

The background research section was organized in accordance with three stages for the future 450mm wafer foundry. This review began with R&D funding as the first stage. Jiménez, Mediavilla, and Temponi (2012) predicted that the R&D funding needed to develop 450mm wafer-processing tools will cost 20 to $40 billion (p. 408). To develop efficient R&D funding schemes, Dulluri and Raghavan (2008) developed a two-stage real option with a cost-benefit analysis to maximize foundry revenue and to reduce risk (pp. 962-964). The Electronics Leaders Group (2014) reported to Neelie Kroes, the Vice-President of the European Commission, with plans to double Europe's semiconductor market share to 20% by the 2020-2025 time frame to meet the demand for the Internet of Things (pp. 6-12). This forecast can be accomplished by supplying a capacity of 250,000 WSPM, which is based on 300mm wafers. Iwai (2013) forecasted wafer processing during the 450mm wafer-foundry era will produce products with four or five generations of multigate MOSFET transistors with the following technology nodes: 16, 11.5, 8, 5.5, and possibly 4 nanometers (pp. 3-4). Abraham, Brand, Naik, Schuegraf, and Thakur (2013) forecasted advanced-technology node production would begin with 10nm by 2016, 7nm by 2018, 5nm by 2020, 3.5nm by 2022, and finally 2.5nm by 2024 (p. 67). Ahmed and Schuegraf (2011) described a paradigm shift away from one-dimensional transistors to three-dimensional (3D) transistors using plasma doping to fabricate 3D transistors down to the 7nm node for improved performance (pp. 63, 66). These authors described several process technologies to manufacture three-dimensional

10nm FinFET transistors down to the 5nm node and predicted 450mm wafer processing will likely occur in 2019.

In regard to construction of a 450mm wafer fab complex, the current issue is the need to increase the ceiling height to prevent traffic-jam bottleneck problems experienced with the AMHS transportation system inside 300mm wafer foundries. Chen, Shih, and Wu (2010) proposed raising the ceiling height for 450mm semiconductor wafer fabs to install a multilevel AMHS transportation system; however, this will likely increase the fab construction cost (p. 3698). To prevent the bottleneck problems experienced in 300mm fabs, Hennessy (2012) recognized that the AMHS monorail system for 450mm wafer fabs would need to cover greater distances; this will likely impact capacity planning decisions and increase the fab construction cost (pp. 245-246).

Palmer (2012) described the revolutionary EUV lithography tools for 450mm wafer fabs as a paradigm shift from optical lithography to nonoptical lithography tools (p. 47). Palmer predicted EUV lithography would debut with a production-ready 14nm tool sometime between 2013 and 2015 (p. 47). McGrath (2012) reported that Intel is positioned at the forefront of technology by at least 2-years ahead of the competition. To continue, Intel has invested $4.1 billion into ASML with the objective to speed up EUV lithography tool development to fabricate 10 nanometer node products by 2015 (p. 12). Harned and Wagner (2010) described the revolutionary attributes of nonoptical EUV lithography imaging tools to miniaturize transistors below 10 nanometers (pp. 24-25). Anscombe (2011) stated that EUV scanners must have a throughput of 60 wafers per hour for a pilot fab and a low cost of ownership. Brandt and Farrar (2009) discussed three types of cost of ownership issues for first-generation EUV scanner tools (pp. 10-11). Akiyama et al. (2010) compared the cost of ownership for two different types of EUV light sources (p. 1661). To reduce EUV lithography cost of ownership, Banine, Lammers, Moors, and Scaccabarozzi (2009) described two innovative engineering techniques to dry clean EUV reticles (p. 1604).

Wafer-processing tools for 450mm wafer fabs are being developed. Goldstein et al. (2012) modified a 300mm chemical mechanical planarization (CMP) machine to construct a 450mm tool with the intent to examine the operational characteristics and changes to the CMP process (p. 272). Ahn and Morrison (2010) conducted design of experiments on a three-chamber cluster tool with a single-arm robotic wafer handler to investigate the operational efficiency to manufacture small-lot wafer orders (p. 39). Morrison and Park (2011) performed computer simulations to model small mixed-wafer lots to compare throughput efficiency of circular cluster tools with linear cluster tools for future 450mm wafer fabs (pp. 1873-1876). Hu, Qin, and McTeer (2012) described the revolutionary plasma doping tools to implant homogeneous dopants to fabricate three-dimensional transistors below the 22 nanometer node (pp. 1-3). Akiki et al. (2013) reported that members of the Global 450mm Consortium (G450C) consisting of Intel, IBM, GlobalFoundries, TSMC, Samsung, and the SUNY College of Nanoscale Science and Engineering, have developed standards for “450mm notchless wafers” to utilize “laser-inscribed fiducial marks” on the backside of the wafer (pp. 365-366). Moreover, Akiki et al. (2013) reported on the development of the 450mm roadmap that predicted

R&D process tool availability by 2015, pilot tool availability by 2016, and high-volume production tool availability by 2018 (p. 365).

The ITRS executive summary (2011) recommended that ESH facilities should follow four guidelines (p. 59). First, materials should be characterized during process development. Second, risk should be mitigated by using safe green chemistries instead of hazardous substances. Third, processes should be designed to conserve resources. Finally, safety should be improved to protect workers and the surrounding communities. Bagchi et al. (2010) suggested that fab managers should oversee cost issues involving automated wafer-processing tools, to perform safety checks because chemicals are used by each tool, to perform periodic tool maintenance, to understand risks, to identify capacity constraints, and to forecast future product demand (pp. 3, 25). Musee (2010) advocated stricter EHS nanomaterial guidelines for production, handling, and waste disposal to protect humans and the biodiversity from “nanopollution” (pp. 825-832).

Positive Social Change From Semiconductors

The semiconductor technology trend continues to advance. The 2011 ITRS executive summary stated, “decreasing cost-per-function will continue; historically, this has led to significant improvements in economic productivity and overall quality of life through proliferation of computers, communication, and other industrial and consumer electronics” (p. 1). Based on these positive social change achievements, the ITRS recognized the importance of maintaining economic growth based on a strategy of continuous productivity (p. 4).

Ahuja (2012) predicted the recent global electronics boom represents the beginning of the "golden age of electronics" is expected to bring economic growth and better quality of life (pp. 3-4). Burt (2013) reported that Intel and AMD will develop advanced low-cost processors to be used by Cisco Systems to create Internet of Everything products (p. 4). Burt reported that Cisco predicts the Internet of Everything market will likely be responsible for generating $14.4 trillion in profits by 2020. Kristian (2013) stated the Internet of Things will converge into the Internet of Everything to include people, places, and things such as jet engines conveying in-flight information or workers and machines communicating to a cloud (pp. 695-697). Jalali (2013) predicted that semiconductor chips in 2020 will make a significant impact with innovative devices making 50 billion connections to the Internet of Things (IoT) (pp. 210-213). Jalali (2013) foresaw advanced electronics would create machine to machine (M2M) communications, smart grid metering, factory automation, smart buildings or homes, traffic monitoring, energy metering, and other innovations without human intervention. Fukushima et al. (2011) are developing next generation automotive collision-avoidance 3D IC chips that communicate with other automobiles and to the roadway infrastructure (p. 755). Demestichas et al. (2013) predicted that semiconductor sensors and actuators in 2020 will likely be applied to develop the Internet of Things, which would converge as a cognitive network where mobile machines such as self-driving automobiles will recognize patterns, learn, and develop autonomous behavior (pp. 91-92). Barolli et al. (2013) explained that RFID semiconductors will likely enable communication and cooperation between a team of autonomous humanoid robots to work together in factories, explore space, or to assist the elderly while connected to the Internet of Things (pp. 589-591).

Balasubramaniam and Kangasharju (2013) foresaw the Internet of Nano Things, such as nanoscale biosensors and wireless semiconductors embedded in humans, would transmit medical data such as electrocardio pulses or information about pathogens or allergens (pp. 62-63). Kaku (2011) predicted wearable sensor chips embedded in fabrics would screen for human diseases and cancers while “smart pill” chips with wireless TV cameras would be ingested to examine a patient’s stomach and intestines (pp. 35-36). Kaku (2011) described biochips with 78,000 cylindrical columns coated with antibodies to analyze blood and identify “lung, prostate, pancreatic, breast, and colorectal cancer cells” with a 99% accuracy (p. 187). Arai et al. (2010) anticipated that three-dimensional integrated circuit (3D IC) chips will likely be fabricated on 450mm wafers, which would lead to improved medical techniques, health, and safety (pp. 485-486). Kaiho et al. (2009) developed a 3D IC retinal prosthesis chip comprised of four levels to restore vision to blind patients suffering from two retinal diseases: retinitis pigmentosa and age-related macular degeneration (p. 1). Andreou (2011) foresaw future 3D IC semiconductors would significantly improve health and medical discoveries after implanting 3D ICs inside human beings to monitor and diagnose a condition, and distribute medication (p. S36). Bajaj, Bashir, Damhorst, and Hassan (2013) described future low-cost semiconductor bio lab-on-chip sensors to screen blood and to detect pathogens, bacteria, and viruses, such as those that cause HIV/AIDS, and to count white blood cells (pp. 2539-2541). Baik et al. (2011) foresaw future semiconductor advancements in the 21st century with ultra-fast Terahertz space applications, nondestructive medical imaging, homeland security applications, and “ultra-fast computing” (p. 2716).

Review of Research Methodologies

In the literature review, researchers were found to have used both qualitative and quantitative approaches. Researchers Jiménez, Mediavilla, and Temponi (2012) demonstrated qualitative methods by conducting an exploratory study on future 450mm wafer foundries by directing semiconductor participants to a secure website to take a survey (p. 412). These researchers explained participant selection and their use of e-mails to obtain a 62% response rate for the total sample size of $n = 22$. These researchers described good research practices by presenting statistical analysis details such as checking the reliability of their data with Cronbach’s α as well as checking for validity (p. 412). Finally, these researchers tested several hypotheses, presented predictions in tables, and discussed their findings (pp. 410-413).

Madhumathi and Parthasarathy (2010) presented a case study that analyzed secondary data (pp. 9-10). Instead of testing a hypothesis, these researchers solved their problems using three different construct types; each concluded with a sensitivity analysis.

Most authors used the quantitative approach. Varma (2011) developed a quantitative study with a theoretical framework based on the Black-Scholes model to develop a defer investment option (pp. 7-11). This was accomplished when Varma investigated the works by Trigeorgis to solve a deferral option with secondary data using two different numerical techniques (pp. 8-17, 21).

Summary

The literature review focused on the following three topics: an analysis of source material, the theoretical background of the study, and background research. The key finding was a lack of economic models and financial research devoted to 450mm semiconductor wafer foundries. A review of source material revealed a statement by SEMI that the IEM economic model was updated to provide semiconductor managers with forecasts based on market demand. Investigation of this IEM model revealed it was inadequate because it lacked real options to provide management with wise investment decision making capabilities during the three stages of operations from fab construction, developing a process recipe in the pilot fab, and production ramp-up for commercialization.

Next, the literature review focused on the development of a theoretical foundation with a goal to solve seven research questions. Theoretical material was collected to investigate the construction of four real options to provide wise decision making to plan, build, and operate a 450mm wafer foundry. The literature review has also shown a lack of real option studies using the Black-Scholes sensitivity parameters, and only one journal article was found in which the researchers used response surface methods.

Finally, the literature review focused on background research. This study focused on current technology developments needed to build and operate 450mm wafer foundries. The first part of this literature review focused on R&D funding, product development, fab construction, the development of EUV lithography and wafer-processing tools, and EHS facilities to support operations. The second part of this literature review focused on positive social change from semiconductors and examples of how future semiconductor products will likely impact global society.

This chapter concluded with highlights of research methodologies that were employed by other researchers. In summary, this study will likely fill a gap in the literature with an application of four flexible real options and use of sensitivity parameters for wise investment decision-making in 450mm semiconductor wafer foundries. Chapter 3 describes methodologies used in this study.

Chapter 3: Research Method

In Chapter 3, I discuss the characteristics of the quantitative method to construct real option models to solve seven research questions. The five independent variables investigated were the underlying asset value (S), investment cost (X), volatility (σ), the risk free interest rate (r), and lifetime (T). The Black-Scholes equations were applied to calculate the dependent variables: the call value (C), put value (P), and the five sensitivity parameters delta (Δ), vega (ν), theta (θ), gamma (Γ), and rho (ρ).

I begin this chapter by justifying the quantitative methodology, and I continue with discussions of the population and setting, instrumentation, data collection and analysis, ethical protection of participant rights, and conclude with a summary. The section on population and setting introduces the sampling plan, the sampling frame, and sample size determination. I discuss eligibility criteria for study participants, followed by descriptions of various aspects of instrumentation. In the next section on instrumentation, I review the survey instrument, score determination, reliability, validity, and the location where raw data will be stored. The data collection and analysis section describes variable scales, hypothesis construction, and analytical tools. The expected outcomes prior to conducting this study are given, and these expectations are compared to the actual findings as presented in Chapter 5. The ethical rights of participants were considered along with the consent-to-participate form and confidentiality, followed by a summary.

Justification for the Research Design and Approach

Three methods of inquiry, comprised of the quantitative, qualitative, and mixed methods, were examined prior to selecting the quantitative method. This section highlights several advantages and disadvantages of the quantitative method. Advantages of the quantitative method include the postpositivist worldview, in which the reductionist approach encourages researchers to focus on a topic with one reality and to identify specific variables related to the phenomenon of interest. The quantitative method provides researchers with the deterministic process to focus upon causality problems and techniques to improve reliability and validity with an objective to reduce bias and errors. The advantage of the quantitative method of inquiry is the use of structured, close-ended survey instruments to collect data, to test a theory, and to create inference models that can be applied to make generalizations.

The quantitative method of inquiry is at a disadvantage when compared to the mixed method approach, which can provide a higher level of completeness using two methods of inquiry beginning with a broad overview and then synthesizing to converge on a phenomenon with greater accuracy. The quantitative method of inquiry is again at a disadvantage when compared to the qualitative approach, which encourages mutual collaboration with research participants as researchers can rely on listening with empathy. The quantitative approach often relies on structured, closed-ended questions that ignore vital feedback from participants; this is usually not the case for the other two research methods. Despite these limitations, the quantitative method was selected for this study.

Population Setting and Sampling

In this section, I discuss the population, which was composed of semiconductor industry professionals such as executives, stakeholders, engineers, scientists, managers, operators, and equipment suppliers in America and Europe. This section describes the sampling plan, sampling frames, sample size determination, and eligibility criteria that were used to select participants.

Population

One of the leading global consortia to support the semiconductor industry is the Semiconductor Equipment Materials International (SEMI). Its mission is to promote semiconductor research, to develop standards, and to assist semiconductor foundries and suppliers.

The population consisted of American and European Semiconductor industry participants who had attended the 2013 SEMICON Europa and the 450mm Wafer Forum. The second data collection method was the snowball sampling method. Many suppliers support semiconductor wafer foundries by supplying capital equipment, materials, services for processes and equipment, and information. Supplier participants were preferred as they had significant time over the 4-day conference to participate by taking a survey and discussing several topics. In addition, regular attendees of the 2-day 450mm Wafer Forum technical paper presentations were surveyed because these participants had first-hand knowledge and better insight about next generation semiconductor wafer foundries. The 2013 SEMICON Europa website stated the venue population from October 7th to October 10th was composed of 360 exhibitor companies and 125 participants who had attended the 450mm Wafer Fab Forum as indicated by Table 1. In summary, two target populations consisting of American and European supplier participants at the 2013 SEMICON Europa in Dresden, Germany, were examined.

Additional American participants were contacted by snowball sampling. The estimated population was comprised of N = 4,332 participants.

Table 1

Potential Strata Populations to Research

Strata	Location	Pop	Companies	Dates
2013 Semicon Europa	Dresden, Germany	4,322	360	Oct 7-10
450mm Wafer Forum	Dresden, Germany	125		Oct 9-10
Snowball Sampling	American Cities	10		Sept 12 to Nov 1st

Note. Retrieved from the 2013 SEMICON Europa website Post Show Report, *N=4,332*

Sampling Plan

In addition to snowball sampling, three probability sampling plans (cluster sampling, stratified random sampling, and systematic sampling) were examined for their ability to make reliable inferences. Cochran (1977) stated that systematic sampling begins by selecting an appropriate sample size, then dividing the sampling frame into equal intervals followed by a process of random selection (pp. 205, 212). In this study, I began with snowball sampling. Data collection was also conducted with face-to-face surveys for which participants were selected by random sampling. Both methods were justified to improve external validity. Moreover, Aczel and Sounderpandian (2009) stated systematic random sampling has a similar precision in comparison to stratified random sampling (pp. 16-20).

Sampling Frame

Deming (1960) recommended sampling frames because probability sampling cannot be accomplished when complete coverage cannot be established (pp. 38-41). Without sampling frames, inferences about a population or universe could be biased.

A preliminary exhibitor list, or sampling frame, was downloaded from the 2013 SEMICON Europa website prior to the event. This sampling frame included participant booth numbers, which were copied into an Excel spreadsheet prior to making random assignments. The zoning interval technique, as recommended by Deming (1960), was applied to create random assignments (pp. 94, 99, 104). The zoning interval was determined by the total frame size divided by the required sample size. Overall, this process divided the frame into several groups, and a random number was used to select a group to survey; this process ensured a method of unbiased random selection.

Sample Size Determination

Sample size was determined by a response surface method using the Box-Behnken design (BBD) process. The BBD was centered on the Black-Scholes model, which contains five independent variables. For each variable, three levels were selected. Based on this BBD criterion of five variables with three levels, 46 sample runs were required. For a normal probability distribution with a two-sided 95% confidence interval, with three standard deviations, the estimated margin of error for 46 samples would be 0.891%. To improve reliability, a few additional samples were sought to eliminate outlier data. Overall, 50 data sets were obtained because Aczel and Sounderpandian (2009) recommended taking a larger sample size that a researcher could still afford (p. 243).

In Chapter 4, statistical power was calculated using a paired-difference test with statistical analysis programs Minitab 16 and MegaStat 2007. Statistical power was calculated for each research question based on an alternative hypothesis using a one-tailed hypothesis test, a sample size $n = 46$, and a significance level of $\alpha = 0.05$.

Eligibility Criteria to Study Research Participants

Prior to obtaining consent from participants to take part in the study, as a criterion for eligibility, exhibitor participants were asked in English if they were knowledgeable about technical and business aspects of the 450mm wafer fab transition. If participants were not familiar with the 450mm wafer fab transition, despite the fact that they could converse in English, they were denied. Participants were told that no personal data would be collected, that their ethical rights would be recognized, and that confidentiality would be ensured. Participants were told they had the right not to answer any question they felt uncomfortable with, the right to ask any question, and the right to terminate the research study at any time. All participants were presented with a consent permission letter to inform them about this study prior to being presented with the survey instrument. In summary, eligibility acceptance occurred based on mutual agreement.

Characteristics of the Selected Sampled

I believed that exhibitor participants and the 450mm Wafer Forum attendees represented the best population to study because these professionals were knowledgeable about wafer foundries. I anticipated that the best participants to query were supplier participants who understood the English language, had business and technology knowledge of semiconductor fabrication, and were familiar with 450mm wafer fab standards, wafer fab facilities, and EHS regulations and operations. Moreover, the entire 2-day 450mm Wafer Forum was conducted in English. Prior to conducting the study, it was assumed most exhibitor participants would want to participate in this study. This assumption was correct, as there was a high turnout, with greater than 95% survey participation obtained at both the 2013 SEMICON Europa conference and the 450mm Wafer Fab Forum.

Instrumentation

In this section I describe the data-collection instrument, concepts measured by the instrument, determination of scores, and reliability and validity. Other instrumentation topics include the participant process to complete the instrument, the location for raw data, the survey database, and a description of data for each variable. All questions in the survey instrument were based on the independent Black-Scholes real option variables. Each question was unique and none were adapted from other researchers.

Data Collection Instrument

Structured data collection survey instruments were developed with the goal of collecting data to solve seven research questions as presented by Appendix D. The survey instruments were designed based on the needs of four real options: to expand or contract capacity, to defer the EUV lithography investment, or to abandon the wafer fab project. Both surveys consisted of 23 questions. The first half of the survey focused on construction of the pilot fab while the second half focused on the production fab and commercialization. Questions were kept to a minimum because the time to collect data was limited. After completion of the survey, a general debriefing conversation took place, followed by a polite thank you, and business cards were exchanged in case the participants were interested in receiving a summary of the findings.

Concepts Measured by the Instrument

The survey instrument was designed with the purpose of obtaining four of the five independent variables for the Black-Scholes model. The investment strike cost (X) was determined using two methods. For the first method, participants were asked to provide individual investment costs for the 450mm wafer fab. The summation of sequential investment strike cost equated to $X_{1A} + X_{1B} + X_{2A} + X_{2B} + X_{3A} + X_{3B} + X_{3C} = X$, as illustrated by Figure 5. Participants were asked to provide the total cost (X) for an average 450mm foundry, and both methods were compared, as discussed in Chapter 5.

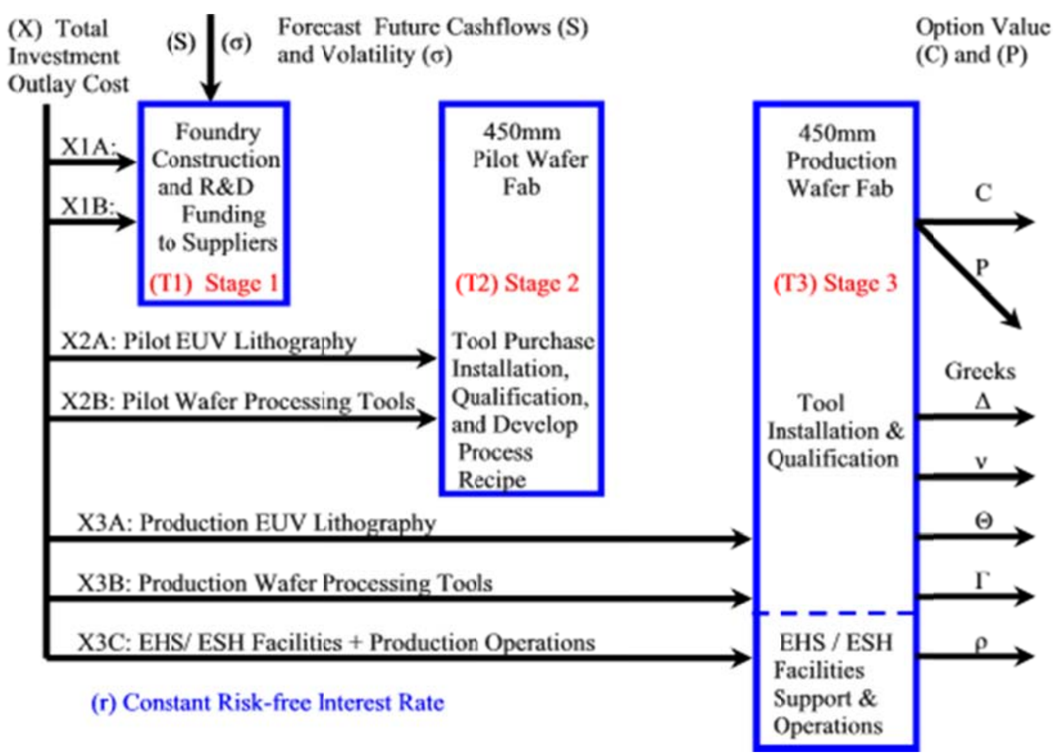

Figure 5. A three-stage compound real option for the 450mm wafer foundry.

The strike price (X) is the first independent variable. The first milestone investments for the 450mm wafer fab project included the wafer-foundry construction cost (X_{1A}) and R&D funding to support suppliers (X_{1B}). The second milestone included pilot fab investments for EUV lithography (X_{2A}) and wafer-processing tools (X_{2A}). The third milestone included production fab investments for EUV lithography (X_{3A}), wafer-processing tools (X_{3B}), and EHS facilities to support operations (X_{3C}).

The option lifetime (T) is the second independent variable. Lifetime was divided into three milestone periods: T_1, T_2, and T_3. The first stage, T_1, represents the time to construct the foundry complex and R&D investments to encourage supplier firms to speed up development of 450mm tools. The second stage, T_2, represents the time to develop the pilot fab with purchasing and installation of EUV lithography and wafer-processing tools and to develop the process recipe. The third stage, T_3, represents the time to purchase and install production EUV lithography and wafer-processing tools, and to ramp operations to achieve commercialization (T_{3D}). The survey question focused on finding the three milestones (T_1, T_2, and T_3) and the option lifetime, $T = (T_{3D} – T_{1A})$.

The third independent variable is the underlying asset value (S); in other words, the expected cash flow stream. This underlying asset value was calculated from the best-case annual revenue, the worst-case annual revenue, and the revenue lifespan from wafer fab operations, as illustrated in Chapter 4. The fourth independent variable is the implied volatility (σ). Equation 5 was applied with the best-case and worst-case revenues and the option lifetime to calculate the implied volatility.

The fifth independent variable is the risk free interest rate (*r*). This variable was determined from the 10 year US Treasury rate. After defining each independent variable, the dependent variables, consisting of the call value, put value, and the five sensitivity parameters delta (Δ), vega (ν), gamma (Γ), theta (θ) and rho (ρ), were calculated.

Determination of Scores

The survey instrument contained 23 structured, closed questions, as indicated in Appendix D. For each question, scores were carefully designed because improper scores could have led to skewed or biased data. The survey instrument was divided into two parts. Part I, as illustrated by Figure 6, consisted of Stage 1, the R&D and construction phase, and Stage 2, the 450mm pilot fab. Part II, as illustrated by Figure 7, focused on Stage 3, production ramp-up, and Stage 4, commercialization. Scores for some questions were determined from journal articles; for others, there was a gap in the literature.

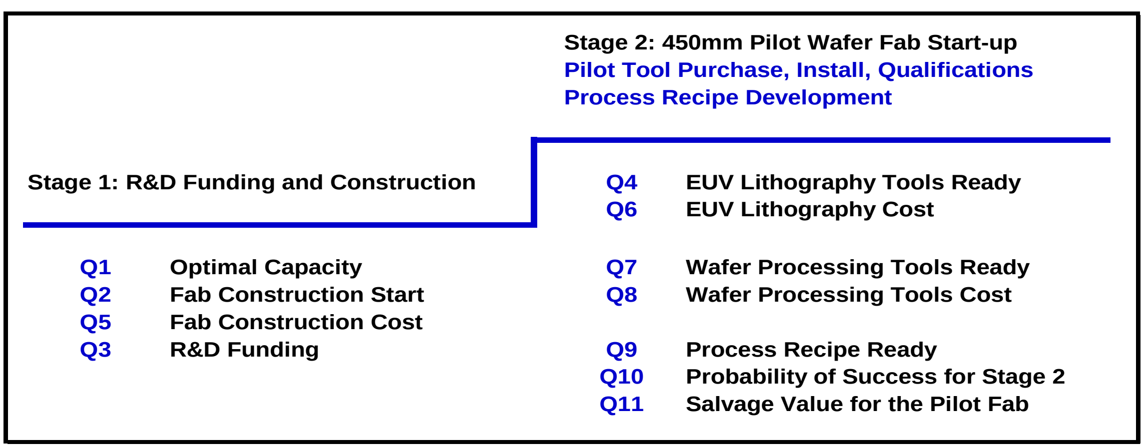

Figure 6. Survey part I: R&D and construction of a pilot 450mm wafer foundry.

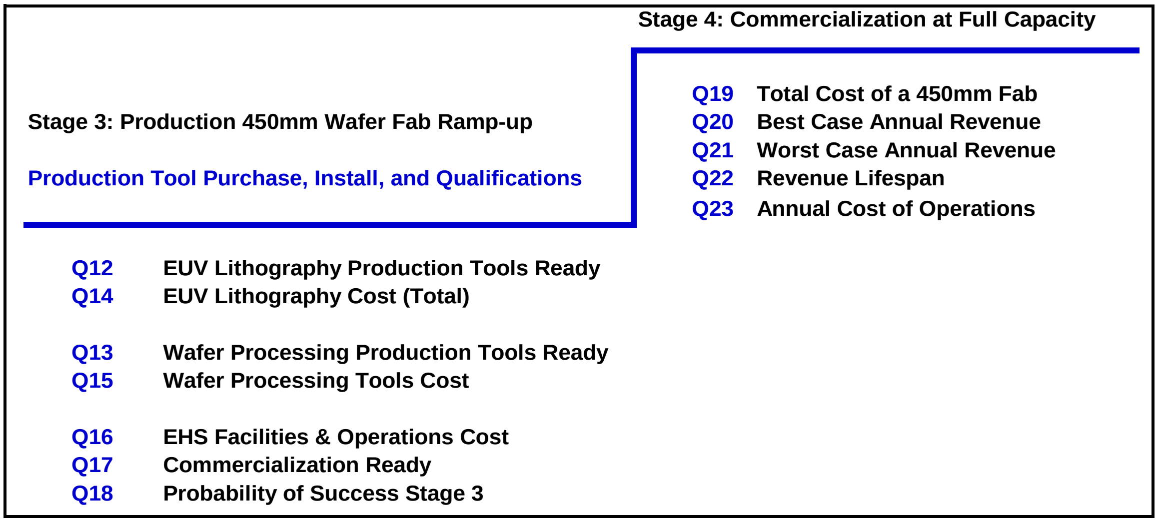

Figure 7. Survey part II: Production ramp-up and commercialization.

Question Q1 focused on operational capacity for the 450mm wafer foundry. Chen, Shih, and Wu (2010) stated that the optimal capacity for 300mm wafer fabs averaged from 25,000 to 60,000 wafer starts per month (WSPM) (p. 3698). Hennessey (2012) predicted 450mm foundries would operate with the same starting wafer capacity as with 300mm wafer foundries (p. 248). With this information and the fact that 450mm wafers are 2.25 times larger than 300mm wafers, the endpoints were set at ≤15,000 and ≥60,000 WSPM.

Question Q2 examined the best year to start construction of a 450mm fab. Scores began in 2010 with Intel’s first 450mm wafer foundry, and the range ends in 2019.

Question Q3 investigated R&D funding that foundry companies may provide EUV lithography and wafer-processing tool suppliers to speed up tool development. Singer (2012) reported that Intel and TSMC invested more than $5 billion in 2012 to obtain a 20% share in ASML, the leading EUV lithography tool supplier, with the goal to speed up development of the scanner tool. Based on this article, the low score was set at ≤$1 billion and was incremented by $1 billion steps to ≥$10 billion.

Question Q4 was designed to collect data on when EUV lithography will be ready for pilot 450mm wafer fabs. Peters (2011) stated that EUV lithography is not ready and reticles have not been made (p. 7). Based on this uncertainty, scoring for EUV lithography readiness began in 2013 and was incremented for 10 years until 2022.

Question Q5 examined the construction cost to build a 450mm wafer fab. Swartz (2011) claimed that Intel had spent $5 billion to construct the one-million-square-foot Fab 42 complex (p. 1B). This information was applied to this survey question, with $5 billion placed at the midpoint between ≤$1 billion and ≥$10 billion.

Question Q6 examined the cost for EUV lithography; this included the purchase and installation of lithography tools, photoresist chemistry, and a set of reticles. Chou and Lin (2009) indicated a single reticle was a few million dollars; however, this cost most likely was for a reticle for 300mm wafers (p. 61). Despite the literature gap, the scoring range was set from ≤$50 million to ≥$500 million.

Question Q7 asked about the availability of the wafer-processing toolset. The literature review did not reveal this information. For score determination, the low score was set to 2013 and scores were incremented annually for 10 years to 2022.

Question Q8 examined the cost to outfit a pilot 450mm wafer fab with wafer-processing tools. The literature review did not provide much information. In comparison to Q6, the score was doubled to provide a range from ≤$100 million to ≥$1 billion.

Question Q9 asked when the process recipe using 450mm tools would be ready. The literature review did not reveal this information. The low score was set to 2013 and scores were incremented annually for 10 years to 2022.

Question Q10 asked about the probability of success to construct the pilot 450mm wafer foundry. Scores for probability extended from 0% to 100%.

Question Q11 examined the salvage value of the pilot fab after completion in case the project fails. The literature review did not provide this information. Salvage value for the pilot 450mm wafer fab ranged from ≤$2 billion to ≥$7 billion.

The second half of the survey instrument focused on the Stage 3 production ramp up. The last part of the survey focused on Stage 4 commercialization.

Question Q12 asked about the expected date EUV lithography production tools would be available for full-production 450mm wafer fabs. The scoring range began in 2013 and was incremented annually for 10 years to 2022.

Question Q13 inquired about the availability of production wafer-processing toolset for the 450mm wafer fab. The literature review did not reveal this information. The scoring began in 2013 and was incremented annually for 10 years until 2022.

Question Q14 investigated the expected cost of EUV lithography to support a full-production 450mm wafer foundry. This question was designed based on the knowledge that 10 to 15 EUV lithography tools most likely will be needed. Since each EUV scanner may cost $100 million, the mid-range score was set to $1 billion and the range was extended from ≤$200 million to ≥$2 billion.

Question Q15 asked about the cost for all wafer-processing tools to operate a 450mm foundry at full capacity. There was a gap in the literature because most 450mm wafer-processing tools have not been developed. The scoring range for the toolset cost extended from ≤$0.5 billion to ≥$5 billion.

Question Q16 examined the cost of EHS facilities to ramp up and operate a 450mm wafer fab at full-production capacity. Similar to Q15, there was a gap in the literature because 450mm wafer fabs have not been constructed yet. Most likely, the cost to ramp up EHS facilities and operations will be between ≤$100 million to ≥$1 billion.

Question Q17 asked about what year production of 450mm wafer fabs would operate at full capacity. Although there have been various articles, a gap in literature still exists because 450mm wafer fabs have not been built yet. The scoring range began in 2013 and was incremented annually for 10 years until 2022.

Question Q18 inquired about the probability to purchase production wafer processing and EUV lithography tools, to install and qualify tools, to ramp up operations with EHS facilities management, and to successfully operate a production 450mm wafer foundry. Success probability scores ranged from 0% to 100%.

Question Q19 examined the total investment cost for an average 450mm wafer fab to run at full-production capacity. Jiang, Quan, and Zhou (2010) claimed Intel’s new wafer fab would cost $7 billion (pp. 1-2). Swartz (2011) stated that Fab 42 would cost $10 billion (p. 1B). Rupp and Selberherr (2011) analyzed the cost of wafer foundries from 1970 to 2005 and concluded the wafer-foundry cost constant for 2010 was $5 billion with a growth factor of 0.13 (pp. 1-2). The two values from this article were needed to apply Moore's second law to estimate the total cost of a future wafer foundry. Scores were determined by applying Moore's second law expression for foundry cost = $5 billion*EXP(0.13*Year), as illustrated in Figure 8. Here, the variable Year ranges from 0 to 12. The scoring range for the strike investment cost (*X*) for 2013 began at ≤$7.4 billion and ended with ≥$23.8 billion for 2022.

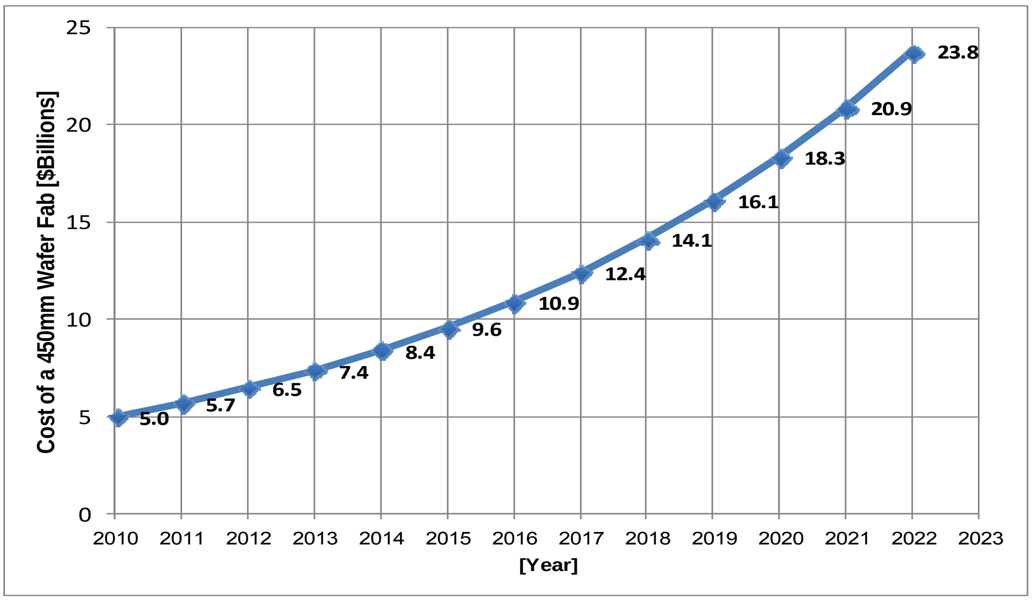

Figure 8. Theoretical cost (*X*) for a 450mm wafer foundry.

Question Q20 examined the best-case annual revenue for a 450mm wafer foundry that can operate at full production capacity. Intel and TSMC most likely have forecasted the best-case annual revenue for 450mm wafer foundries, but to maintain competitive advantages, this financial information was not disclosed. Best-case annual revenue scores were set from ≤ $1 billion to ≥ $10 billion.

Question Q21 investigated the worst-case annual revenue from a full-production 450mm wafer foundry that can operate at full-production capacity. Like Q20, scores ranged from ≤ \$1 billion to ≥ \$10 billion.

Question Q22 examined the future revenue stream lifetime to operate a 450mm wafer fab at full-production capacity. This financial information was not found in the literature. Scoring ranged from ≤10 to ≥30 years.

Question Q23 examined the annual cost of operations to run a 450mm wafer foundry at full-production capacity. Scores ranged from ≤250 million to ≥\$2.5 billion.

Process to Assess Reliability of the Instruments

A few processes to assess the reliability of the survey instruments were discussed. Trochim (2001) recommended two reliability tests (pp. 92-96). The first was the test-retest reliability method. This test-retest method was utilized with nearly identical survey instruments, as one survey with US dollars was given to American participants and a second survey with euros was provided to the Europeans at the 2013 SEMICON Europa conference. The only change to the survey was currency from American dollars to European euros. In this study, I ignored the exchange rate fluctuations. However, at the time of the questionnaire was presented, the exchange rate in Dresden, Germany was noted. Internal consistency was the second reliability method proposed by Trochim to estimate the average inter-item correlation or the average inter-total correlation (pp. 99-100). Estimation of the reliability for the strike cost (X) and option life (T) was performed because the determination of strike cost and option life was repeated; this yielded the inter-item correlation. In conclusion, correlations were calculated with the objective to understand sources of bias or errors caused by the instrument.

Process to Assess Validity of the Instruments

There are many threats to validity; these include external validity, internal validity, construct validity, and statistical conclusion validity. Trochim (2001) described three threats to external validity; each has the potential to reduce the ability to make accurate generalizations about a population (p. 43). These threats can occur from various participants, different venue locations, and time frames. Trochim suggested techniques to strengthen external validity using random sampling, framing, and collecting data from different participants at different venue locations and times. These recommended procedures were performed in this study.

Creswell (2009) listed several threats to internal validity that have the potential to produce invalid inferences based on causal relationships (pp. 162-164). Two that pertained to this study were the instrumentation and selection threats. To mitigate the instrumentation threat, the scaling for each question was not changed during the data collection process. (p. 164). To counter the selection threat, Creswell supported a process of random selection in order to reduce research participant bias (p. 163). Both procedures were performed in this study.

Trochim (2001) listed several threats to construct validity; each depends on how the construct variables are defined and their relation to the actual measurements to be performed (pp. 69, 75-77). The two threats that pertained to this study were the "inadequate preoperational explication of constructs" and "mono-operation bias" (p. 75).

The first construct threat suggested the construct was poorly defined. To reduce this threat, Trochim suggested rethinking the construct and obtaining expert advice. Trochim supported the implementation of various construct methods. This threat was reduced with the development of two constructs and then by comparing the results. The first construct was structured on closed-form equations. The second construct was created using binomial lattices.

Trochim (2001) listed several threats to statistical conclusion validity (pp. 259-265). The four threats that pertained to this study were the “violated assumptions of statistical tests, reliability of measures, fishing and error rate problems, and low statistical power” (pp. 260-261). The first threat to statistical conclusion validity was to make an improper assumption that can invalidate the statistics with an abnormal distribution. This threat was mitigated by checking for normal distributions. The second threat was the possibility of a poorly designed survey instrument. The third threat was fishing and error rate problems that can occur when multiple variables are treated independently. To prevent this threat, Trochim suggested adjusting the significance level while performing a multiple variable analysis. The last threat was the statistical conclusion validity, which refers to inadequate statistical power (pp. 262-266). To reduce this threat, Trochim recommended increasing power to be greater than 0.8 by increasing the significance level, α, or increasing sample size, n (p. 265). Statistical conclusion validity was increased with a large sample size of $n = 46$.

Participant Process to Complete the Instrument

Participants were directed to a mobile laptop PC with a blank electronic survey form with pull-down menus. Participants were given instructions to complete the survey instrument. Answers to each question were embedded in pull-down menus. Participants were encouraged to double check their answers, as they were free to change them at any time.

Location for the Raw Data

The storage location for raw data obtained from participants responding to the survey instruments resides in an Apple laptop PC, specifically inside a Microsoft Access 2010 database. This raw data will be retained for 5-years.

Data Collection and Analysis

This data collection and analysis section presents variable scales, hypothesis construction for each research question, the data collection process, analytical tools, the expected outcome, and the ethical protection of participants' rights. The first section on variable scales discusses attributes such as the variable type for each question in the survey instrument. The second section focuses on hypothesis construction for each research question. The third section describes the integrated electronic survey instrument with the data collection database. The fourth section on analytical tools discusses the use of software tools to perform descriptive statistics, reliability assessment, hypothesis testing, validity checking, and response surface methods. The fifth section describes the expected outcome for each research question. The sixth and final section discusses the ethical protection of participant rights in accordance with the Institutional Review Board

(IRB). In addition, the IRB gave approval (09-06-13-0039881) to conduct research on September 9th, 2013. This chapter concludes with a research design summary.

Variable Scales

All variables in the survey instrument were based on ratio scale measurements because each variable has a zero point reference, as illustrated by Table 2. Moreover, all variables in the survey instrument are independent variables.

Table 2

Black-Scholes Model Variables for a Production 450mm Wafer Fab

Question	Variable Description	Abbreviation	Scale	Scale Size
Q1	Optimal Capacity Planning (Stage 1)	Capacity	Ratio	10
Q2	Wafer Fab Construction (Stage 1 Begins)	T1A	Ratio	10
Q3	R&D Funding Investment (Stage 1)	X1B	Ratio	10
Q4	EUV Pilot Lithography Ready (Stage 2)	T2A	Ratio	10
Q5	Fab Construction Cost (Stage 1)	X1A	Ratio	10
Q6	EUV Pilot Lithography Cost (Stage 2)	X2A	Ratio	10
Q7	Wafer-processing Pilot Tools Ready (Stage 2)	T2B	Ratio	10
Q8	Wafer-processing Pilot Tools Cost (Stage 2)	X2B	Ratio	10
Q9	Process Recipe Ready (Stage 2 Ends)	T2C	Ratio	10
Q10	Probability of Stage 2 Success	p2	Ratio	11
Q11	Salvage Value of the Pilot Wafer Fab	Sv	Ratio	11
Q12	EUV Lithography Production Ready (Stage 3)	T3A	Ratio	10
Q13	Wafer-processing Production Tools Ready (Stage 3)	T3B	Ratio	10
Q14	EUV Lithography Production Cost (Stage 3)	X3A	Ratio	10
Q15	Wafer-processing Production Tools Cost (Stage 3)	X3B	Ratio	10
Q16	EHS Facilities & Operations Cost (Stage 3)	X3C	Ratio	10
Q17	Commercialization Ready (End of Stage 3)	T3D	Ratio	10
Q18	Probability of Stage 3 Success	p3	Ratio	11
Q19	Total Cost of the 450mm Fab	X	Ratio	10
Q20	Best-case Annual Revenue	Sbest	Ratio	10
Q21	Worst-case Annual Revenue	Sworst	Ratio	10
Q22	Revenue Lifespan	Lifespan	Ratio	11
Q23	Annual Operations Cost	Op Cost	Ratio	10

Hypothesis Construction for Each Research Question

The null hypothesis ($H_Ø$) statement for each research question was tested using a paired-difference test with a significance level of $\alpha = 0.05$ to determine if $H_Ø$ would be rejected.

RQ1: Based on a real option to expand capacity with a 450mm wafer foundry-project in America, will the NPV be less than or equal to one in Europe?

H_A1: NPV(America) > NPV(Europe)

RQ2: Based on a real option to contract capacity with a 450mm wafer foundry-project in America, will the NPV be less than or equal to one in Europe?

H_A2: NPV(America) > NPV(Europe)

RQ3: In case EUV lithography is not ready for the Stage 2 pilot 450mm wafer foundry, with the real option to defer the EUV investment X_{2A}, will the NPV for a fab in America be less than or equal to one in Europe?

H_A3: NPV(America) > NPV(Europe)

RQ4: Based on a real option to abandon production ramp-up in a 450mm wafer foundry at time T_{3A}, will NPV in America be less than or equal to one in Europe?

H_A4: NPV(America) > NPV(Europe)

RQ5: Will the sensitivity parameter delta (Δ) be less than or equal for a 450mm wafer foundry in America compared to one in Europe?

H_A5: Δ(America) > Δ(Europe)

RQ6: Will the sensitivity parameter vega (ν) be less than or equal for a 450mm wafer foundry in America compared to one in Europe?

H_A6: ν(America) > ν(Europe)

RQ7: Will the sensitivity parameter theta (θ) be less than or equal for a 450mm wafer foundry in America compared to one in Europe?

H_A7: θ(America) > θ(Europe)

Data Collection Process

The data collection process was developed using a survey instrument with 23 questions. Response data were collected using a Microsoft Access 2010 database. This database presented participants with questions and provided multiple-choice answers in pull-down menus. After the data collection process had ended, the stored tabular data were exported to Microsoft Excel 2003 to be used by several analytical software tools.

Analytical Tools

Analytical software tools were employed to perform a descriptive statistics analysis, to assess reliability, to perform hypothesis testing, to check the validity, and to create inferential models using response surface methods. The raw data from the data collection process were exported to Minitab 16 and Mega Stat 2007 to perform a descriptive statistics analysis, to measure dispersion for each set of scores, to determine central tendency using histograms, and to construct box plots. The descriptive statistics examined the range, mean, median, first and third quartiles, skew, kurtosis, and identified outliers. Extreme outliers were checked using box plots. Residuals plots were created to examine normality and the severity of outliers, and their cause such as the existence of a new phenomenon or simply bad data. A reliability assessment, as recommended by Deming (1960), was performed to calculate sampling errors (pp. 38-39, 425-426).

The first of two constructs were created using Mathematica 8.0. The first construct applied closed-form equations and provided numerical results for call options, put options, compound options, and Greek sensitivity parameters. The second construct consisted of binomial lattice models developed using Excel 2010 to emulate real options for 450mm wafer foundries. Each binomial lattice featured seven investment stages that spanned 10 years. These binomial lattices were constructed to calculate the Greek parameters for each input combination.

Hypothesis testing was performed with a level of significance $\alpha = 0.05$ to determine if the null hypotheses were rejected using Minitab 16 and Mega Stat 2007. For each research question, the hypothesis test consisted of a sample size $n = 46$, the mean, the p value for the upper tail, confidence intervals, and the operating characteristic curves (OCC) to determine the probability of making type I and type II errors. Statistical power was also calculated for each research question.

To validate hypothesis testing and to make predictions using the five Black-Scholes variables, multiple regression models were created using response surface methods (RSM) in accordance with Anderson-Cook, Montgomery, and Myers (2009, p. 220). Although there are several RSM techniques to choose from, the Box-Behnken design (BBD) was selected since this technique is efficient and uses fewer runs in comparison to the central composite design (CCD) (p. 319). For each research question, five independent Black-Scholes variables (S, r, T, X, σ) were used to build predictive models using the two statistical software packages, Minitab 16 and Stat Ease Design

Expert 8. The BBD setup consisted of five variables, three levels, and 46 runs to create second-order regression models with the general form as shown by Equation 24.

$$y = \beta_0 + \beta_1 * X_1 + \beta_2 * X_2 + \beta_3 * X_3 + \beta_4 * X_4 + \beta_5 * X_5 + \beta_{12} * X_1 * X_2 + \beta_{13} * X_1 * X_3 + \beta_{14} * X_1 * X_4 + \beta_{15} * X_1 * X_5 + \beta_{23} * X_2 * X_3 + \beta_{24} * X_2 * X_4 + \beta_{25} * X_2 * X_5 + \beta_{34} * X_3 * X_4 + \beta_{35} * X_3 * X_5 + \beta_{45} * X_4 * X_5 + \beta_{11} * X_1\hat{}2 + \beta_{22} * X_2\hat{}2 + \beta_{33} * X_3\hat{}2 + \beta_{44} * X_4\hat{}2 + \beta_{55} * X_5\hat{}2 \quad (24)$$

In accordance with Anderson-Cook, Montgomery, and Myers (2009), this second-order polynomial was developed from a Taylor Series expansion for five variables where the dependent variable y represents the response (pp. 220, 288). The five independent Black-Scholes variables S, r, T, X, σ were represented by the variables X_1, X_2, X_3, X_4, and X_5. Based on 46 different combinations as determined by the BBD and their responses, the two software applications calculated identical regression coefficients using the least squares method. Box and Draper (1987) explained the β_0 coefficient represents an intercept for the response surface plane (p. 22). Similarly, coefficients β_1, β_2, β_3, β_4, and β_5 represent gradients or slopes. For example, coefficients β_1 represents a slope in the X_1 direction (pp. 22-23). For each of the five independent variables, the coefficients β_{11}, β_{22}, β_{33}, β_{44} and β_{55} occurred when the independent variable were squared. The remaining coefficients, β_{12}, β_{13}, β_{14}, β_{15}, β_{23}, β_{24}, β_{25}, β_{34}, β_{35}, and β_{45} represent interactions between the independent variables.

Based on the BBD design as illustrated by Appendix E, Minitab 16 and Stat Ease Design Expert 8 were applied to calculate RSM coefficients. Multiple regression models were constructed for each research question as presented in Appendix F. These predictive models were then exported into Excel. The goal seek function was applied to determine specific NPV and annual revenue values, to create tables with predictions, and to validate each hypothesis. The RSM software was applied to produce contour and three-dimensional response surface plots. Anderson-Cook, Montgomery, and Myers (2009) explained that RSM is an effective tool to develop predictive computer simulation models which have advantages in comparison to Monte Carlo simulations (p. 435).

Statistical calculations were performed twice using two different analytical techniques to ensure the application tools were used correctly and to improve internal validity. To ensure the validity for each inferential model, multicollinearity, the coefficient of determination, R^2, and the variance inflation factor, VIF, were checked. These modeling performance parameters are presented in Appendix G.

Expected Outcome

For each of the seven research questions, the expected outcome was predicted based on the theories by Chevalier-Roignant and Trigeorgis (2011). If the findings revealed a greater NPV for each of the research questions as well as greater delta, vega, and theta values, this evidence would identify the leader's domination and the ability to select the differentiation business strategy. The expectation was the American foundries, as the industry leaders, would create greater NPV and would pursue a differentiation business strategy. This competitive strategy would then force European fab management operating 450mm wafer foundries to choose a cost leadership business strategy, as illustrated by Table 3.

The actual NPV findings are reported in Chapter 4 using tables and graphical plots. Chapter 5 compares the expected research findings described in this section with the actual NPV findings from Chapter 4. Chapter 5 also discusses inherent bias, weaknesses, reasons for expected and unexplained results, implications for the semiconductor industry, and future social change.

Table 3

Expected Outcome

	America	Europe
RQ1: NPV Option to Expand	Greater	Lower
RQ2: NPV Option to Contract	Greater	Lower
RQ3: NPV Option to Defer	Greater	Lower
RQ4: NPV Option to Abandon	Greater	Lower
RQ5: Delta (Δ)	Greater	Lower
RQ6: Vega (ν)	Greater	Lower
RQ7: Theta (θ)	Greater	Lower
Differentiation Strategy	X	
Cost Leadership Strategy		X

Ethical Protection of Participants' Rights

The ethical protection of participants' rights was recognized as a sensitive issue because participants provided vital response data for this academic study. During the recruiting phase, all randomly selected participants were asked if they would take part in the academic study by taking a short survey. Each of the 23 survey questions had focused on the participants' perspectives of 450mm wafer foundries. Participants were informed with a consent-to-participate document, as recommended by Creswell (2007, pp. 123-124). This consent form, as shown in Appendix H, described the purpose for this study. The consent form had identified this researcher as a Walden University student. The form had stated that participants have rights and complete freedom to terminate the survey instrument at any time, to ask any question about the study, and the right to refuse to respond to any verbal query. An oral introduction and the consent form described the study and stated that participants should not be alarmed or feel uneasy if they could not answer any question. Personal questions and sensitive information about semiconductor companies were not asked. There were no known risks that could have resulted from this study. Participants were told the benefits and the satisfaction of contributing to a worthy cause. Participants were told that they could receive a research summary via e-mail or on a compact disc (CD) provided that they left a contact mail address. The same benefit statement appeared in the consent form. All participants were briefed, and each was told that his or her participation would remain anonymous and his or her name would not appear in the dissertation. To ensure confidentiality, participant conversations were not recorded. Participants were reassured the survey instruments were not structured to benefit any company. Participants were told that this researcher was not affiliated with any semiconductor company and their responses supported academic scholarship at Walden University. The Institutional Review Board (09-06-13-0039881) granted permission to conduct this study. Likewise, the National Institute of Health granted permission to perform extramural research with certificate #954896, as shown in

Appendix I. Moreover, an official from SEMICON Europa in Berlin provided a letter of cooperation that granted permission to conduct a study at the 2013 SEMICON Europa, as presented in Appendix J. In summary, professional standards and ethical protection of participants' rights in accordance with the IRB were practiced.

Summary

Chapter 3 began with a discussion about advantages and disadvantages of the quantitative method. One of the key points to justify the quantitative method was the perspective of a postpositivist worldview to solve seven research questions. In the population section, I stated how snowball sampling was used to study the replies from American participants. In addition, I explained how systematic random sampling was applied to study Americans and Europeans attending the 2013 SEMICON Europa conference and the 450mm Wafer Fab Forum. Another discussion described the use of a structured survey instrument. This discussion was followed by one on the determination of scores. The next section described how reliability was built into the study using the test-retest and inter-item correlation. A discussion of various types of validity described threats to external validity, internal validity, construct validity, statistical conclusion validity, and techniques to counter those threats. Variable scales for each survey question were discussed followed by the construction of testable hypothesis expressions.

Participant responses were collected using an electronic survey instrument and stored in a Microsoft Access 2010 database. The section on analytical tools discussed the use of statistical tools to perform a descriptive statistical analysis, reliability assessment, hypothesis testing, validity testing, and the use of response surface methods to develop inferential models. The section on the expected outcome described the anticipated results for each research question. This chapter concluded with a discussion of the ethical protection of participants' rights in accordance with the IRB.

Chapter 4 begins with an introduction of the study results. Several discussion topics are then presented on the data collection process, descriptive statistics, hypothesis testing, and the creation of inferential models using second-order multiple regressions.

Chapter 4: Results

The purpose of this quantitative study was to develop wise investment decision making models using real options to expand capacity, to contract capacity, to defer the EUV investment, or to abandon the project with a goal to compare NPV for American 450mm wafer foundries versus those to be built in Europe.

I begin this chapter with a discussion of the data collection process, I then describe the quantitative process to solve seven research questions, and conclude with a summary section. This chapter focuses on the seven research questions that guided this study, specifically the application of real option models and the analysis of three Greek sensitivity parameters.

RQ1: Based on a real option to expand capacity with a 450mm wafer foundry-project in America, will the NPV be less than or equal to one in Europe?

RQ2: Based on a real option to contract capacity with a 450mm wafer foundry-project in America, will the NPV be less than or equal to one in Europe?

RQ3: In case EUV lithography is not ready for the Stage 2 pilot 450mm wafer foundry, with the real option to defer the EUV investment X_{2A}, will the NPV for a fab in America be less than or equal to one in Europe?

RQ4: Based on a real option to abandon production ramp-up in a 450mm wafer foundry at time T_{3A}, will NPV in America be less than or equal to one in Europe?

RQ5: Will the sensitivity parameter delta (Δ) be less than or equal for a 450mm wafer foundry in America compared to one in Europe?

RQ6: Will the sensitivity parameter vega (ν) be less than or equal for a 450mm wafer foundry in America compared to one in Europe?

RQ7: Will the sensitivity parameter theta (θ) be less than or equal for a 450mm wafer foundry in America compared to one in Europe?

Data Collection

The data collection activity began on September 12th and ended on November 1st, 2013. The survey contained 23 questions. The first set of 11 questions focused on the pilot 450mm wafer fab while the second set of 12 questions focused on ramping up production and commercialization. The American and European surveys are presented in Appendix D.

Quantitative data were collected using two different data collection approaches. The first approach began with snowball sampling. The data collection activity began by building a Microsoft Access 2010 database to control the snowball data collection activity. This database kept track of all surveys sent to respondents, the correspondence, and the completed surveys. This database had fields to retain information such as name, position, address, time and date stamping, and the ability to capture e-mail messages.

Over a 6-week period, 215 surveys were sent out to American participants. Most of the completed questionnaires were received from referrals who were contacted by the original recipient; hence, the snowball technique worked. Reminder e-mails were sent out and several more surveys were received. By November 1st, 10 completed surveys were received. The final snowball sampling response rate was 4.65%.

The second data collection method was implemented by obtaining a community partner letter from a SEMI representative in Berlin. The letter granted permission to conduct the study at the 2013 SEMICON Europa, as indicated by Appendix J. With this community partner letter, the IRB granted permission to collect data using a face-to-face data collection process at the 2013 SEMICON Europa conference in Dresden, Germany. In addition to granting approval, the SEMI representative had recommended data collection during a 2-day 450mm Wafer Fab Forum.

Two Microsoft Access 2010 databases were developed for each questionnaire on a light-weight Apple MacPro Retina laptop PC with extra-long battery life. Each survey was developed using pull-down menus that provided respondents with quantitative answers. This efficient survey instrument enabled respondents to complete the survey in less than 10 minutes. All data retained in the database were exported to Excel.

Data collection at SEMICON Europa in Dresden, Germany began on October 7th and ended in the evening of October 10th. Survey data were collected from 50 European participants. Surveys were given to 38 Americans since they were attending both the SEMICON Europa conference and the 450mm Wafer Fab Forum. The overall response rate for this face-to-face survey method was approximately 95%.

A review of the collected data revealed two European participants were unable to complete the survey, while two more data sets with excessive outliers were discarded. Two American data sets with outliers were also discarded. The final data collected were 46 data sets from the Europeans and 46 from the Americans.

The SEMICON Europa post show report (2013) presented a demographic breakdown and a list for the 450mm Forum attendees. According to the list, at least 90% were men. These demographics were expected, because most professionals in the semiconductor industry are men. Moreover, women historically are not attracted to engineering and the sciences at universities. A few young engineering students found the survey questions difficult because the study had focused on a topic that most likely was not taught at most universities. Most participants were between the ages of 25 to 65, and the average age appeared to be in their 30s.

Overall, the 23 questions appeared to cover important points for both the American and European populations. Therefore, external validity was provided from a short debriefing conversation conducted after each participant had completed the survey. During the debriefing, most participants responded by saying they found the survey stimulating. One respondent remarked this was the first time he was asked all the right questions in one compact survey and asked why other researchers were not asking the same critical questions. In conclusion, since the same number of participants had taken the survey in America and Europe, the response data should be proportional and should represent the general views from the semiconductor industry.

Quantitative Analysis and Results

This section summarizes the data received from American and European survey respondents. Question Q1 focused on capacity planning. The answer to this question was important because it provided information about the optimal size to build a 450mm wafer-foundry complex. American respondents indicated a 450mm wafer fab should operate at 100% capacity with a production rate of 37,717 wafer starts per month (WSPM). In order to compete against American foundry leaders, European respondents predicted a wafer fab in Europe should operate with a larger production capacity rate of 40,217 WSPM.

Question Q2 examined the best year to start construction of the 450mm fab wafer complex. American respondents indicated fab construction should begin by the third quarter of 2014, while the Europeans indicated the first quarter of 2015.

Question Q3 asked about the amount of R&D funding that foundry companies should provide to EUV lithography and wafer-processing tool suppliers to quicken development and delivery. American respondents indicated $5.195 billion was needed, while the Europeans indicated €4.655 billion, or $6.2782 billion was needed.

Question Q4 examined the time frame to install a pilot EUV lithography scanner, to assess photoresist chemistries, and to try out the process using EUV reticle sets in a pilot 450mm wafer fab. American participants predicted this time frame would occur during the third quarter of 2015, while the Europeans predicted the second quarter of 2015.

Question Q5 examined the construction cost of a 450mm wafer-foundry complex, which includes the cleanroom ballrooms, utility yards, and the office buildings. This cost excluded all wafer-processing tool investments. The Americans indicated the construction cost will be $5.304 billion while the Europeans estimated the construction cost will be €4.326 billion, or $5.8345 billion.

Question Q6 examined the cost of ownership for a pilot EUV lithography scanner, the photoresist chemistry, the EUV reticle set, and electricity consumption for this tool. The Americans forecasted the EUV lithography cost of ownership for a pilot fab will be $275 million while the Europeans estimated €264 million, or $356 million.

Question Q7 investigated the availability of the wafer-processing toolset for a pilot line. The Americans estimated pilot wafer-processing tools will be available by the second quarter of 2015, while the Europeans anticipated the third quarter of 2015.

Question Q8 inquired about the total investment to purchase 450mm wafer-processing tools for the pilot fab. The Americans estimated an investment of $606.5 million, while the Europeans estimated pilot tools will cost €626.1 million, or $844.4 million.

Question Q9 asked about the expected time frame for when the 450mm process recipe would be developed. American respondents forecasted the recipe would be ready by the third quarter of 2016, while the Europeans forecasted the start of 2017.

Question Q10 examined the probability of success for a pilot 450mm wafer foundry, in other words, to develop a process recipe. The American estimated a success rate of 74.35%, while the European estimated 73.91%.

Question Q11 investigated the salvage value for the pilot fab in case the project is terminated. In that case, the fab would be sold because the development of 450mm process recipe was unsuccessful. The Americans estimated a salvage value of $3.228 billion, while the Europeans estimated €3.152 billion, or $4.251 billion.

Question Q12 focused on the time frame for when EUV lithography production tools with acceptable throughput capability will be available to operate at full capacity. Both the Americans and Europeans expected production of 450mm EUV tools will be available by the second quarter of 2017.

Question Q13 examined the time frame for when production 450mm wafer-processing tools will be available. The Europeans anticipated fab tools would be available by the third quarter of 2016, while the Americans forecasted the second quarter of 2017.

Question Q14 investigated the investment cost to acquire production EUV lithography tools to outfit a full-production 450mm wafer foundry. The Americans estimated the EUV investment would be $1.110 billion, while the Europeans estimated €1.195 billion, or $1.612 billion.

Question Q15 focused on the investment cost for all wafer-processing tools except for EUV tools to outfit a 450mm production foundry capable of operating at full-production capacity. The Americans forecasted $3.413 billion, while the Europeans forecasted €3.032 billion, or $4.0893 billion.

Question Q16 examined the cost of EHS facilities and operations to ramp up 450mm wafer production to full capacity. The Americans predicted EHS facilities would cost $491.3 million, while the Europeans estimated €454.5 million, or $613 million.

Question Q17 inquired about the time frame for when production of 450mm wafer fabs will be able to run at full capacity, in other words, when commercialization begins. The Americans anticipated commercialization will begin during the third quarter of 2018, while the Europeans estimated the start of 2019.

Question Q18 investigated the probability to successfully ramp up production capacity in a 450mm wafer foundry. The Americans forecasted a success rate of 77.83%, while the Europeans estimated 76.74%.

Question Q19 examined the total investment cost for an average 450mm wafer foundry that will run at full-production capacity. The Americans estimated the total cost of a 450mm wafer foundry will be $14.643 billion, while the Europeans forecasted €13.208 billion, or $17.814 billion.

Question Q20 asked about the best case annual revenue for 450mm wafer foundries that will run at full production capacity. The American respondents estimated an average 450mm fab will be able to generate annual revenues of $5.804 billion, while the Europeans forecasted €4.935 billion, or $6.656 billion.

Question Q21 inquired about the worst case annual revenue for 450mm wafer foundries that will run at full production capacity. The Americans estimated an average 450mm foundry will be able to obtain worst case annual revenues of $2.783 billion, while the Europeans forecasted annual revenues of €2.261 billion, or $3.049 billion.

Question Q22 examined the operational lifespan of a 450mm wafer foundry to run at full-production capacity, in other words, the length of the revenue stream. The Americans expected a 450mm wafer foundry will operate for 18.09 years, while the Europeans anticipated a lifespan of 16.87 years.

Question Q23 asked about the annual cost of operations, in other words, the running cost to operate a 450mm wafer foundry at full production capacity. American respondents forecasted the cost of operations to be $1.288 billion, while the Europeans forecasted €1.261 billion, or $1.701 billion.

Descriptive statistics were performed on 46 data sets, as illustrated by Tables 4 and 5. For each response, these tables present the abbreviated symbol, mean data, and quality measures such as the standard error, the standard deviation, skew, kurtosis, three quartiles, and the Anderson-Darling test results.

Table 4

Descriptive Statistics for American Wafer Foundries

Q#	Abbrev	Mean	Std. Error	Std. Dev	Skew	Kurtosis	1stQ	Median	3rdQ	AD
Q1	Capacity	37,717	2.196	14.896	0.28	-1.19	25,000	35,000	51,250	1.331
Q2	T1A	2014.8	0.238	1.61	0.03	-0.38	2014	2015	2016	0.860
Q3	X1B	5.195B	0.406B	2.754B	0.21	-0.85	3.75B	5B	7.25B	0.772
Q4	T2A	2015.8	0.211	1.43	-0.41	-0.67	2015	2016	2017	1.394
Q5	X1A	5.304B	0.370B	2.511B	0.30	-0.38	3.75B	5B	7B	1.077
Q6	X2A	275.0M	17.5M	115.3M	0.15	-0.57	200M	300M	350M	0.494
Q7	T2B	2015.6	0.203	1.38	-0.11	-0.51	2015	2016	2017	1.074
Q8	X2B	606.5M	37.1M	251.6M	0.40	-1.03	400M	500M	825M	1.652
Q9	T2C	2016.7	0.22	1.47	-0.14	-1.02	2016	2017	2018	1.458
Q10	p2	74.35%	2.19%	14.86%	-0.21	-0.85	60%	80%	90%	1.219
Q11	Sv	3.228B	0.228B	1.545B	1.48	1.22	2B	2.50B	3.5B	3.868
Q12	T3A	2017.2	0.22	1.51	-0.03	-1.33	2016	2017	2018.3	1.818
Q13	T3B	2017.5	0.206	1.39	0.00	-0.63	2017	2017	2019	1.080
Q14	X3A	1.110B	0.085B	0.573B	0.13	-1.00	0.6B	1.0B	1.6B	0.778
Q15	X3B	3.413B	0.017B	1.132B	0.07	-1.27	2.5B	3.0B	4.125B	1.473
Q16	X3C	491.3M	31.98M	216.7M	0.40	-0.06	300M	400M	600M	0.544
Q17	T3D	2018.7	0.235	1.59	0.25	-0.58	2018	2018	2020	1.015
Q18	p3	77.83%	1.81%	12.28%	-0.39	0.14	70%	80%	90%	1.504
Q19	X	14.643B	0.639B	4.332B	0.73	-0.71	10.9B	12.4B	18.34B	2.360
Q20	Sbest	5.804B	0.321B	2.177B	-0.02	-0.30	4.75B	6B	8B	0.650
Q21	Sworst	2.783B	0.234B	1.590B	0.82	-0.34	2B	2B	4B	2.245
Q22	Lifespan	18.09Y	0.73Y	4.93Y	0.56	0.06	14Y	20Y	20Y	1.890
Q23	Op Cost	1.288B	0.077B	0.527B	0.45	-0.02	1.00B	1.25B	1.5B	0.984

Note. B represents $billions, M represents $millions and Y represents years.

Table 5

Descriptive Statistics for European Wafer Foundries

Q#	Abbrev	Mean	Std. Error	Std. Dev	Skew	Kurtosis	1stQ	Median	3rdQ	AD
Q1	Capacity	40,217	1.990	13.497	0.28	-1.16	30,000	35,000	55,000	1.714
Q2	T1A	2015.0	0.227	1.54	0.42	-0.12	2014	2015	2016	1.116
Q3	X1B	4.655B	0.406B	2.750B	0.62	-0.52	2B	4.5B	6B	1.115
Q4	T2A	2015.5	0.201	1.36	0.39	-0.09	2014	2015	2016	1.218
Q5	X1A	4.326B	0.435B	2.952B	0.74	-0.58	2B	3B	6.25B	1.757
Q6	X2A	264.1M	17.7M	120.0M	0.60	-0.73	150M	250M	350M	1.401
Q7	T2B	2015.7	0.189	1.28	0.45	-0.73	2015	2015.5	2016.3	1.713
Q8	X2B	626.1M	36.4M	247.1M	0.15	-1.08	400M	600M	800M	1.067
Q9	T2C	2017.0	0.2121	1.44	0.38	-0.61	2016	2017	2018	1.209
Q10	p2	73.91%	2.57%	17.45%	-0.14	-0.89	60%	70%	90%	0.949
Q11	Sv	3.152B	0.194B	1.316B	1.32	1.33	2B	2.75B	4B	2.828
Q12	T3A	2017.2	0.289	1.96	0.39	-0.69	2016	2017	2019	1.229
Q13	T3B	2016.8	0.285	1.93	0.65	-0.01	2015	2016	2018	1.476
Q14	X3A	1.195B	0.061B	0.412B	0.11	0.42	1B	1.2B	1.4B	0.602
Q15	X3B	3.032B	0.014B	1.008B	0.13	-0.72	2.0B	3.0B	3. 63B	0.834
Q16	X3C	454.5M	30.40M	206.2M	0.63	-0.62	300M	400M	600M	1.444
Q17	T3D	2019.0	0.238	1.61	-0.06	-0.66	2018	2019	2020	0.919
Q18	p3	76.74%	1.97%	13.34%	-0.36	0.35	70%	80%	90%	1.290
Q19	X	13.208B	0.578B	3.918B	0.73	0.18	10.9B	12.4B	16.1B	0.967
Q20	Sbest	4.935B	0.364B	2.471B	0.57	-0.32	3B	4B	7B	0.977
Q21	Sworst	2.261B	0.242B	1.639B	1.49	1.72	1B	2B	3B	3.732
Q22	Lifespan	16.87Y	0.77Y	5.23Y	0.17	-0.88	12Y	18Y	20Y	1.273
Q23	Op Cost	1.261B	0.076B	0.516B	0.32	-0.63	0.75B	1.25B	1.5B	1.347

Note. B represents €billions, M represents €millions and Y represents years.

Figure 9 presents the descriptive statistics for question Q12 data. The designator T_{3A} represents the EUV lithography availability for production fabs in America. The statistics obtained for Q12 were unique for two reasons. First, skew measured -0.025; therefore, this near-zero skew exemplified a symmetric distribution about the year 2017. Second, Q12 had the lowest measure for kurtosis of -1.335. This kurtosis illustrated a platykurtic distribution, in other words, a flat distribution. In summary, this is an important question because the results were applied to solve research question RQ4 and the results have great implications for the semiconductor industry.

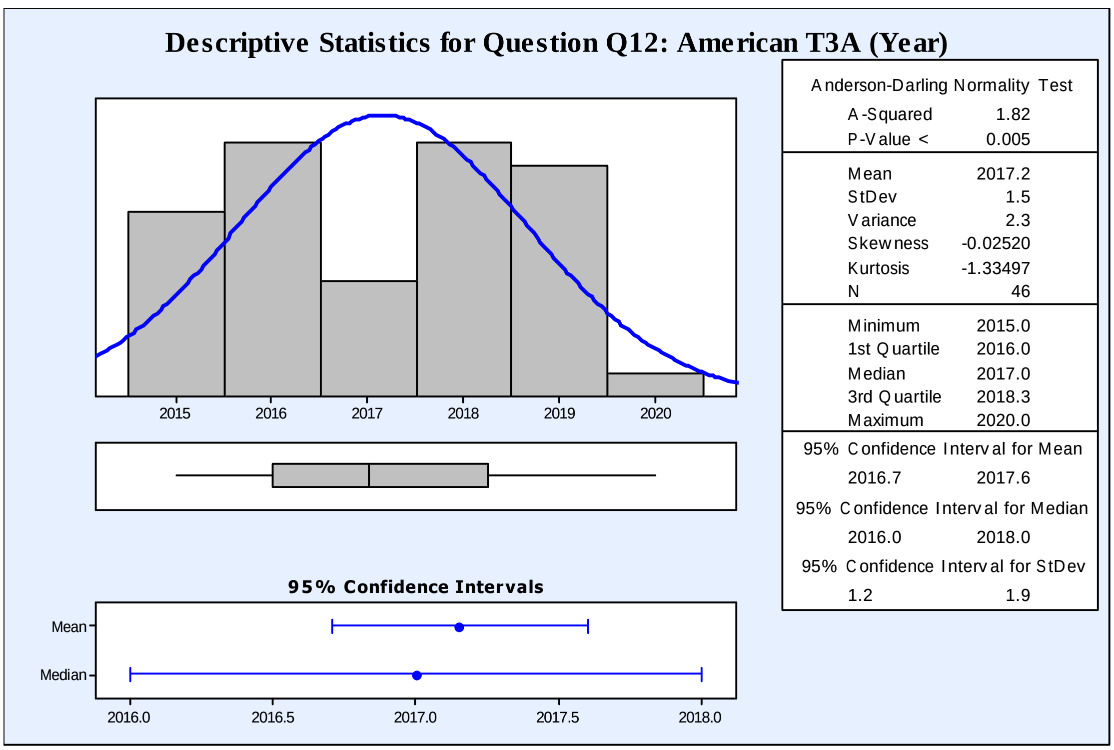

Figure 9. Descriptive statistics for Q12, production EUV for American fabs.

Figure 10 summarizes the descriptive statistics for question Q21 as presented in Tables 4 and 5. The abbreviation *Sworst* represents the worst-case future annual revenue for an average 450mm wafer foundry. These data were unique for two reasons. First, after a comparison of all the data collected in this study, the plot below illustrates the highest skew at 1.49; this was an indication of a right-skewed distribution with a mean of €2.261 billion. Within the box plot, the asterisk represents an outlier. Second, Q21 had the highest measure of kurtosis at 1.71. The kurtosis presented here exemplifies a leptokurtic distribution; in other words, a peaked distribution.

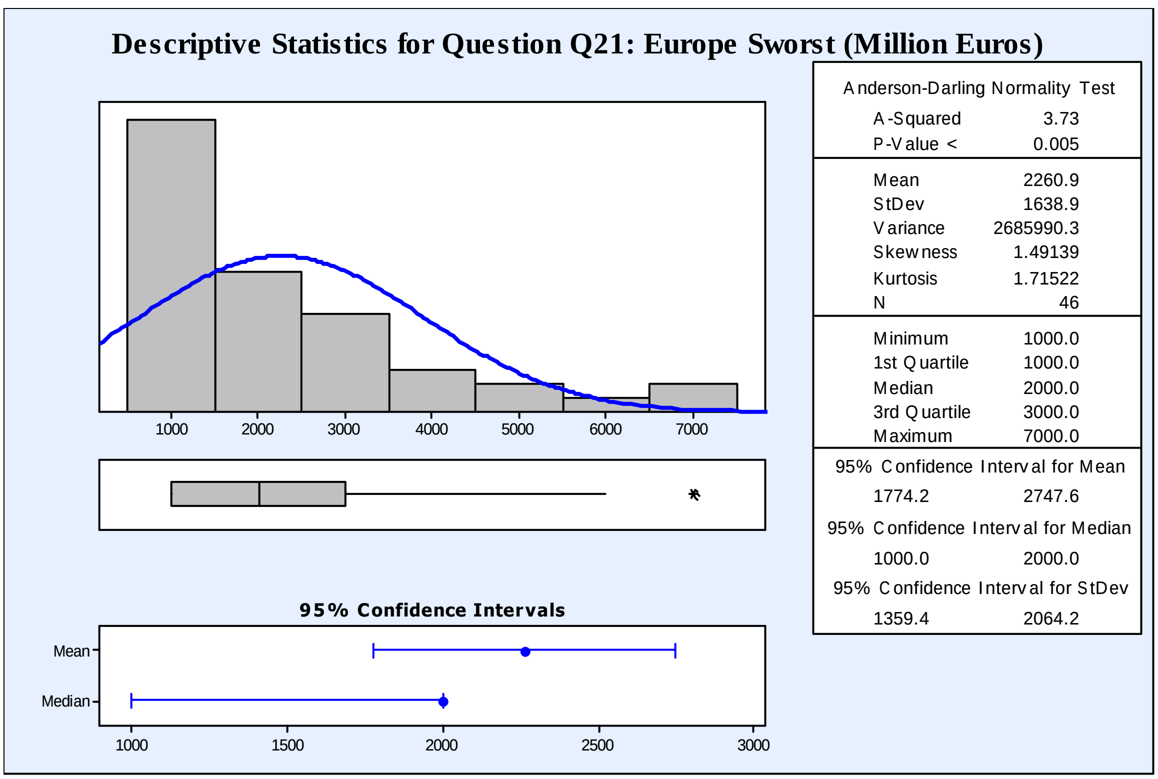

Figure 10. Descriptive statistics for Q21, Sworst for European fabs.

A key assumption made in this study was that each of the 46 sample data sets would represent a Gaussian distribution. A normal distribution is preferred because it ensures valid inferences can be made. Figure 11 illustrates the best-case normality obtained from American and European participants who had answered question Q14. From a subjective point of view, normality was approximated by data points that form a straight line. From a quantitative point of view, the two data sets were compared with the Anderson-Darling (AD) test, a test that utilizes the empirical cumulative distribution function. The AD test results for the American and European data corresponded to 0.778 and 0.602; both test results suggested a normal distribution.

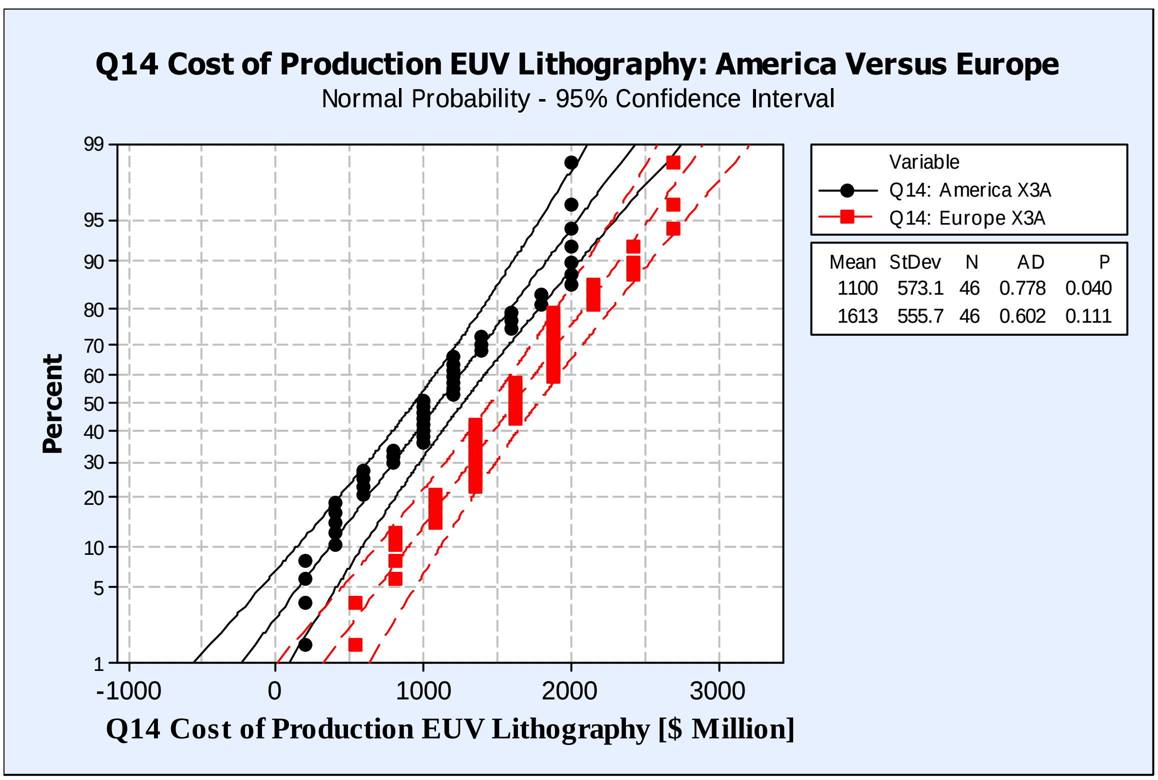

Figure 11. Comparative probability plot exemplifies the best-case normality.

Figure 12 illustrates the worst-case normality for this study. This slightly abnormal distribution most likely occurred when participants misunderstood question Q11. The skew to the left represents a $2 billion salvage value for an unsuccessful 450mm pilot wafer fab. The skew to the right at the other extreme is unlikely since participants may have misinterpreted question Q11 as asking for a total value instead of salvage value. This right skew is unlikely because buyers would not buy an expensive investment project that failed. The Anderson-Darling (AD) values of 3.868 and 2.828 suggested less than an ideal normality. Overall, the salvage value for the American fab is $3.228 billion and $4.251 billion for the European fab.

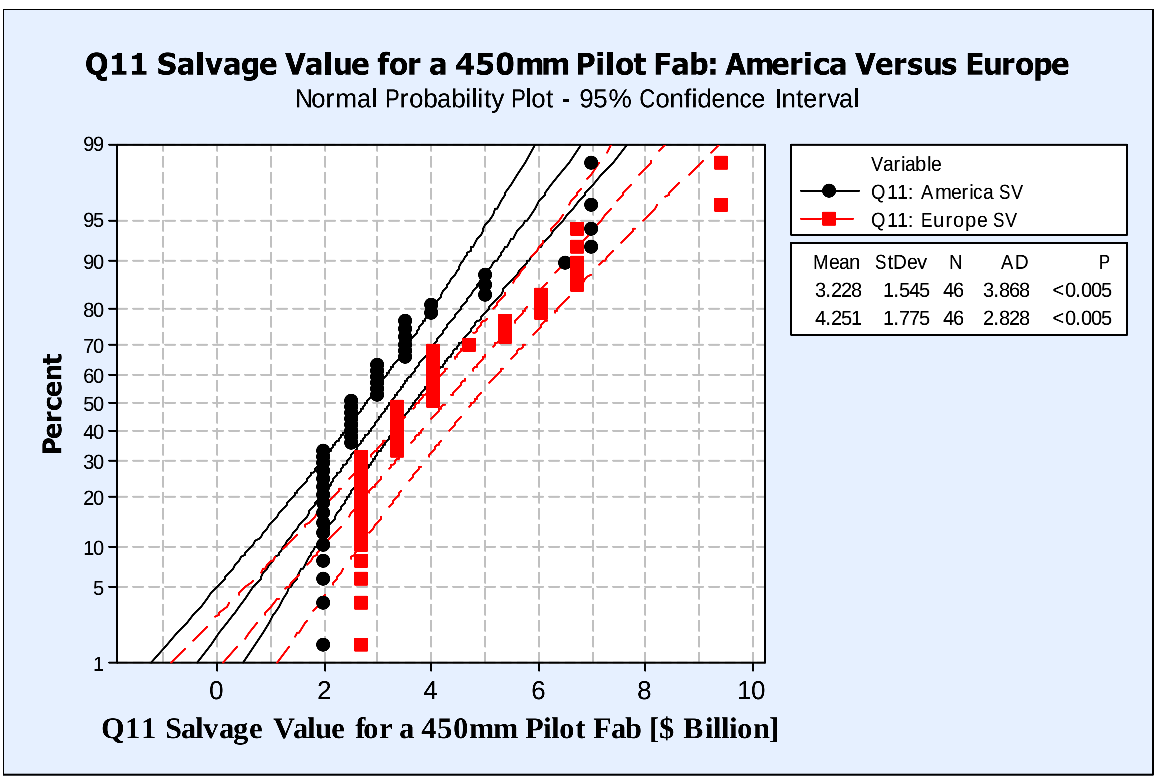

Figure 12. Comparative probability plot exemplifies the worst-case normality.

Three milestones are illustrated in Figure 13. The first milestone, T_{1A}, represents ground breaking to start construction of a 450mm wafer fab complex. The second milestone, T_{2C}, represents the completion of the process recipe. The third milestone, T_{3D}, represents achieving commercialization. For the first milestone, the American responses to question Q2 indicated the third quarter of 2014 was best, while the Europeans indicated the first quarter of 2015 to begin construction. For the second milestone, the American responses to question Q9 forecasted the third quarter of 2016, while Europeans predicted the start of 2017. For the third milestone to achieve commercialization, the Americans forecasted the third quarter of 2018, while the Europeans predicted the start of 2019.

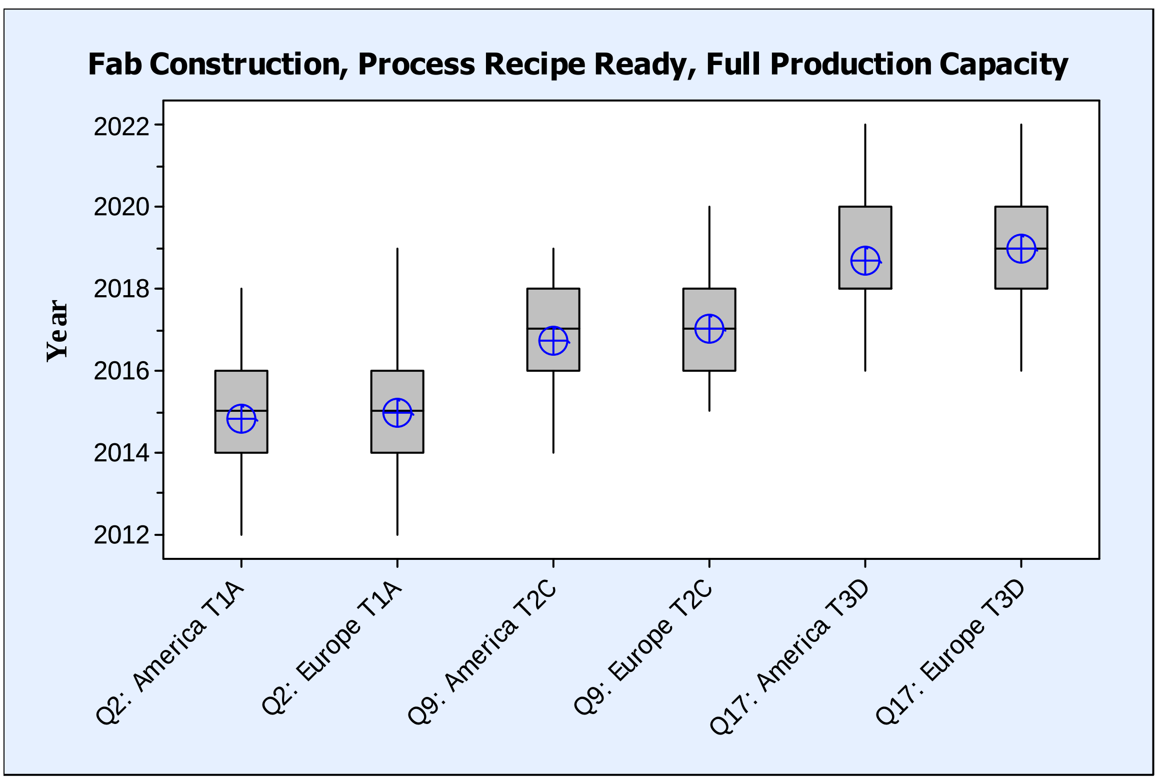

Figure 13. Milestones are fab construction, process recipe, and commercialization.

Figure 14 compares the average construction cost for American and European 450mm wafer fabs. The complex consists of clean-room ballrooms, the facility-utility yards, and offices. For question Q5, the American participants predicted a construction cost of $5.304 billion, while the Europeans forecasted €4.326 billion. Based on an exchange rate of $1.3487 per euro, the average European construction cost translates to $5.835 billion. If development of a process recipe in the 450mm wafer fab is unsuccessful, then the Q11 salvage value for the fab complex, EUV lithography, and pilot tools for an American fab was expected to be $3.228 billion. In Europe, the salvage value for 450mm wafer fabs was estimated to be €3.152 billion, or $4.251 billion.

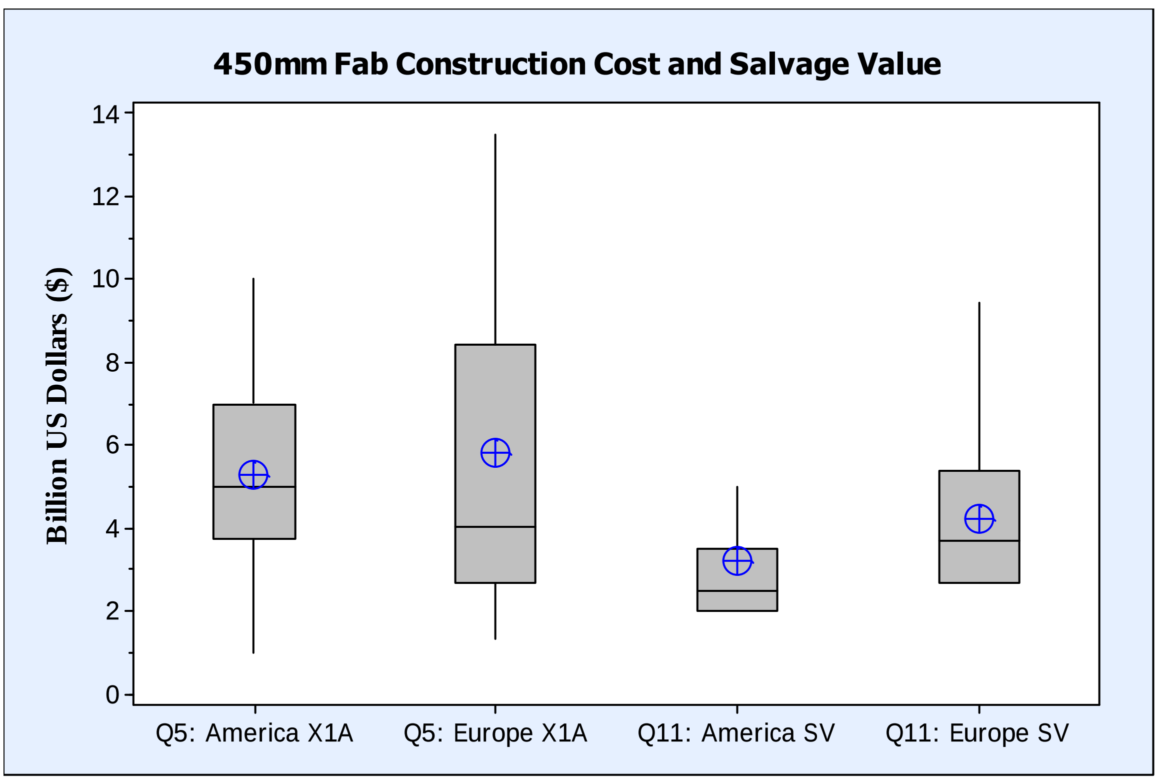

Figure 14. 450mm wafer fab construction cost and salvage value.

Figure 15 illustrates the average availability for EUV lithography scanner tools, photoresist chemistry, and reticles for pilot and production 450mm wafer fabs in America and Europe. The blue fiducial marks represent the mean values. For question Q4, the Americans expected pilot EUV lithography tools and process availability T_{2A} will occur by the third quarter of 2015, while the Europeans anticipated the second quarter of 2015. Both the American and European respondents to Q12 predicted the availability for production EUV lithography tools will be 2017. The wider box plot represents greater variability and less certainty among Europeans in comparison to the Americans.

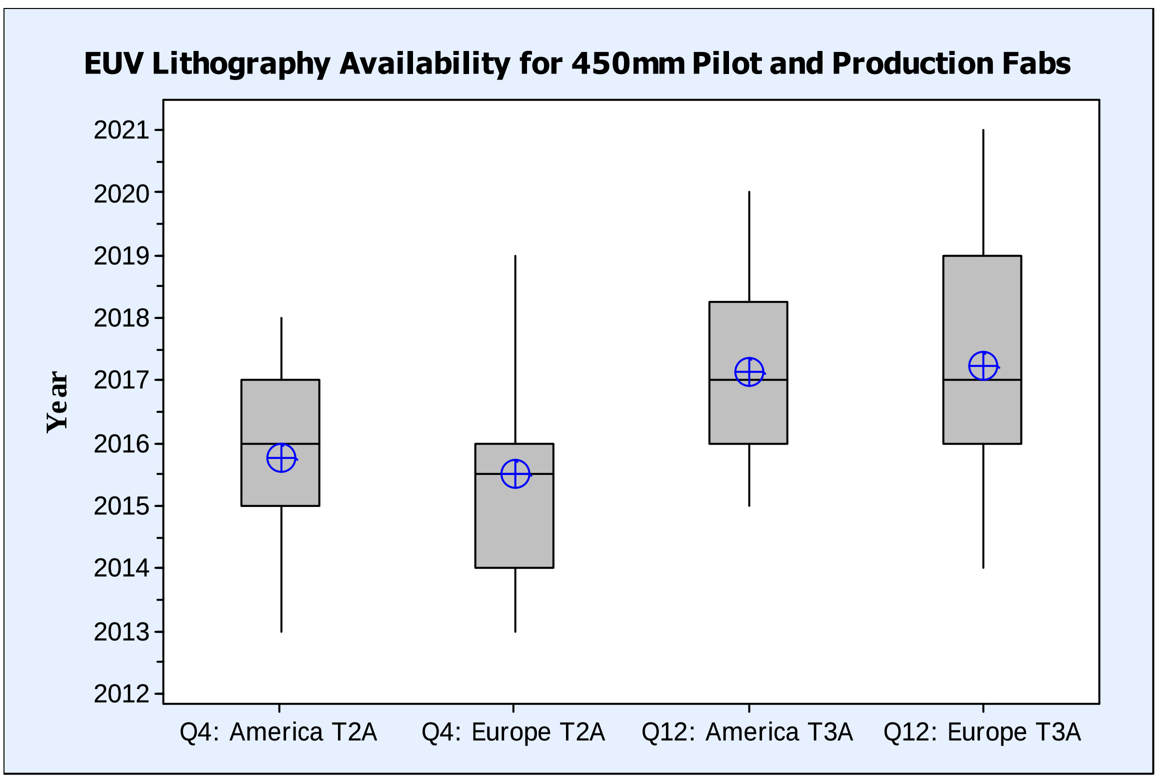

Figure 15. EUV lithography availability for 450mm pilot and production fabs.

Figure 16 illustrates the availability of wafer-processing tools for pilot and production 450mm wafer fabs in America and Europe. The blue fiducial marks represent the mean values. According to the responses to question Q7, Americans and Europeans expected the availability T_{2B} for 450mm wafer-processing toolset will be the third quarter of 2015. American participants responding to question Q13 anticipated production wafer-processing tools at T_{3B} will be available by the second quarter of 2017. The Europeans expected the production toolset will be available by the third quarter of 2016. Moreover, the wider box plot represents greater uncertainty.

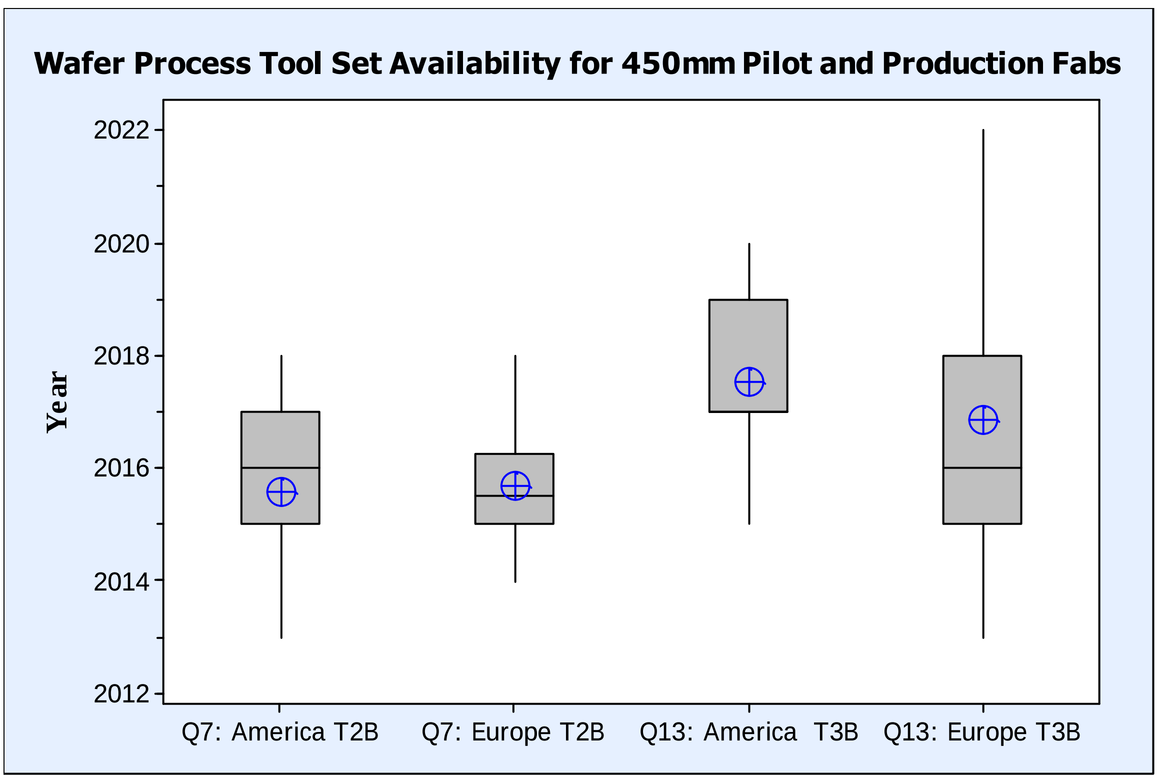

Figure 16. Wafer process tools availability for 450mm pilot and production fabs.

Figure 17 compares the cost of ownership for EUV lithography scanner tools, photoresist chemistry, and reticles for pilot and production 450mm wafer foundries in America and Europe. The American respondents to question Q6 expected the cost of ownership for pilot EUV tools and processes will be $275 million. On the other hand, the Europeans expected the EUV cost of ownership to be €264 million, or $356 million. For question Q14, American respondents expected the cost of ownership for full production EUV lithography tools will be $1.1 billion while the Europeans estimated €1.2 billion, or $1.6 billion. For the Q14 box plot, the wider spread suggested greater uncertainty.

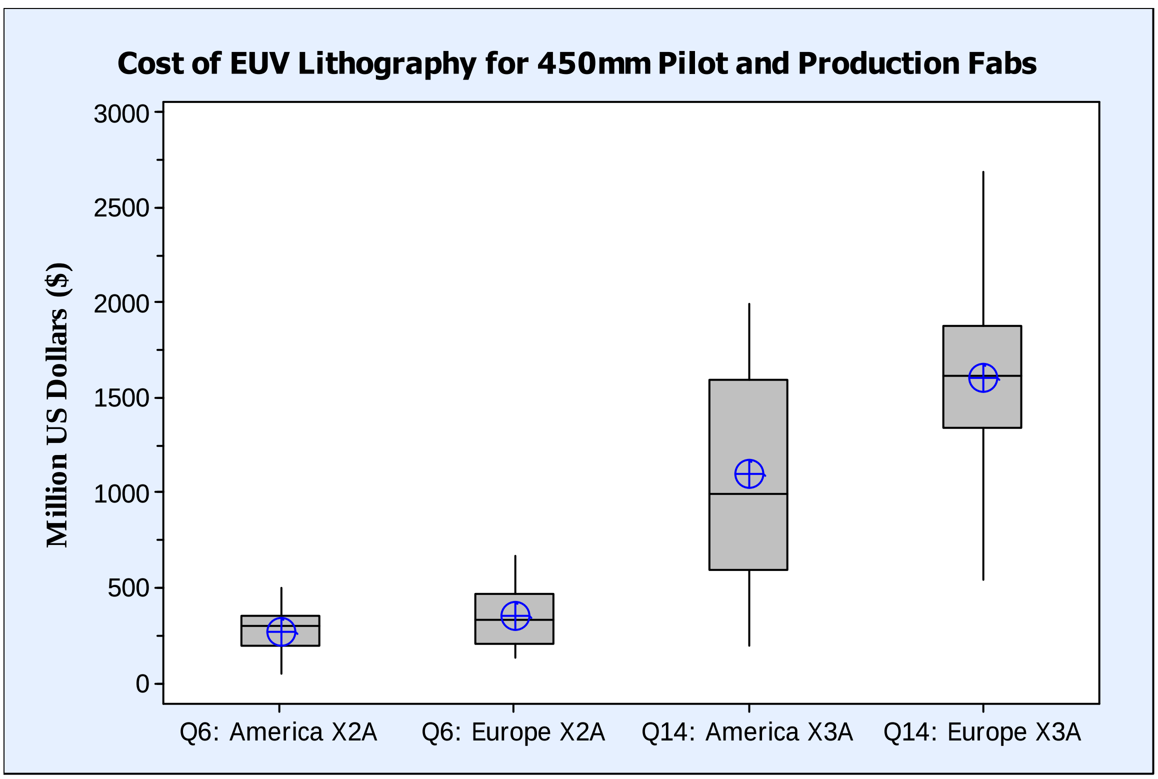

Figure 17. Cost of EUV lithography for 450mm pilot and production fabs.

Figure 18 compares the cost of ownership for pilot and production 450mm wafer foundries in America and Europe. The blue fiducial marks represent the mean values. According to the answers to question Q8, the Americans expected that the cost of ownership for pilot fab tools will be $607 million, while the Europeans estimated €626 million, or $844 million. Based on responses to question Q15, the Americans expected a wafer-processing toolset for a full-production fab will cost $3.4 billion. For the same question, the Europeans estimated the investment cost will be €3.0 billion, or $4.1 billion.

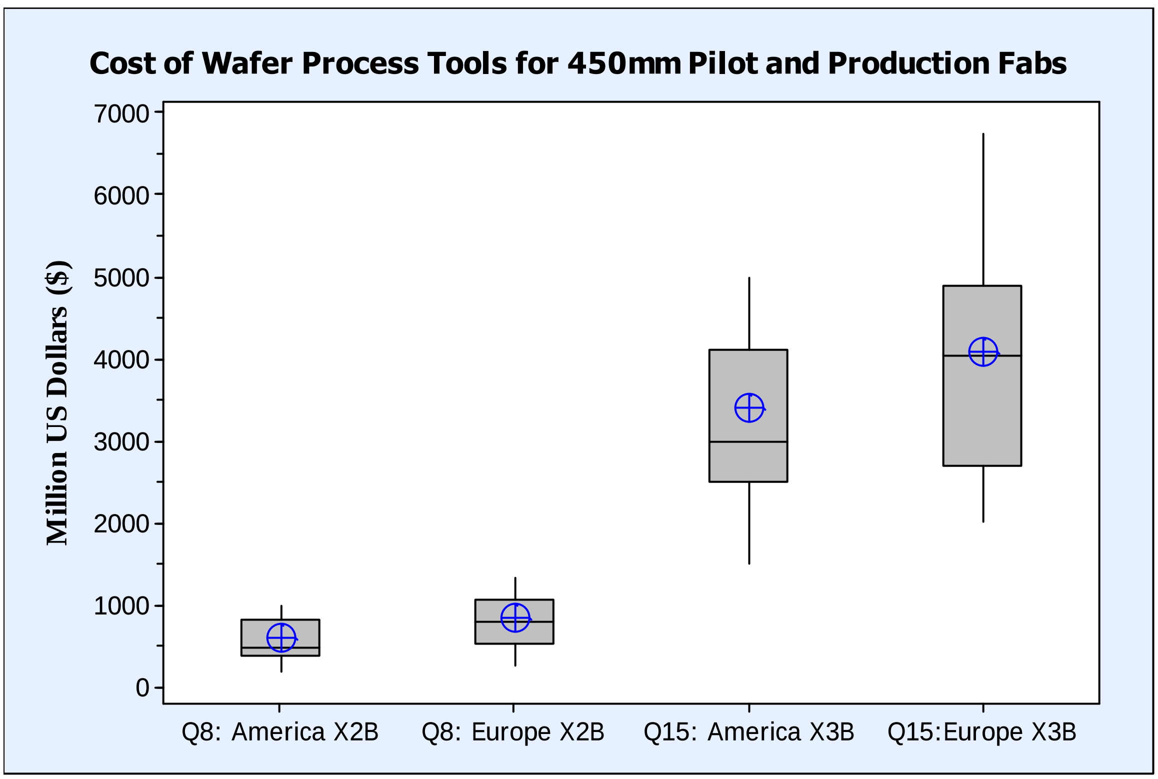

Figure 18. Cost of wafer process tools for 450mm pilot and production fabs.

Figure 19 compares the production ramp-up cost for EHS facilities and the annual cost of operations for full-production 450mm wafer foundries in America and Europe. For question Q16, the Americans estimated the production ramp-up cost would be $491 million, while Europeans estimated the cost to be €455 million, or $613 million. Based on the American responses to question Q23, the annual cost of operations to run at full-production capacity of 37,717 wafer starts per month is expected to be $1.29 billion. In contrast, the annual running cost for a European fab is expected to be €1.26 billion, or $1.70 billion for a 450mm fab with 40,217 wafer starts per month.

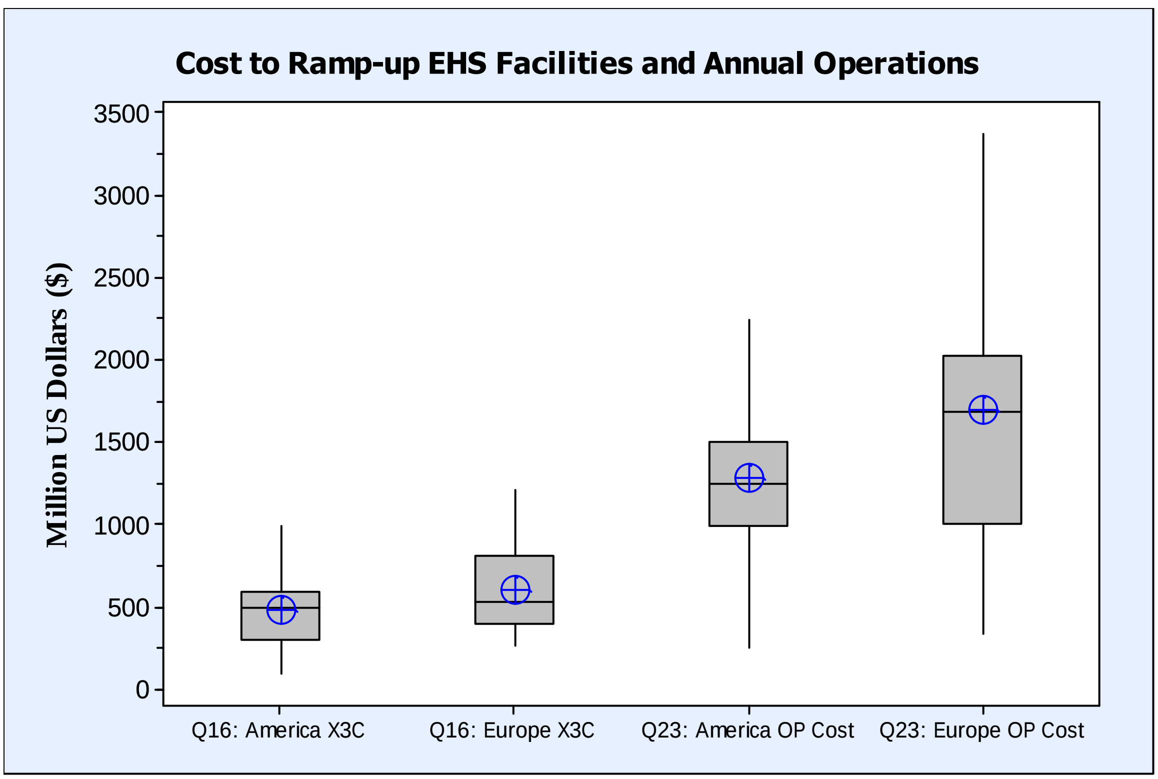

Figure 19. Cost to ramp up EHS facilities and annual operations cost.

Figure 20 compares the probability of success for 450mm pilot and production wafer fabs in America and Europe. For the responses to question Q10, the Americans estimated the probability of success for 450mm pilot foundries will be 74.35%, while the Europeans estimated 73.91%. For the responses to question Q18, the Americans estimated the probability of success for production 450mm wafer foundries operating at full capacity will be 77.83%, while the Europeans expect 76.74%. Overall, the wider box plot illustrates greater uncertainty for pilot wafer fabs in comparison to production fabs.

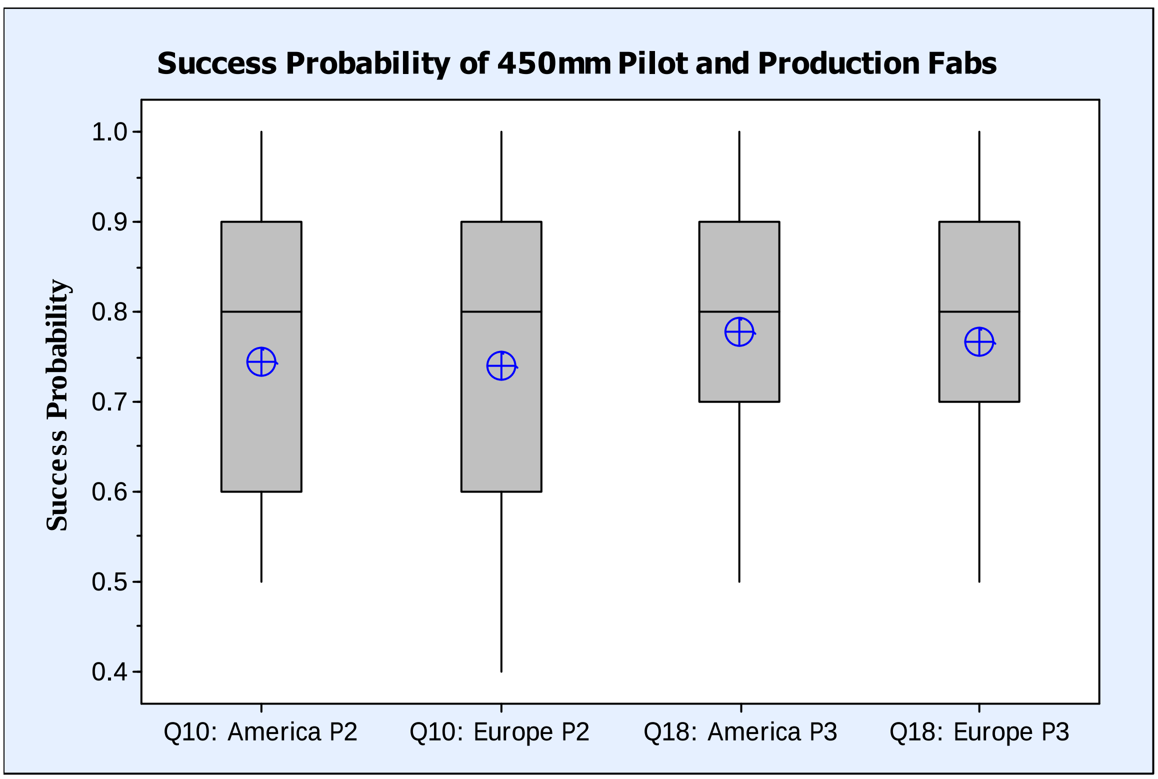

Figure 20. Probability of success for 450mm pilot and production fabs.

Figure 21 compares the best-case and worst-case future annual revenues generated from American and European production foundries operating at full capacity. The response to question Q20 revealed the best-case annual revenue for an American fab is \$5.8 billion and €4.9 billion, or \$6.7 billion for a European fab. For Q21, the worst-case annual revenue for an American fab is \$2.8 billion and €2.8 billion, or \$3 billion for a European fab. From these best-case and worst-case annual revenues, cash flow uncertainty or volatility can be measured. This volatility is represented by sigma and can be calculated by using Equation 5. For an American 450mm fab, the mean sigma value was calculated to be 52% and 43.33% for a European 450mm wafer fab.

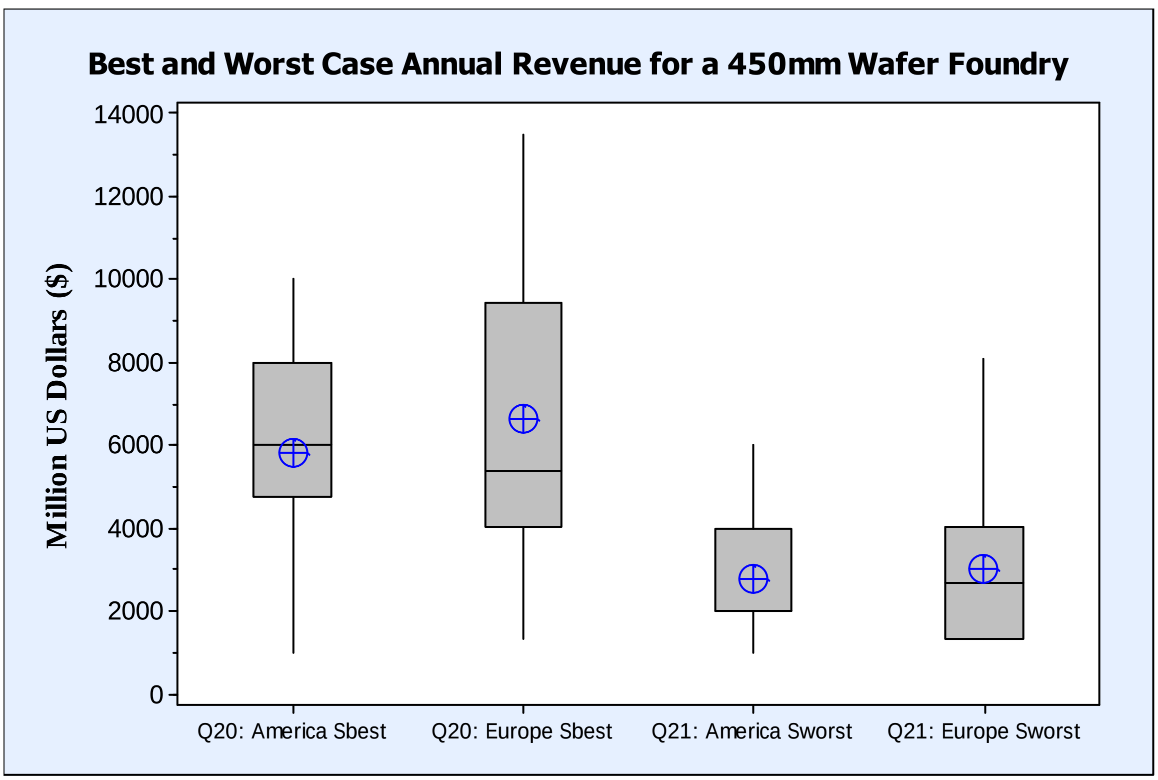

Figure 21. Best- and worst-case annual revenue for a 450mm wafer foundry.

Figure 22 illustrates the R&D funding investment with respect to the total investment for future 450mm wafer foundries. American participants answering question Q3 expected the R&D funding investment X_{1B} to be \$5.2 billion. R&D investment made by 450mm wafer fab companies will likely encourage suppliers to quicken development and delivery of EUV lithography and wafer-processing tools. The Europeans anticipated 450mm fabs companies will need to provide €4.7 billion in R&D funding, or \$6.3 billion. For question Q19, the Americans estimated the total turn-key investment represented by the strike price X for 450mm wafer foundries will likely be \$14.64 billion while the Europeans estimated €13.21 billion, or \$17.81 billion.

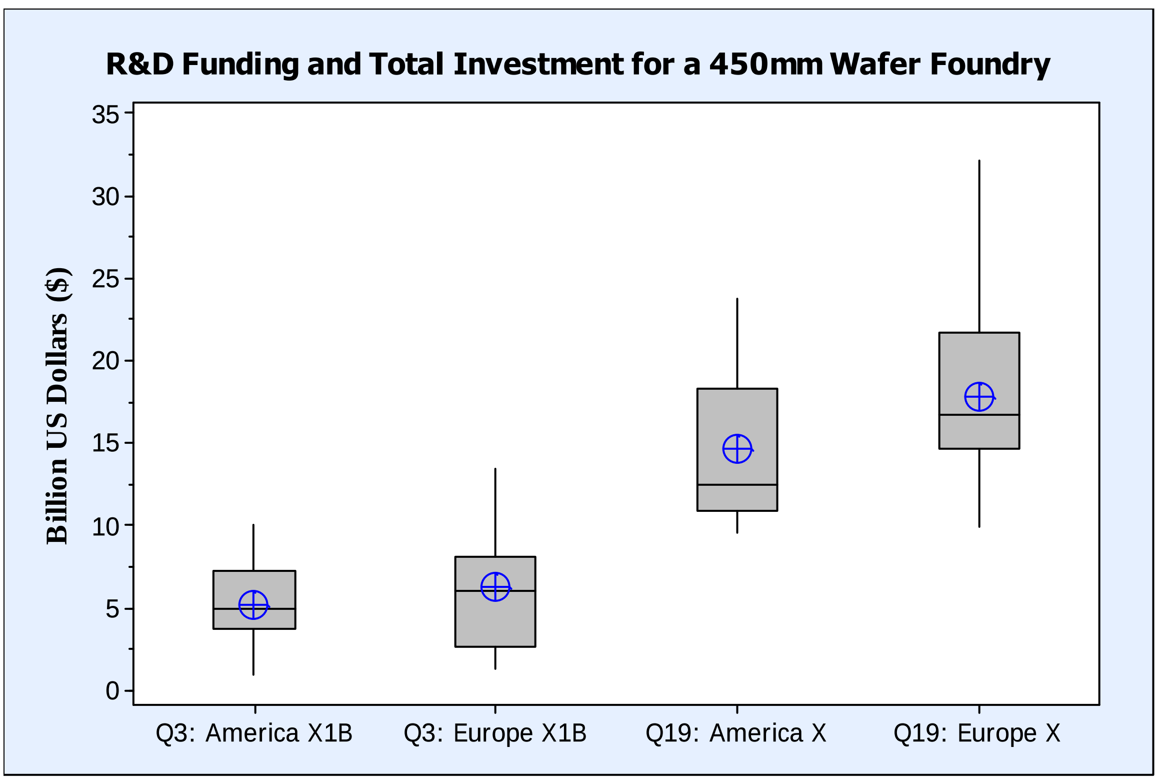

Figure 22. Initial R&D funding and total investment for a 450mm wafer foundry.

A conservative perpetuity without growth was modeled for both foundry projects to determine the underlying asset value (*S*) using an Excel financial spreadsheet prior to solving the seven research questions. This underlying asset value is the present value of the expected cash flows during the entire project lifetime (*T*). The data needed to forecast future cash flows was obtained from questions Q20, the best-case annual revenue (*Sbest*); Q21, the worst-case annual revenue (*Sworst*); Q22, the number of cash flow years (*Lifespan*); and Q23, the cost of operations (*Op Cost*). Based on the three levels obtained from the box plots and three discount factors of 10%, 20%, 30%, the pessimistic, moderate, and optimistic underlying asset values were calculated as presented in Figure 23, for the American 450mm wafer fab project. The average *S* value of $13.391 billion for American 450mm wafer fabs was assumed to be the mean value. Similarly, Figure 24 shows three levels of the underlying asset value for a European 450mm wafer foundry project and the mean was calculated to be €8.4213 billion. This conservative perpetuity was justified in order to prevent inflating the NPV values.

America: Low Level S Calculations [Billion $]																
Year: (Q22L)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Total
Annual Revenue: (Q21L)		2	2	2	2	2	2	2	2	2	2	2	2	2	2	
Annual Op Cost : (Q23H)		1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	
Annual Net Cash Flow : (Q21 - Q23)		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	
Discount Rate	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	
Discount Factor	1	0.7692	0.5917	0.4552	0.3501	0.2693	0.2072	0.1594	0.1226	0.0943	0.0725	0.0558	0.0429	0.033	0.0254	
PV of Annual Cash Flow		0.3846	0.2959	0.2276	0.1751	0.1347	0.1036	0.0797	0.0613	0.0471	0.0363	0.0279	0.0215	0.0165	0.0127	1.6243
S = PV of Expected Future Cash Flows	$1.624															

America: Median S Calculations [Billion $]																					
Year: (Q22M)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Annual Revenue : (Ave Q20 & Q21)		4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Annual Op Cost :(Q23M)		1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
Annual Net Cash Flow : (AveQ20-Q21)-Q23		2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75
Discount Rate	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%
Discount Factor	1	0.8333	0.6944	0.5787	0.4823	0.4019	0.3349	0.2791	0.2326	0.1938	0.1615	0.1346	0.1122	0.0935	0.0779	0.0649	0.0541	0.0451	0.0376	0.0313	0.0261
PV of Annual Cash Flow		2.2917	1.9097	1.5914	1.3262	1.1052	0.921	0.7675	0.6396	0.533	0.4441	0.3701	0.3084	0.257	0.2142	0.1785	0.1487	0.124	0.1033	0.0861	0.0717
S = PV of Expected Future Cash Flows	$13.391																				

America High Level S Calculations [Billion $]																					
Year: (Q22H)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Annual Revenue: (Q20H)		8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Annual Op Cost : (Q23L)		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Annual Net Cash Flow: (Q20 - Q23)		7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Discount Factor	1	0.9091	0.8264	0.7513	0.683	0.6209	0.5645	0.5132	0.4665	0.4241	0.3855	0.3505	0.3186	0.2897	0.2633	0.2394	0.2176	0.1978	0.1799	0.1635	0.1486
PV of Annual Cash Flow		6.3636	5.7851	5.2592	4.7811	4.3464	3.9513	3.5921	3.2656	2.9687	2.6988	2.4535	2.2304	2.0277	1.8433	1.6757	1.5234	1.3849	1.259	1.1446	1.0405
S = PV of Expected Future Cash Flows	$59.595																				

Figure 23 : Underlying Asset (S) Calculation for an American 450mm Wafer Fab Project

Europe Low Calculations [Billion €]														
Year: (Q22L)	0	1	2	3	4	5	6	7	8	9	10	11	12	Total
Annual Revenue: (Q21L)		2	2	2	2	2	2	2	2	2	2	2	2	
Annual Op Cost : (Q23H)		1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	
Annual Net Cash Flow : (Q21 - Q23)		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	
Discount Rate	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	
Discount Factor	1	0.7692	0.5917	0.4552	0.3501	0.2693	0.2072	0.1594	0.1226	0.0943	0.0725	0.0558	0.0429	
PV of Annual Cash Flow		0.3846	0.2959	0.2276	0.1751	0.1347	0.1036	0.0797	0.0613	0.0471	0.0363	0.0279	0.0215	1.5951
S = PV of Expected Future Cash Flows	€ 1.5951													

1

Europe Median Calculations [Billion €]																				
Year: (Q22M)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
Annual Revenue : (Ave Q20 & Q21)		3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	
Annual Op Cost :(Q23M)		1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	
Annual Net Cash Flow : (AveQ20-Q21)-Q23		1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	
Discount Rate	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	
Discount Factor	1	0.8333	0.6944	0.5787	0.4823	0.4019	0.3349	0.2791	0.2326	0.1938	0.1615	0.1346	0.1122	0.0935	0.0779	0.0649	0.0541	0.0451	0.0376	
PV of Annual Cash Flow		1.4583	1.2153	1.0127	0.8439	0.7033	0.5861	0.4884	0.407	0.3392	0.2826	0.2355	0.1963	0.1636	0.1363	0.1136	0.0947	0.0789	0.0657	8.4213
S = PV of Expected Future Cash Flows	€ 8.4213																			

Europe High Calculations [Billion €]																					
Year: (Q22H)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Annual Revenue: (Q20H)		7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
Annual Op Cost : (Q23L)		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Annual Net Cash Flow: (Q20 - Q23)		6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Discount Factor	1	0.9091	0.8264	0.7513	0.683	0.6209	0.5645	0.5132	0.4665	0.4241	0.3855	0.3505	0.3186	0.2897	0.2633	0.2394	0.2176	0.1978	0.1799	0.1635	0.1486
PV of Annual Cash Flow		5.4545	4.9587	4.5079	4.0981	3.7255	3.3868	3.0789	2.799	2.5446	2.3133	2.103	1.9118	1.738	1.58	1.4364	1.3058	1.1871	1.0792	0.981	0.8919
S = PV of Expected Future Cash Flows	€ 51.0814																				

Figure 24 : Underlying Asset (S) Calculation for a European 450mm Wafer Fab Project

The option lifetime (T) was the second Black-Scholes parameter calculated. This project lifetime was described previously in Chapter 2 with the equation $T = T_{3D} - T_{1A}$. This time frame is the difference between the start of commercialization T_{3D} (Q17) minus the date fab construction T_{1A} (Q2) begins. For American wafer fabs, the T_{3D} (Q17) mean was 2018.7, while the T_{1A} (Q2) mean was 2014.8; this yielded a 4-year option lifetime (T). For the European wafer fabs, the T_{3D} (Q17) mean was 2019 and the T_{1A} (Q2) mean was 2015; this yielded approximately the same 4-year option lifetime.

Volatility (σ) was the third Black-Scholes parameter calculated for the American and European wafer fabs. Equation 5 in Chapter 2 was utilized along with the data obtained from questions Q20, the best-case annual revenue, Q21, the worst-case annual revenue, and Q17, along with the option lifetime to calculate volatility. For the American wafer fab, the mean volatility was calculated to be 52%. Excel's goal seek function was applied to find the upper-level volatility of 60.9% and a lower-level volatility of 43.1%. For the European wafer fab, the mean volatility was calculated to be 43.33%, and the upper and lower volatility levels were found to be 47.2% and 39.5%.

Strike price (X) was the fourth Black-Scholes parameter investigated. The strike price was obtained from question Q19, which provided the total investment for an average 450mm fab project. For the American fab, the strike price was $14.643 billion for the American fab and €13.208 billion, or $17.8136 for the European fab.

The last Black-Scholes parameter was the risk free interest rate (r). The 10 year historical treasury risk free interest rates were obtained from the United States Department of the Treasury. From 2003 to 2014, the rates ranged from 1.5% to 5.3%.

Prior to solving each research question, the traditional static NPV for the American and European 450mm wafer fab project were calculated. The static NPV was determined by subtracting the total investments (*I*) from the total gross project value (*V*); in other words, NPV = $V - I$. An average 20% discount rate yielded a total project value of $13.391 billion, as indicated by Figure 23. Table 6 shows the forecasted investments for American 450mm wafer fabs discounted at 20% will be $10.2193 billion. As a result, the static NPV was calculated to be $13.391 billion – $10.2193 billion = $3.1717 billion. Based on a positive NPV, this project would have been accepted.

Table 6

Present Value of Investments for an American 450mm Wafer Fab

	Y0 = 2013	Y1 = 2014	Y2 = 2015	Y3 = 2016	Y4 = 2017
Investment 1	0.0000	0.0000	5.1950	0.2750	1.1100
Investment 2	0.0000	0.0000	5.3040	0.6065	3.4130
Investment 3	0.0000	0.0000	0.0000	0.0000	0.4913
Total	0.0000	0.0000	10.499	0.8815	5.0143
Present Value	0.0000	0.0000	7.2910	0.5101	2.4182
Total PV	10.2193				

Note. Mean investments [$ Billions] and years from the American survey instrument
Estimated risk-adjusted discount rate of 20%

The static NPV value for the European 450mm wafer fab was found. All expected investments for the European fab listed in Table 5 were placed into Table 7 to find the present value of €9.0096 billion at a 20% discount rate. In addition, the underlying asset value (*S*) of €8.4213 billion was previously determined as the present value of all future cash flows discounted at 20% rate, as indicated by Figure 24. The static NPV = $V - I$ was calculated to be €8.4213 billion minus €9.0096 billion to become negative €0.5883 billion. Based on a traditional NPV analysis, this project would not have been accepted.

Table 7

Present Value of Investments for a European 450mm Wafer Fab

	Y0 = 2013	Y1 = 2014	Y2 = 2015	Y3 = 2016	Y4 = 2017
Investment 1	0.0000	0.0000	4.6550	0.2641	1.1950
Investment 2	0.0000	0.0000	4.3260	0.6261	3.0320
Investment 3	0.0000	0.0000	0.0000	0.0000	0.4545
Total	0.0000	0.0000	8.9810	0.8902	4.6815
Present Value	0.0000	0.0000	6.2368	0.5152	2.2577
Total PV	9.0096				

Note. Mean investments [€ Billions] and years from the European survey instrument
Estimated risk-adjusted discount rate of 20%

Research Question 1

Research question 1 RQ1 investigated the option to expand production capacity in case the outlook of the 450mm wafer foundry project will likely be more profitable than previously expected. Production capacity beyond the anticipated 100% reflects expansion from 110% to 150% and is accomplished with more capital investments.

With a goal of improving construct validity, the first four research questions, RQ1 through RQ4, were solved with two construct types. For RQ1, the first construct consisted of closed-form solutions that originated from the Black-Scholes Equations 1 through 5, as presented in Chapter 2. This closed-form construct was developed with an American call option and solutions were calculated using Wolfram's Mathematica 8 software. The second construct was developed from a binomial lattice built using Microsoft Excel compound IF statements and several MAX functions.

Table 8 shows the closed-form solutions for American and European 450mm wafer foundries. This construct was created using an American call option. The left-hand column shows the option value to produce additional production capacity from 110% to 150% of the original planned capacity. The values to the right are the Greek sensitivity parameters. According to the responses to question Q1, American wafer fabs will likely be designed with a capacity of 37,717 WSPM, while European fabs will likely be designed for a capacity of 40,217 WSPM. In summary, Mun (2006) stated the expand option values obtained from the binomial lattice are more accurate in comparison to the option values obtained from the closed-form American call option (p. 167).

Table 8 shows the closed-form option value solutions for capacity expansion in 10% increments for the American and European wafer foundries. The underlying asset value, *S* was calculated from answers to questions Q20, Q21, and Q23 as presented by Figures 23 and 24. The 4-year time frame T_3 represents the option lifetime to expand capacity. The incremental expansion costs were obtained from the responses to questions Q14, Q15, and Q16. The sum of these investments equates to 100% production capacity, specifically \$5.014 billion for the American fab and €4.6816 billion for the European fab.

Table 8

Option to Expand Capacity: Closed-Form American Call Option

	Capacity	Option Value	Call Value	Delta	Gamma	Rho	Theta	Vega
American Fab	+110%	$14.3491	$12.9550	0.9995	0.0001	1.7042	-0.0165	0.0308
American Fab	+120%	$15.3031	$12.5190	0.9991	0.0001	3.4087	-0.0330	0.0615
American Fab	+130%	$16.2670	$12.0999	0.9961	0.0007	4.9148	-0.0591	0.2672
American Fab	+140%	$17.2139	$11.6811	0.9932	0.0013	6.4181	-0.0855	0.4755
American Fab	+150%	$18.1815	$11.2910	0.9872	0.0023	7.6481	-0.1189	0.8291
European Fab	+110%	€8.9079	€8.0137	0.9995	0.0001	1.6058	-0.0151	0.0266
European Fab	+120%	€9.3927	€7.6065	0.9990	0.0004	3.2113	-0.0302	0.0533
European Fab	+130%	€9.8861	€7.2132	0.9947	0.0019	4.6299	-0.0525	0.2422
European Fab	+140%	€10.3664	€6.8225	0.9896	0.0036	6.0131	-0.0761	0.4613
European Fab	+150%	€10.8597	€6.4563	0.9799	0.0064	7.1450	-0.1043	0.8050

Note. America Inputs: S = $13.391 Billion, T_3 = 4 Years, r = 3.4%, σ = 52%
American Fab Capacity Expansion Cost, X_E [Billion] = $0.5014, $1.0029, $1.5043, $2.0057, $2.5072
European Inputs: S = €8.421 Billion, T_3 = 4 Years, r = 3.4%, σ = 43.33%
European Fab Capacity Expansion Cost, X_E [Billion] = €0.4682, €0.9363, €1.4045, €1.8726, €2.3408

Table 9 shows the option values obtained from the binomial lattice, and the independent variables are listed in the footer. The European call values were obtained using the standard Black-Scholes Equations 1 through 5 while the Greek sensitivity parameters were obtained using Equations 18 through 23. The American fab capacity rates correspond to: 110% = 41,489, 120% = 45,260, 130% = 49,032, 140% = 52,804 and 150% = 56,576 WSPM. The European fab capacity corresponds to: 110% = 44,239, 120% = 48,260, 130% = 52,282, 140% = 52,304 and 150% = 60,325 WSPM. In summary, the closed-form option values were similar to the binomial lattice values.

Table 9

Option to Expand Capacity: Binomial Lattice European Call Option

	Capacity	Option Value	Call Value	Delta	Gamma	Rho	Theta	Vega
American Fab	+110%	$14.3477	$12.9537	0.9999	0.0000	1.7457	-0.0153	0.0076
American Fab	+120%	$15.3043	$12.5200	0.9992	0.0002	3.4394	-0.0342	0.0766
American Fab	+130%	$16.2609	$12.0954	0.9970	0.0006	5.0243	-0.0584	0.2416
American Fab	+140%	$17.2176	$11.6836	0.9934	0.0013	6.4743	-0.0874	0.4979
American Fab	+150%	$18.1742	$11.2865	0.9881	0.0022	7.7828	-0.1200	0.8278
European Fab	+110%	€8.9065	€8.0124	1.0000	0.0000	1.6329	-0.0140	0.0030
European Fab	+120%	€9.3921	€7.6060	0.9991	0.0004	3.2299	-0.0302	0.0509
European Fab	+130%	€9.8775	€7.2069	0.9961	0.0016	4.7237	-0.0508	0.1969
European Fab	+140%	€10.3631	€6.8203	0.9900	0.0037	6.0650	-0.0759	0.4502
European Fab	+150%	€10.8486	€6.4497	0.9807	0.0064	7.2337	-0.1044	0.7926

Note. America Inputs: S = $13.391 Billion, T_3 = 4 Years, r = 3.4%, σ = 52%
American Fab Capacity Expansion Cost, X_E [Billion] = $0.5014, $1.0029, $1.5043, $2.0057, $2.5072
European Inputs: S = €8.421 Billion, T_3 = 4 Years, r = 3.4%, σ = 43.33%
European Fab Capacity Expansion Cost, X_E [Billion] = €0.4682, €0.9363, €1.4045, €1.8726, €2.3408

Figure 25 illustrates the binomial lattice to expand capacity to 130%. For the American fab, this capacity expansion will likely require a $1.5043 billion capital investment. From survey questions Q14, Q15, and Q16, these investments add up to $5.014 billion to achieve 100% capacity for the American fab. Based on these investments, the cost for additional capacity was determined at 10% intervals. The response to question Q1 of 37,717 WSPM represented 100% capacity for American 450mm wafer foundries. An additional 30% capacity expansion represents 49,032 WSPM to yield a real option value of $16.2609 billion.

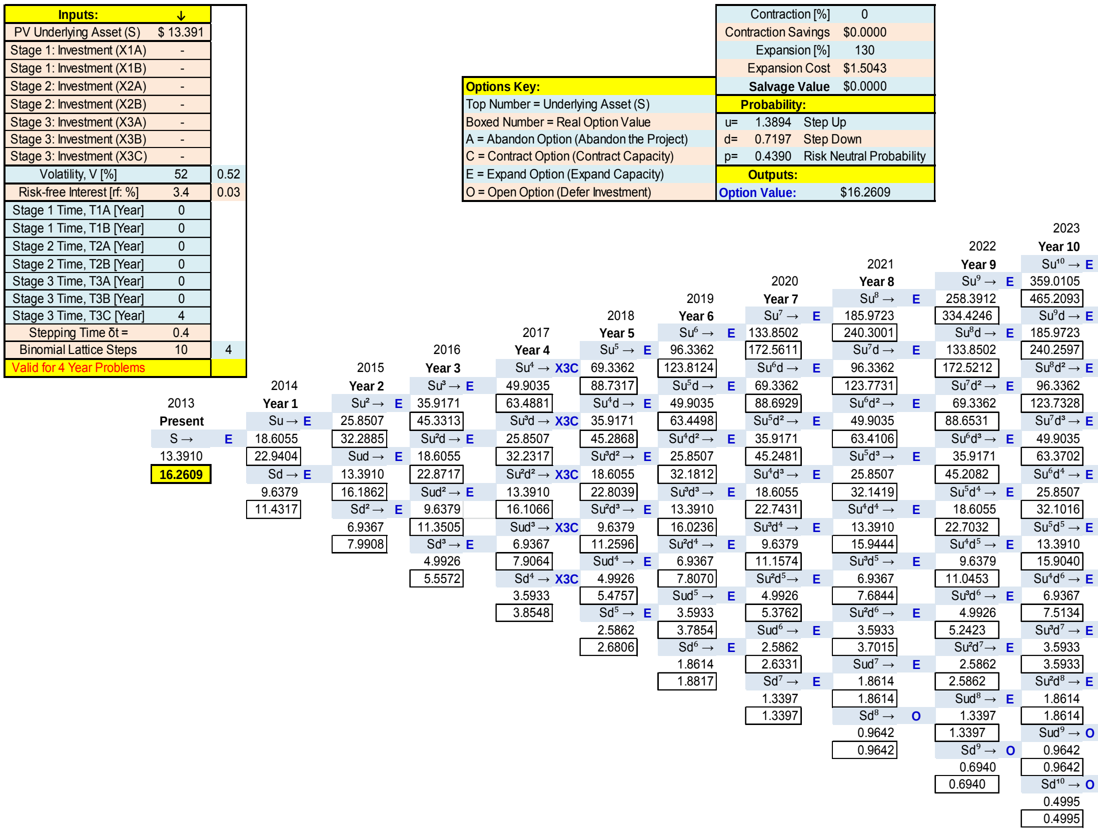

Figure 25. Expand capacity option for an American 450mm wafer fab.

Figure 26 illustrates the binomial lattice model to expand capacity to 130% with an additional capital investment of €1.4045 billion for European 450mm wafer fabs. Europeans responding to question Q1 forecasted European foundries will likely operate at 100% capacity with 40,217 WSPM. The binomial lattice utilizes a linear capacity rate. An additional 30% production increase equates to 52,282 WSPM with the option value of €9.8775 billion. Combined with the static NPV of negative of €0.5883, the total NPV equates to €9.2892 billion. Based on the exchange rate of $1.3487 per euro, the total NPV for the European 450mm wafer fab project is expected to be $12.5283 billion.

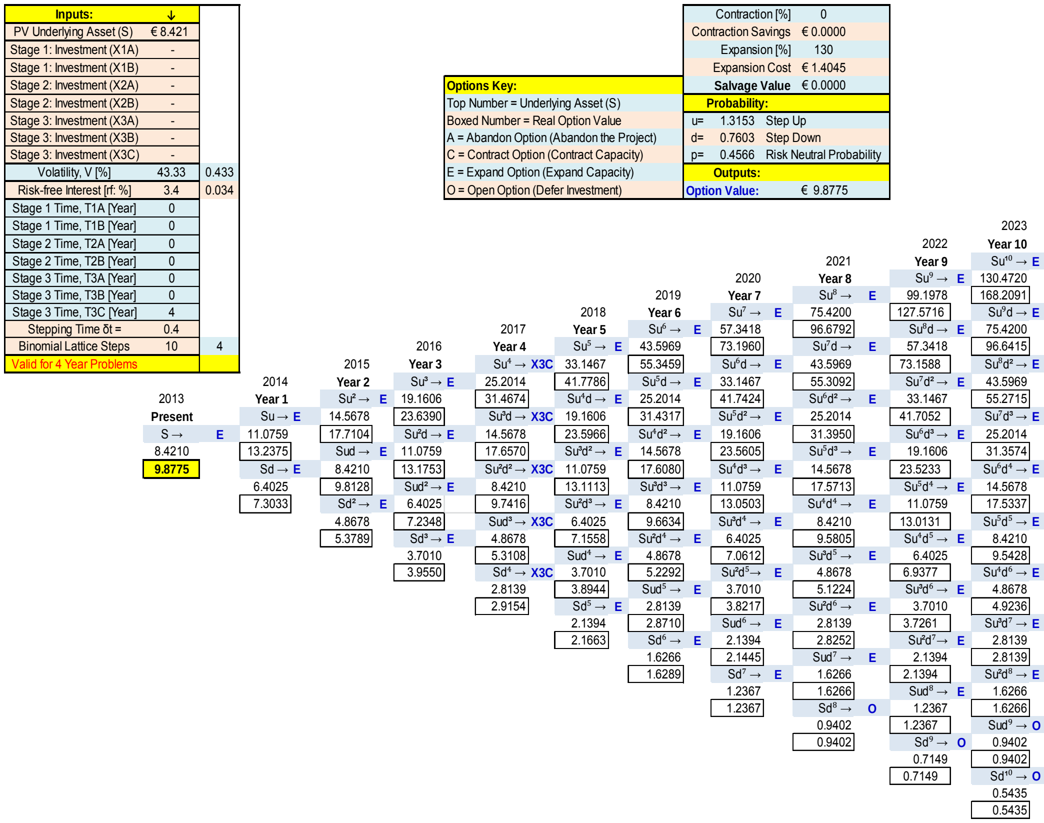

Figure 26. Expand capacity option for a European 450mm wafer fab.

For the American 450mm wafer foundry with a 30% capacity expansion, the total NPV is the sum of the real option NPV of $16.2609 billion plus the static NPV of $3.1717; this yields $19.4326 billion, as shown in Table 10. The total NPV for the European fab is $12.5283 billion. Both NPV values are conservative because the underlying asset values were based on a perpetuity model with constant cash flows without growth.

Hypothesis testing was performed with a paired-difference test and Mega Stat 2007 statistical software. The results are presented in Table 10. The 95% confidence level was applied by setting α to 0.05. Since the $p < 0.0000$ was less than α, the test results showed the null hypothesis was rejected. The operating characteristic curve (OCC) for hypothesis testing was analyzed. The OCC results indicated the probability to accept the null hypothesis with a type I error was 0.00%.

Table 10

Option to Expand: Hypothesis Test for Two Population Means

	NPV Mean	Standard Deviation	Sample Size
American 450mm Fab	19.4326	2.177	46
European 450mm Fab	12.5283	2.471	46
Test Statistic Z	14.2194		
95% Confidence Interval	[5.9526, 7.8560]		
p value	0.0000		

Note. The NPV mean values are shown in $ billion. H_0: $\mu_1 \leq \mu_2$, $\alpha = 0.05$ (upper-tail)

Inferential models were developed to make predictions, to support the RQ1 hypotheses, and to improve internal validity. Response surface methods were employed to construct two multiple regression models with a goal to predict additional capacity value. Mun (2006) stated option values from the binomial lattice were more accurate in comparison to the closed-form American call option. The binomial lattice model emulated a calculator where input parameters were entered to obtain real option values. These values were used to develop inferential models as presented in Appendix F.

A multiple regression began with the analysis of the normal plot of residuals. The residual plot demonstrated an excellent fit along a straight line without outliers. A review of the modeling parameters suggested a good regression relationship. Appendix G presents the modeling parameters for the coefficient of determination R^2, the adjusted R^2, the p value, and the F ratio. The high F ratio was an indication the model was significant. Multicollinearity was investigated and the variance inflation factor (VIF) showed that multicollinearity was not a problem. The 95% prediction interval ranged from \$16.0929 billion to \$16.4289 billion. Reliability of the inferential model to make predictions was checked by setting the predictor variables to: $S = 13.391$, $X_E = 1.5043$, $T_3 = 4$, $r = 3.4$, and $\sigma = 52$. For capacity expansion to 130% with an additional capital investment of \$1.5043 billion, this expand option predicted an option value of \$16.2609 billion with an increase in production capacity to 49,032 WSPM.

A similar expand capacity model was developed for the European fab. Diagnostic checking revealed the assumption for normality was valid and there were no outliers. Reliability performance indicators for the model are found in Appendix G. The high F ratio indicated the model was significant. Likewise, the VIF parameter indicated multicollinearity was not a problem. The 95% prediction interval ranged from €9.7394 billion to €10.0156 billion. Reliability of the inferential model in its ability to make predictions was checked by setting the predictor variables to: $S = 8.421$, $X_E = 1.4045$, $T_3 = 4$, $r = 3.4$, and $\sigma = 43.33$. With these mean inputs, the model yielded an option value of €9.8775 billion. This real option value listed in Table 9 was identical to the option value presented in Table 11.

For the American wafer fab with a 30% capacity expansion to 49,032 WSPM, the inferential capacity model predicted an option value of \$16.2609 billion. In contrast, the forecast for the European wafer fab with a 30% capacity expansion to 52,282 WSPM will likely have an NPV option value of $13.3218 billion. In summary, the real option to expand capacity will likely yield greater NPV for the American 450mm wafer foundry.

Table 11

Predictions to Expand Production Capacity

	American 450mm Wafer Fab		European 450mm Wafer Fab			
Capacity	Option Value	Expand Cost	Option Value		Expand Cost	
[WSPM]	[$ Billion]	[$ Billion]	[€ Billion]	[$ Billion]	[€ Billion]	[$ Billion]
49,032	16.2609	1.5043	9.4674	12.7687	1.0262	1.3840
50,000	16.5128	1.6330	9.5896	12.9335	1.1389	1.5360
51,000	16.7731	1.7660	9.7158	13.1037	1.2553	1.6930
52,282	17.1068	1.9364	9.8775	13.3218	1.4045	1.8942

Note. American fab variables held constant: S = 13.391, T_3 = 4, r = 3.4, σ = 52
European fab variables held constant: S = 8.421, T_3 = 4, r = 3.4, σ = 43.33

Research Question 2

Just as important as the ability to expand capacity as presented in RQ1, organic growth also depends on the ability to conserve limited resources. Research question RQ2 explored a management decision making tool to conserve limited resources with the ability to contract or reduce production capacity in case market demand for semiconductors is lower than expected or in case the outlook to provide production wafers needs to be limited due to a supply difficulty such as low EUV lithography throughput. The goal was to compare option values from two constructs as operational capacity is reduced from the anticipated 100% capacity in 10% increments from 90% to the worst-case 50% reduction. The contract capacity model provides management with the ability to determine the optimal operating point prior to making large investments to purchase semiconductor tools with a goal to save money. The contract capacity real options were constructed using closed-form and binomial lattice models. From these models, a predictive model was developed to make what-if optimal capacity inferences such as the ability to determine the optimal value based on a set number of wafer starts per month.

The closed-form contract model was developed with Equations 2 through 6. Both constructs emulate an American put option with a set option lifetime. Similar to the European put option, Mun (2006) stated that the American put option was preferred because the contract option can be exercised at any time (p. 171). Table 12 presents the closed-form contraction option solutions for the American and European 450mm wafer foundries. This closed-form construct was developed from an American put option since it can be applied early.

Closed-form real option models were developed and utilized to examine a 30% reduction to 70%. The closed-form savings of \$1.5043 billion will likely yield an option value of \$13.4142 billion. For European 450mm wafer foundries, a capacity reduction by 30% will likely save €1.4045 billion with a real option value of €8.4393 billion.

Table 12

Option to Contract Capacity: Closed-Form American Put Option

	Capacity	Option Value	Put Value	Delta*	Vega	Theta*	Gamma	Rho*
American Fab	90%	\$13.3931	\$0.0021	-0.00039	0.03541	-0.00203	0.00009	-0.03236
American Fab	80%	\$13.3952	\$0.0042	-0.00078	0.07084	-0.00405	0.00019	-0.06473
American Fab	70%	\$13.4142	\$0.0232	-0.00363	0.28122	-0.01577	0.00075	-0.29509
American Fab	60%	\$13.4345	\$0.0435	-0.00668	0.49926	-0.02837	0.00135	-0.47981
American Fab	50%	\$13.4837	\$0.0927	-0.01277	0.87218	-0.04843	0.00236	-0.97174
European Fab	90%	€8.4224	€0.0014	-0.00050	0.02784	-0.00127	0.00020	-0.02774
European Fab	80%	€8.4239	€0.0029	-0.00100	0.05567	-0.00254	0.00039	-0.05548
European Fab	70%	€8.4393	€0.0183	-0.00534	0.24574	-0.01101	0.00192	-0.27046
European Fab	60%	€8.4584	€0.0374	-0.01075	0.47293	-0.02165	0.00384	-0.46682
European Fab	50%	€8.5022	€0.0812	-0.02097	0.83933	-0.03728	0.00686	-0.96286

Note. America Inputs: S = \$13.391 Billion, T_3 = 4 Years, r = 3.4%, σ = 52%, * Indicates Put Values
American Fab Capacity Savings, X_S [Billion] = \$0.5014, \$1.0029, \$1.5043, \$2.0057, \$2.5072
European Inputs: S = €8.421 Billion, T_3 = 4 Years, r = 3.4%, σ = 43.33%
European Fab Capacity Savings, X_S [Billion] = €0.4682, €0.9363, €1.4045, €1.8726, €2.3408

Table 13 presents the binomial lattice option values, the European put value and the Greek sensitivity parameters to contract production capacity for the American and European foundries. A comparison with Table 12 revealed a slightly higher option value from the binomial lattice method in comparison to the closed-form solutions. In summary, Mun (2006) pointed out that the closed-form American put option values were approximations, and they were not as accurate in comparison to numerical solutions obtained from the binomial lattice (p. 171).

Table 13

Option to Contract Capacity: Binomial Lattice European Put Option

	Capacity	Option Value	Put Value	Delta*	Vega	Theta*	Gamma	Rho*
American Fab	90%	$13.3911	$0.0003	-0.00007	0.00755	-0.00045	0.00002	-0.00492
American Fab	80%	$13.3976	$0.0043	-0.00084	0.07656	-0.00445	0.00021	-0.06213
American Fab	70%	$13.4275	$0.0174	-0.00295	0.24158	-0.01377	0.00065	-0.22774
American Fab	60%	$13.4941	$0.0432	-0.00664	0.49791	-0.02787	0.00133	-0.52837
American Fab	50%	$13.6754	$0.0839	-0.01186	0.82782	-0.04556	0.00222	-0.97079
European Fab	90%	€8.4210	€0.0001	-0.00004	0.00304	-0.00015	0.00002	-0.00182
European Fab	80%	€8.4251	€0.0023	-0.00089	0.05092	-0.00243	0.00041	-0.03911
European Fab	70%	€8.4526	€0.0118	-0.00394	0.19694	-0.00914	0.00160	-0.17994
European Fab	60%	€8.5319	€0.0338	-0.01003	0.45022	-0.02036	0.00366	-0.47306
European Fab	50%	€8.6948	€0.0719	-0.01934	0.79260	-0.03495	0.00645	-0.93892

Note. America Inputs: S = $13.391 Billion, T_3 = 4 Years, r = 3.4%, σ = 52%, * Indicates Put Values
American Fab Capacity Savings, X_S [Billion] = $0.5014, $1.0029, $1.5043, $2.0057, $2.5072
European Inputs: S = €8.421 Billion, T_3 = 4 Years, r = 3.4%, σ = 43.33%
European Fab Capacity Savings, X_S [Billion] = €0.4682, €0.9363, €1.4045, €1.8726, €2.3408

Figure 27 illustrates the option to contract capacity by 30% as a contingency from the planned 37,717 wafer starts per month for American 450mm wafer fabs. The binomial lattice model represents the cost savings of $1.5043 billion to reduce capacity by 30% to 26,401 wafer starts per month. This capacity reduction will likely decrease the real option value down to $13.4275 billion.

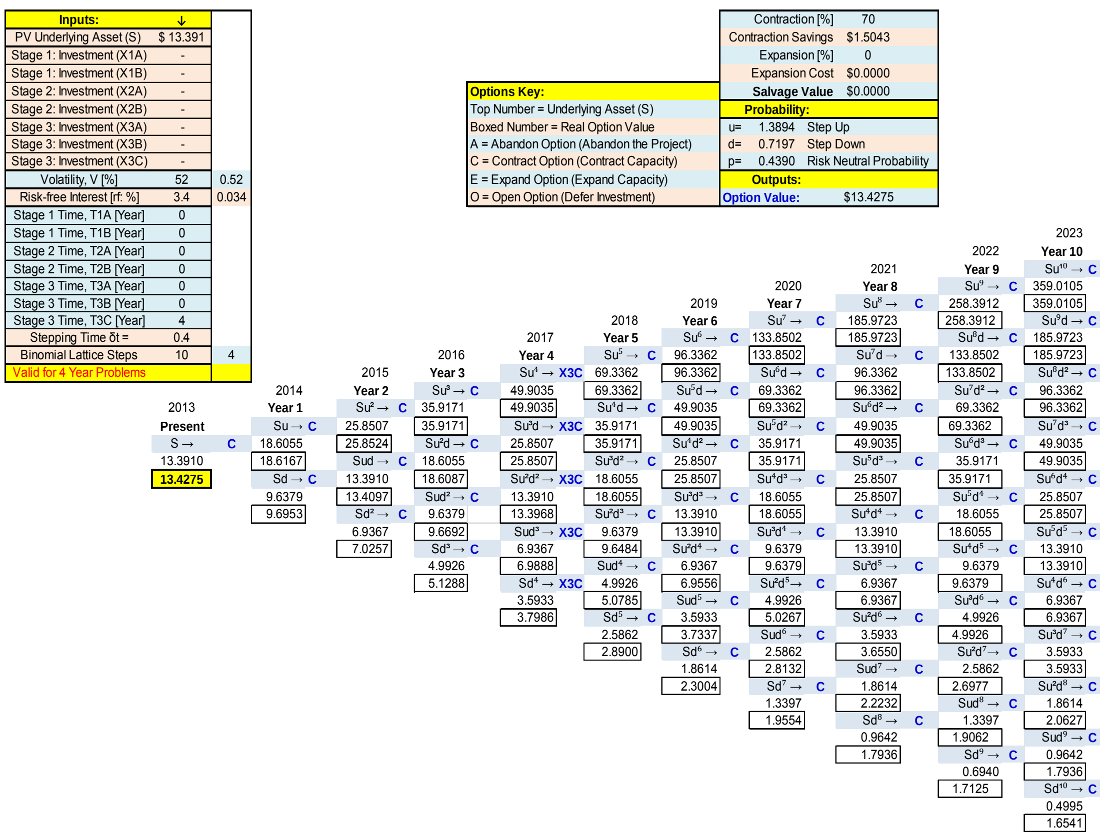

Figure 27. Contract capacity option for an American 450mm wafer fab.

The binomial lattice in Figure 28 illustrates the option to contract capacity by 30%. European participants anticipated a full capacity wafer fab would operate with a capacity of 40,217 wafer starts per month. Based on a linear 30% capacity reduction, production would throttle down to 28,151 wafer starts per month. Operating at 70% capacity will likely save €1.4045 billion and generate a real option value of €8.4526 billion according to the binomial lattice. Based on an exchange rate of $1.3487 per euro, the total option value was calculated to be $11.4000 billion.

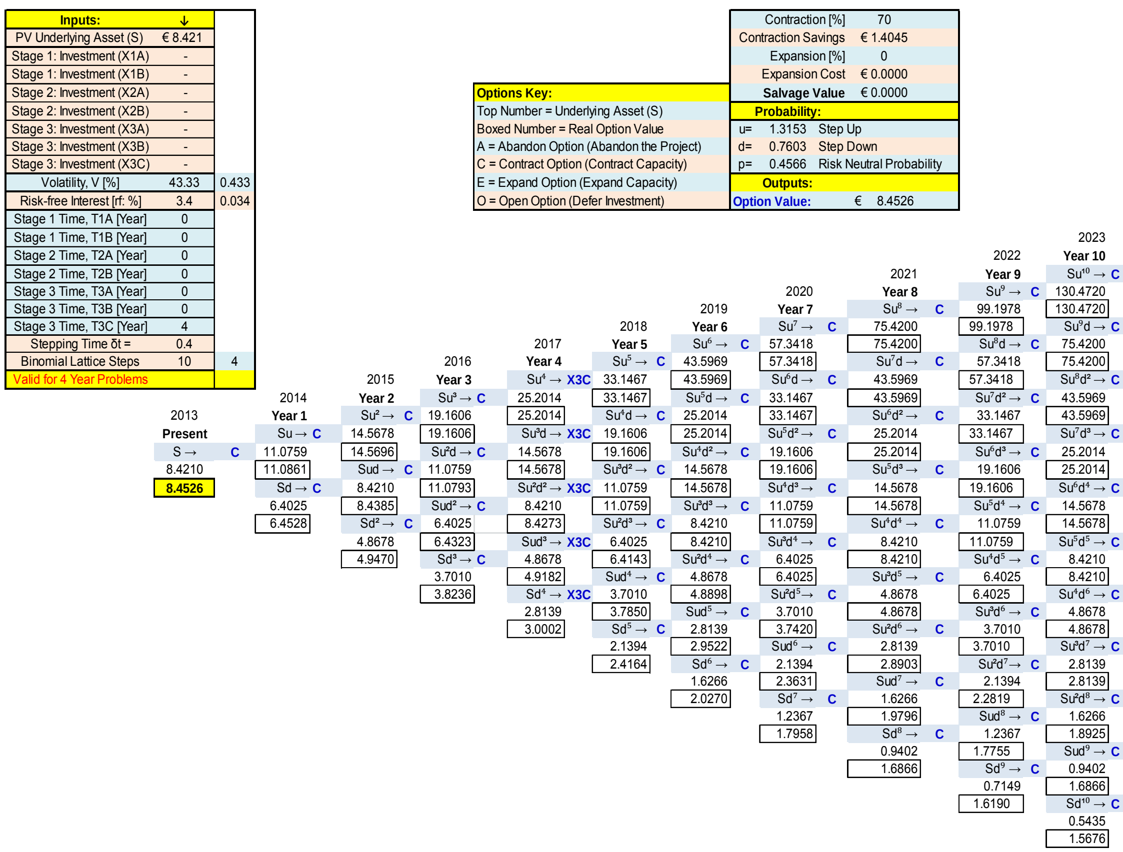

Figure 28. Contract capacity option for a European 450mm wafer fab.

A 30% production capacity reduction will likely save \$1.4045 billion and produce a real option NPV of \$13.4275 billion for American 450mm wafer foundries. With this real option value combined with the static NPV of \$3.1717 billion, the total NPV for an American 450mm wafer fab will likely be \$16.5992 billion, as presented in Table 14. Similarly for the European wafer fab, the real option NPV of €8.4526 billion combined with the static NPV of negative €0.5883 billion will likely yield a total NPV of €7.8643 billion. Based on the exchange rate of \$1.3487 per euro, the total NPV for the European 450mm wafer fab project is expected to be \$10.6066 billion for a 30% capacity contraction.

Hypothesis testing was performed using Mega Stat 2007. The test results revealed a *p* value of 0.0000 as presented in Table 14. At 95% confidence with α set to 0.05, since $p < 0.0000$ was less than α, the test results indicated the null hypothesis was rejected. Moreover, the OCC analysis found the probability for a type I error was 0.00%.

Table 14

Option to Contract: Hypothesis Test for Two Population Means

	NPV Mean	Standard Deviation	Sample Size
American 450mm Fab	16.5992	2.177	46
European 450mm Fab	10.6066	2.471	46
Test Statistic Z	12.3417		
95% Confidence Interval	[5.0409, 6.9443]		
p value	0.0000		

Note. Values are in billion, H_0: $\mu_1 \leq \mu_2$, $\alpha = 0.05$ (upper-tail)

Inference models were developed with response surface methods to validate the RQ2 hypotheses and to make capacity predictions for American foundries, as shown in Appendix F. The reliability of this model was validated by setting the predictor variables to: $S = 13.391$, $X\mathrm{s} = 1.5043$, $T_3 = 4$, $r = 3.4$, and $\sigma = 52$. With these inputs, the contract capacity model produced an option value of \$13.4275 billion. This option value was identical to the value shown in Table 13. The 95% prediction interval ranged from \$13.3373 billion to \$13.5177 billion. The modeling performance parameters are shown in Appendix G.

A second inference model was developed for the European wafer fab to emulate capacity contraction as indicated by Appendix F. Reliability of this model was examined by setting the predictor variables to: $S = 8.421$, $X\mathrm{s} = 1.4045$, $T_3 = 4$, $r = 3.4$, and $\sigma = 43.33$. For these predictor variables, the model yielded an option value of €8.4526 billion. This option value was the same to the value presented in Table 13. The 95% prediction interval ranged from €8.2245 billion to €8.6807 billion. The reliability performance parameters are listed in Appendix G.

Table 15 summarizes the predictions obtained from the inferential models. The Excel goal seek function was applied by specifying a production capacity, which forced the independent contract saving variable to change with a corresponding option value. American wafer fabs that decrease production by 30% capacity to 26,402 WSPM will likely realize a real option value of $13.4275 billion. European wafer fabs with the same 30% capacity reduction to 28,151 WSPM will likely yield an option value of $11.4000 billion. In summary, this inferential model supports the RQ2 hypotheses such that a capacity contraction will likely generate greater NPV for American 450mm wafer fabs.

Table 15

Predictions to Contract Production Capacity

	American 450mm Wafer Fab		European 450mm Wafer Fab			
Capacity [WSPM]	Option Value [$ Billion]	Contract Savings [$ Billion]	Option Value [€ Billion]	[$ Billion]	Contract Savings [€ Billion]	[$ Billion]
30,000	13.3530	1.0259	8.4120	11.3453	1.1894	1.6041
29,000	13.3685	1.1589	8.4324	11.3728	1.3058	1.7611
28,151	13.3847	1.2716	8.4526	11.4000	1.4045	1.8942
27,000	13.4115	1.4248	8.4844	11.4429	1.5386	2.0751
26,402	13.4275	1.5040	8.5028	11.4677	1.6080	2.1687
25,000	14.4707	1.6901	8.5512	11.5330	1.7714	2.3891

Note. American fab variables held constant: $S = 13.391$, $T_3 = 4$, $r = 3.4$, $\sigma = 52$
European fab variables held constant: $S = 8.421$, $T_3 = 4$, $r = 3.4$, $\sigma = 43.33$

Research Question 3

To date, technical issues have delayed the introduction of EUV lithography for a pilot wafer fab. Research question RQ3 focused on the development of real options as a contingency for the possible delay of the revolutionary EUV lithography scanning tool and EUV resist process for the American and European 450mm pilot fabs. If the debut of the pilot EUV lithography scanning tool is delayed, then the impact of deferring the X_{2A} investment can be analyzed for 1, 2, and 3 years.

Defer options were developed using two different constructs. The first construct was developed with the closed-form European compound call on a call option with Equations 7 through 12. The second construct was developed with binomial lattices. Table 16 compares the option values obtained from the closed-form construct and the binomial lattice construct for the American 450mm wafer foundry. Participant responses to question Q4 indicated the availability of EUV lithography for a pilot fab would occur in 2015. The 2-year time frame designated as T_{2A} represents on-time delivery. Because of the technical difficulties with this novel EUV technology, delays of 1, 2, and 3years were presented for both constructs. For the American pilot fab, the closed-form construct predicted a 1-year investment delay of EUV lithography is expected to cost an additional $13.3 million while the binomial lattice predicted $8.5 million. The closed-form construct predicted a 2-year delay will likely cost $33.8 million while the binomial lattice predicted $47 million. The closed-form construct predicted a 3-year delay will likely cost $64.1 million while the binomial lattice predicted $101.2 million.

Table 16 compares the results from two constructs for American pilot wafer fabs. Americans answering question Q4 predicted that pilot EUV lithography tools will likely be available by the third quarter of 2015. Participants answering question Q17 indicated commercialization would begin in 2019. This milestone timeframe to commercialization T_{3D} reveals the 450mm wafer fab project will likely take 6-years to generate first revenue. Since the surveys were taken in 2013, the reference start time began in 2013, and 2015 represents no delay. A 2-year delay of the pilot EUV lithography will likely begin in 2017. Both constructs were built using a compound European call on a call option. The binomial lattice compound call option works like two binomial lattice structures. An inner lattice operates with the smaller short-term investment X_{2A} delay within a central lattice with a 6-year X_3 investment period that matures in 2019.

Table 16

Option to Defer EUV Lithography for an American 450mm Pilot Fab

Method	Year	T_{2A} Delay	Option Value	Delta	Vega	Theta	Gamma	Rho
Closed-form	2015	0 Years	$9.8339	0.94138	3.83346	-0.01061	0.00682	15.6116
Closed-form	2016	1 Year	$9.8472	0.94056	3.86488	-0.01645	0.00701	15.7728
Closed-form	2017	2 Years	$9.8677	0.93924	3.92119	-0.02488	0.00715	15.8325
Closed-form	2018	3 Years	$9.8980	0.93783	3.99120	-0.03675	0.00725	15.7825
Binomial Lattice	2015	0 Years	$9.7709	0.93635	3.85684	-0.28223	0.00776	14.7531
Binomial Lattice	2016	1 Year	$9.7794	0.93634	3.86813	-0.28142	0.00774	14.7907
Binomial Lattice	2017	2 Years	$9.8179	0.93633	3.91792	-0.27778	0.00764	14.9570
Binomial Lattice	2018	3 Years	$9.8721	0.93636	3.98565	-0.27267	0.00751	15.1860

Note. S = $13.391B, T_{2A} = 2 Years, X_{2A} = $0.275B, T_{3D} = 6 Years, X_3 = $5.0153B, r = 3.4%, σ = 52%

Figure 29 shows a binomial lattice structure created from a compound call on a call European option. This binomial lattice was created using Microsoft Excel 2010. The binomial lattice model represents a 2-year delay of the \$275 million EUV lithography investment X_{2A} for American 450mm wafer fabs. The impact of deferring the EUV lithography investment for 2-years in 2017 is a real option value of \$9.8179 billion. The Excel goal seek function was utilized to determine the Greek sensitivity parameters.

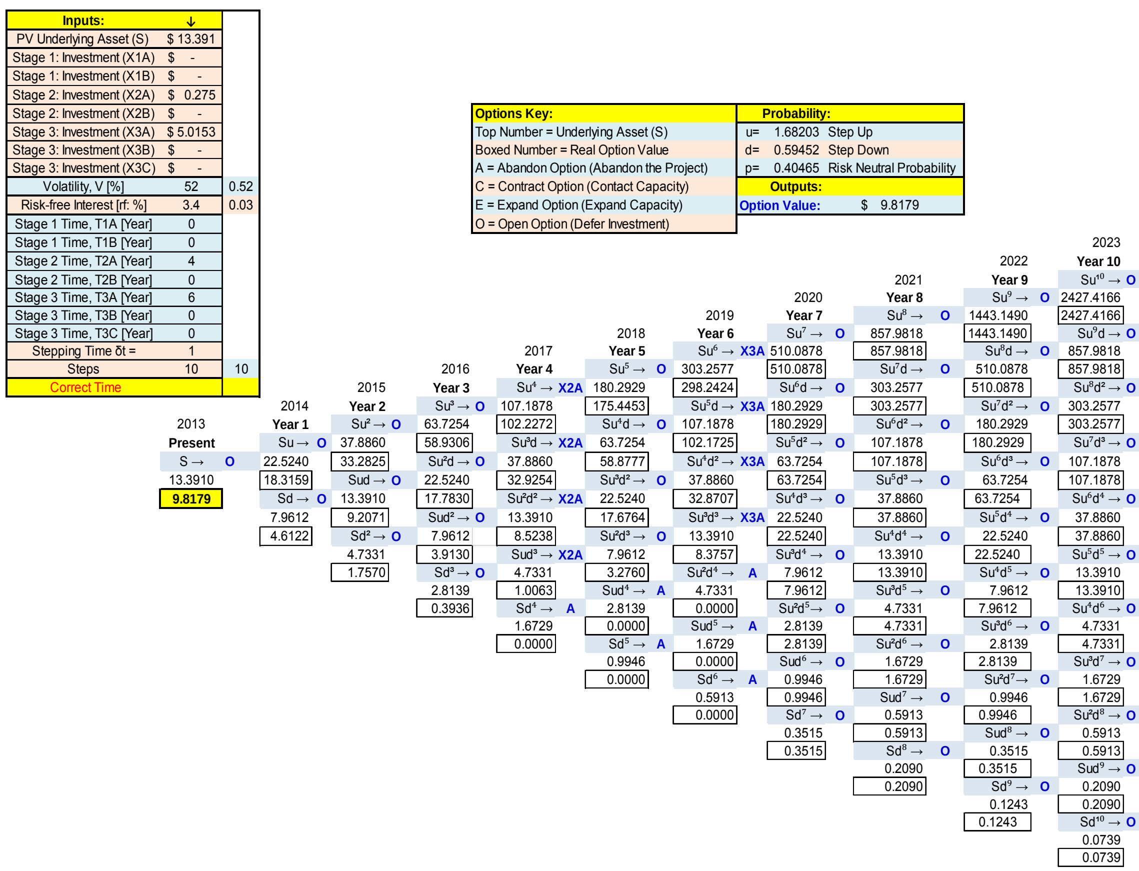

Figure 29. Defer option value for pilot EUV lithography in an American fab.

Table 17 compares both European pilot fab constructs. Responses to question Q4 as presented in Table 5, indicated that EUV lithography for the pilot fab will likely debut in 2015. The findings for both constructs were somewhat similar. For the European pilot fab, the closed-form construct predicted a 1-year investment delay of EUV lithography will cost an additional €15.3 million while the binomial lattice predicted €8.3 million. With the exchange rate of $1.3487 per euro, the 1-year closed-form construct predicted an additional cost of $20.6 million while the binomial lattice predicted $11.2 million. For a 2-year delay, the closed-form delay cost prediction will be €37.9 million or $51.1 million while the binomial lattice predicted €40.2 million, or $54.2 million. For a 3-year delay of the EUV investment, the closed-form construct predicted €68.9 million, or $92.9 million, while the binomial lattice predicted €87.2 million, or $117.6 million.

Table 17

Option to Defer EUV Lithography for a European 450mm Pilot Fab

Method	Year	T_{2A} Delay	Option Value	Delta	Vega	Theta	Gamma	Rho
Closed-form	2015	0 Years	€5.0922	0.89828	3.65748	-0.01202	0.02025	13.8615
Closed-form	2016	1 Year	€5.1075	0.89619	3.69563	-0.01884	0.02091	13.9691
Closed-form	2017	2 Years	€5.1301	0.89362	3.75075	-0.02649	0.02133	13.9805
Closed-form	2018	3 Years	€5.1611	0.89131	3.81178	-0.03635	0.02145	13.9048
Binomial Lattice	2015	0 Years	€5.1379	0.88848	3.80420	-0.22536	0.02188	13.2612
Binomial Lattice	2016	1 Year	€5.1462	0.88002	3.81375	-0.22453	0.02180	13.3060
Binomial Lattice	2017	2 Years	€5.1781	0.88904	3.8497	-0.22137	0.02146	13.4761
Binomial Lattice	2018	3 Years	€5.2251	0.88977	3.90100	-0.21678	0.02098	13.7233

Note. S = €8.421B, T_{2A} = 2 Years, X_{2A} = €0.2641B, T_{3D} = 6 Years, X_3 = €4.6815B, r = 3.4%, σ = 43.33%

Figure 30 shows the binomial lattice model that represents a 2-year delay of the X_{2A} investment totaling €264.1 million for EUV lithography in European pilot wafer fabs. If the debut of EUV lithography were delayed 2-years to 2017, then the real option value will likely be €5.1781 billion. With the exchange rate of $1.3487 per euro, the defer option value is expected to be $6.9837 billion. The additional cost to delay EUV lithography in the pilot fab is expected to be €40.2 million, or $54.2 million.

Inputs:	↓	
PV Underlying Asset (S)	€ 8.4210	
Stage 1: Investment (X1A)	€ -	
Stage 1: Investment (X1B)	€ -	
Stage 2: Investment (X2A)	€ 0.2641	
Stage 2: Investment (X2B)	€ -	
Stage 3: Investment (X3A)	€ 4.6815	
Stage 3: Investment (X3B)	€ -	
Stage 3: Investment (X3C)	€ -	
Volatility, V [%]	43.33	0.4333
Risk-free Interest [rf: %]	3.4	0.034
Stage 1 Time, T1A [Year]	0	
Stage 1 Time, T1B [Year]	0	
Stage 2 Time, T2A [Year]	4	
Stage 2 Time, T2B [Year]	0	
Stage 3 Time, T3A [Year]	6	
Stage 3 Time, T3B [Year]	0	
Stage 3 Time, T3C [Year]	0	
Stepping Time δt =	1	
Steps	10	10
Correct Time		

Options Key:	Probability:		
Top Number = Underlying Asset (S)	u=	1.54234	Step Up
Boxed Number = Real Option Value	d=	0.64837	Step Down
A = Abandon Option (Abandon the Project)	p=	0.43203	Risk Neutral Probability
C = Contract Option (Contact Capacity)	Outputs:		
E = Expand Option (Expand Capacity)	Option Value:		€ 5.1781
O = Open Option (Defer Investment)			

2013	Present	$S \rightarrow$	O	8.4210	5.1781
2014	Year 1	$Su \rightarrow$	O	12.9880	9.1757
		$Sd \rightarrow$	O	5.4599	2.4527
2015	Year 2	$Su^2 \rightarrow$	O	20.0320	15.8027
		$Sud \rightarrow$	O	8.4210	4.6936
		$Sd^2 \rightarrow$	O	3.5400	0.8976
2016	Year 3	$Su^3 \rightarrow$	O	30.8961	26.4133
		$Su^2d \rightarrow$	O	12.9880	8.6941
		$Sud^2 \rightarrow$	O	5.4599	1.9364
		$Sd^3 \rightarrow$	O	2.2952	0.1620
2017	Year 4	$Su^4 \rightarrow$	X2A	47.6522	43.0143
		$Su^3d \rightarrow$	X2A	20.0320	15.3941
		$Su^2d^2 \rightarrow$	X2A	8.4210	4.1272
		$Sud^3 \rightarrow$	X2A	3.5400	0.3880
		$Sd^4 \rightarrow$	A	1.4881	0.0000
2018	Year 5	$Su^5 \rightarrow$	O	73.4958	68.9708
		$Su^4d \rightarrow$	O	30.8961	26.3711
		$Su^3d^2 \rightarrow$	O	12.9880	8.4630
		$Su^2d^3 \rightarrow$	O	5.4599	1.5616
		$Sud^4 \rightarrow$	A	2.2952	0.0000
		$Sd^5 \rightarrow$	A	0.9649	0.0000
2019	Year 6	$Su^6 \rightarrow$	X3A	113.3555	108.6740
		$Su^5d \rightarrow$	X3A	47.6522	42.9707
		$Su^4d^2 \rightarrow$	X3A	20.0320	15.3505
		$Su^3d^3 \rightarrow$	X3A	8.4210	3.7395
		$Su^2d^4 \rightarrow$	A	3.5400	0.0000
		$Sud^5 \rightarrow$	A	1.4881	0.0000
		$Sd^6 \rightarrow$	A	0.6256	0.0000
2020	Year 7	$Su^7 \rightarrow$	O	174.8325	174.8325
		$Su^6d \rightarrow$	O	73.4958	73.4958
		$Su^5d^2 \rightarrow$	O	30.8961	30.8961
		$Su^4d^3 \rightarrow$	O	12.9880	12.9880
		$Su^3d^4 \rightarrow$	O	5.4599	5.4599
		$Su^2d^5 \rightarrow$	O	2.2952	2.2952
		$Sud^6 \rightarrow$	O	0.9649	0.9649
		$Sd^7 \rightarrow$	O	0.4056	0.4056
2021	Year 8	$Su^8 \rightarrow$	O	269.6510	269.6510
		$Su^7d \rightarrow$	O	113.3555	113.3555
		$Su^6d^2 \rightarrow$	O	47.6522	47.6522
		$Su^5d^3 \rightarrow$	O	20.0320	20.0320
		$Su^4d^4 \rightarrow$	O	8.4210	8.4210
		$Su^3d^5 \rightarrow$	O	3.5400	3.5400
		$Su^2d^6 \rightarrow$	O	1.4881	1.4881
		$Sud^7 \rightarrow$	O	0.6256	0.6256
		$Sd^8 \rightarrow$	O	0.2630	0.2630
2022	Year 9	$Su^9 \rightarrow$	O	415.8932	415.8932
		$Su^8d \rightarrow$	O	174.8325	174.8325
		$Su^7d^2 \rightarrow$	O	73.4958	73.4958
		$Su^6d^3 \rightarrow$	O	30.8961	30.8961
		$Su^5d^4 \rightarrow$	O	12.9880	12.9880
		$Su^4d^5 \rightarrow$	O	5.4599	5.4599
		$Su^3d^6 \rightarrow$	O	2.2952	2.2952
		$Su^2d^7 \rightarrow$	O	0.9649	0.9649
		$Sud^8 \rightarrow$	O	0.4056	0.4056
		$Sd^9 \rightarrow$	O	0.1705	0.1705
2023	Year 10	$Su^{10} \rightarrow$	O	641.4483	641.4483
		$Su^9d \rightarrow$	O	269.6510	269.6510
		$Su^8d^2 \rightarrow$	O	113.3555	113.3555
		$Su^7d^3 \rightarrow$	O	47.6522	47.6522
		$Su^6d^4 \rightarrow$	O	20.0320	20.0320
		$Su^5d^5 \rightarrow$	O	8.4210	8.4210
		$Su^4d^6 \rightarrow$	O	3.5400	3.5400
		$Su^3d^7 \rightarrow$	O	1.4881	1.4881
		$Su^2d^8 \rightarrow$	O	0.6256	0.6256
		$Sud^9 \rightarrow$	O	0.2630	0.2630
		$Sd^{10} \rightarrow$	O	0.1106	0.1106

Figure 30. Defer option value for pilot EUV lithography in a European fab.

The closed-form American wafer fab construct forecast for a 2-year EUV lithography delay is likely to produce a real option value of \$9.8677 billion. A summation of this real option NPV with the static NPV of \$3.1717 billion yields a total NPV of \$13.0394 billion. For the binomial lattice method, the real option NPV of \$9.8179 combined with the static NPV is expected to generate a total NPV of \$12.9896 billion.

The closed-form European wafer fab construct for a 2-year EUV lithography delay would yield a real option NPV of €5.1301 billion. With a static NPV of negative €0.5883 billion, the total NPV will likely be €4.5418 billion. For the binomial lattice method, the real option NPV was €5.1781 billion, and combined with the static NPV, the total NPV yields €4.5898 billion. Based on the exchange rate of \$1.3487 per euro, the total NPV for the European 450mm wafer fab project is expected to be \$6.1255 billion for the closed-form construct and \$6.1903 billion for the binomial lattice.

The defer options for both foundries were compared. Hypothesis testing was performed twice because the solutions obtained from both constructs were slightly different as presented in Table 18. The statistical software Mega Stat 2007 was applied and the hypothesis test results revealed a *p* value of 0.0000 for both constructs. For 95% confidence with α set to 0.05 since the *p* value was less than α, the findings showed the null hypothesis was rejected for both constructs. The OCC analysis predicted the probability to accept the null hypothesis type I error was 0.00%.

Table 18

Option to Defer: Hypothesis Test for Two Population Means

	Mean NPV	Standard Deviation	Sample Size
American Fab CF	13.0394	2.177	46
American Fab BL	12.9896	2.177	46
European Fab CF	6.1255	2.471	46
European Fab BL	6.1903	2.471	46
Test Statistic Z CF	14.2391		
Test Statistic Z BL	14.0031		
95% Confidence Interval CF	[5.9622, 7.8656]		
95% Confidence Interval BL	[5.8476, 7.7510]		
p value CF	0.0000		
p value BL	0.0000		

Note. CF: Closed-form, BL: Binomial Lattice, H_0: $\mu_1 \leq \mu_2$, $\alpha = 0.05$ (upper-tail)

Inference models were developed for the both wafer fabs to verify the RQ3 hypothesis and to make investment predictions in case the EUV lithography investment is delayed. Two inference models were developed from option values obtained from the closed-form call on a call European option equations. The five independent variables consisted of the present value of expected cash flows (S), the investments at stage 3 (X_3), the delay time for pilot EUV lithography (T_{2A}), the risk free interest rate (r), and volatility (σ). For both models, the EUV lithography X_{2A} investment and the overall project lifetime (T) were held constant. The two inference models are presented in Appendix F.

Reliability of the inference model for the American fab was examined by setting the predictor variables to: $S = 13.391$, $X_3 = 5.0153$, $T_{2A} = 4$, $r = 3.4$, and $\sigma = 52$. The model produced a defer option value of \$9.8677 billion. This value was the same as listed in Table 16. Appendix G shows the modeling performance parameters. The normal plot of residuals exemplified an excellent fit. A high *F* ratio indicated the inferential model was significant. According to the low VIF value, multicollinearity was not a problem. The 95% confidence interval ranged from \$9.8004 billion to \$9.9450 billion.

A similar inference model for the European 450mm fab was developed and is presented in Appendix F. Diagnostic checking revealed the normality assumption was valid. The review did not find any outliers. Reliability of the regression parameters listed in Appendix G showed the model was significant. The VIF value suggested that multicollinearity was not a problem. The 95% confidence interval ranged from €5.08396 billion to €5.17604 billion. To validate the inference model, the predictor variables were set to: $S = 8.421$, $X_3 = 4.6815$, $T_{2A} = 4$, $r = 3.4$, and $\sigma = 43.33$. With these values, the inference model yielded an option value of €5.1300 billion which was similar to the closed-form construct value of €5.1301 billion as presented in Table 17.

Table 19 presents the EUV lithography forecast to delay the X_{2A} investments. For a 2-year delay of EUV lithography, the defer option value for American wafer fabs is expected to be \$9.8677 billion and \$6.9188 billion for European wafer fabs. In summary, the RQ3 hypothesis was supported because the defer investment option value yields a greater NPV for American 450mm wafer foundries.

Table 19

Predictions to Delay the EUV Lithography Investment

	American 450mm Fab	European 450mm Wafer Fab	
Delay	Option Value	Option Value	
[Years]	[$ Billion]	[€ Billion]	[$ Billion]
0.00	9.8350	5.0972	6.8746
0.50	9.8401	5.1022	6.8813
1.00	9.8573	5.1093	6.8909
1.17	9.8500	5.1122	6.8948
1.50	9.8565	5.1186	6.9035
1.68	9.8600	5.1224	6.9086
2.00	9.8677	5.1300	6.9188
2.50	9.8810	5.1436	6.9372
3.00	9.8963	5.1594	6.9585
3.12	9.9000	5.1635	6.9640
3.50	9.9136	5.1773	6.9826

Note. American fab inputs: S = 13.391 Bil, X_3 = 5.0153 Bil, T_{2A} = 4y, r = 3.4%, and σ = 52%
European fab inputs: S = 8.421 Bil, X_3 = 4.6815 Bil, T_{2A} = 4y, r = 3.4%, and σ = 43.33%

Research Question 4

Research question RQ4 investigated the possibility that the 450mm wafer fab project could fail to produce a process recipe. As a contingency mechanism, the abandon option at time T_{3A} was developed. This is an important milestone that marks a fundamental decision by management whether to invest in all the production wafer-processing tools, which is expected to lead to the qualification, installation, and production ramp up or to abandon the wafer fab project. If the development of the main process recipe proves unsuccessful, management most likely will have the right but not the obligation to terminate the project. If the development of the main process recipe proves successful, management has the right to make the substantial investment to ramp up production to full capacity.

The abandonment option was developed using two different constructs. The first construct was created using closed-form compound call on put option Equations 13 through 17. The closed-form put option equation was validated with Mun (2006, p. 387). The five Greek sensitivity parameters were also calculated. For the second construct, a binomial lattice was constructed with Microsoft Excel 2010 and the lattice operation was verified with examples provided by Mun (2006, pp. 386-392). This binomial lattice was based on a European call on a put option, and the Greek sensitivity equations were embedded into the lattice.

Table 20 compares the option values, put values, and the Greek sensitivity parameters for both constructs. For the abandon option, one of the key parameters applied to both constructs was salvage value. American participants responding to question Q11 forecasted the mean salvage value (*Sv*) for a failed 450mm foundry would be $3.228 billion, while European participants forecasted €3.152 billion, or $4.241 billion.

Based on the probability of success or failure, the put values represent insurance premiums. The closed-form construct was developed from the compound call on a put option equations. For the American fab, the closed-form put value solution was $178.04 million. In contrast, the binomial lattice, which was based on the compound European put option, produced a value of $170.3 million. For the European fab, the closed-form put value was €188.55 million, while the binomial lattice yielded a put value of €181.5 million. Table 20 shows the option values for successful American and European wafer fab projects that do not exercise the abandon option.

Table 20

Option to Abandon American and European 450mm Wafer Fabs

	Method	Option Value	Put Value	Delta*	Vega	Theta*	Gamma	Rho*
American Fab	C-Form	$13.5690 Bil	$178.04 Mil	-0.0227	1.4421	-0.0787	0.0039	-1.7656
American Fab	Lattice	$13.5504 Bil	$170.30 Mil	-0.0218	1.3925	-0.0748	0.0037	-1.8466
European Fab	C-Form	€8.6095 Bil	€188.55 Mil	-0.0439	1.5674	-0.0679	0.0130	-2.0001
European Fab	Lattice	€8.6128 Bil	€181.50 Mil	-0.0423	1.5197	-0.0640	0.0124	-2.1521

Note. America Inputs: S = $13.391 Bil, Sv = $3.228 Bil, T_3 = 4 Years, r = 3.4%, σ = 52%
European Inputs: S = €8.421 Bil, Sv = €3.152 Bil, T_3 = 4 Years, r = 3.4%, σ = 43.33%
* Indicates Put Values

Figure 31 emulates a compound European put option for the American 450mm wafer fab project using a binomial lattice. One of the key parameters is the salvage value (*Sv*), which was obtained from the answer to question Q11. If development of the process recipe is a failure after 4-years at time T_{3A}, management can abandon the project and obtain the $3.228 billion salvage value. If development of the process recipe is successful, management will likely invest in all wafer-processing tools to ramp up production to achieve full capacity operations to obtain the real option value of $13.5504 billion.

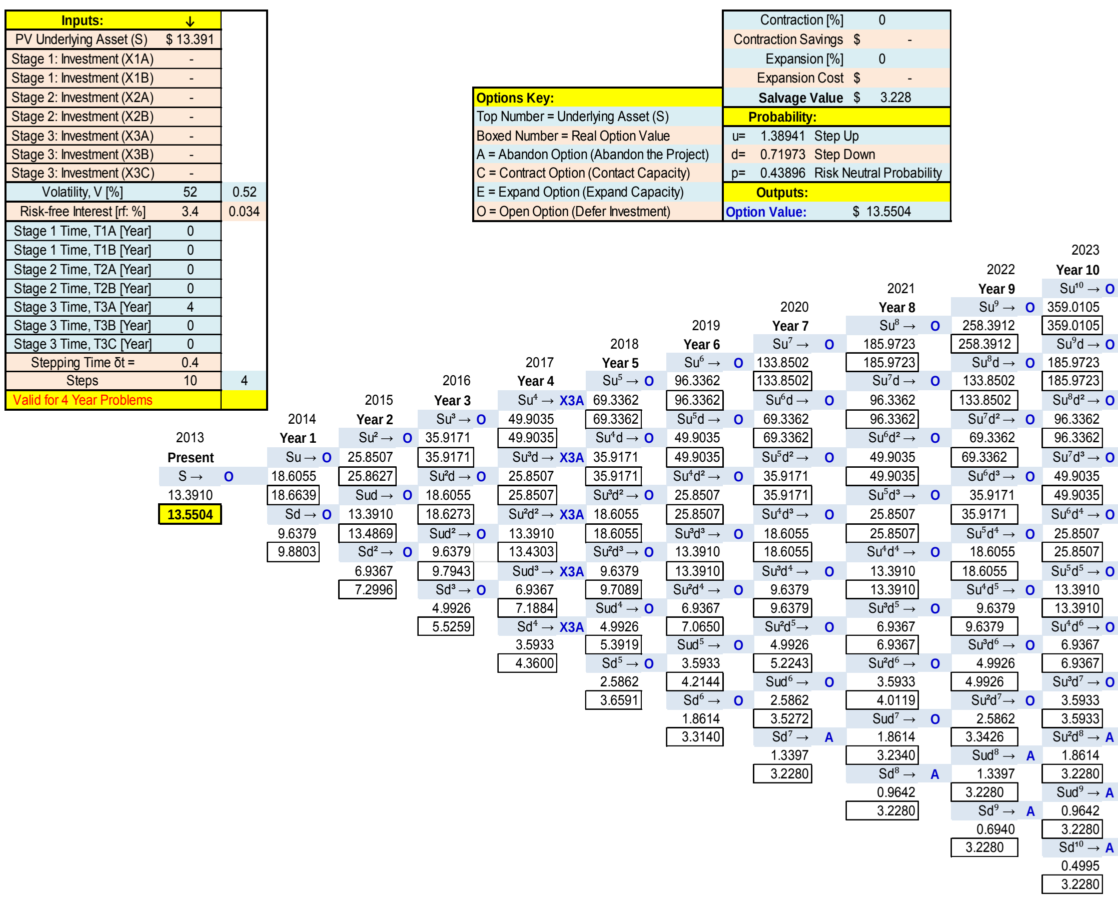

Figure 31. Abandon option value for an American production fab at T_{3A}.

Figure 32 illustrates the binomial lattice model that emulates a compound European put option for the European 450mm wafer fab project. This lattice utilizes the Q11 salvage value of €3.152 billion in case the development of the process recipe fails after 4-years. If the development of the process recipe is successful, the abandon option most likely will not be exercised and the option value will be €8.6128 billion.

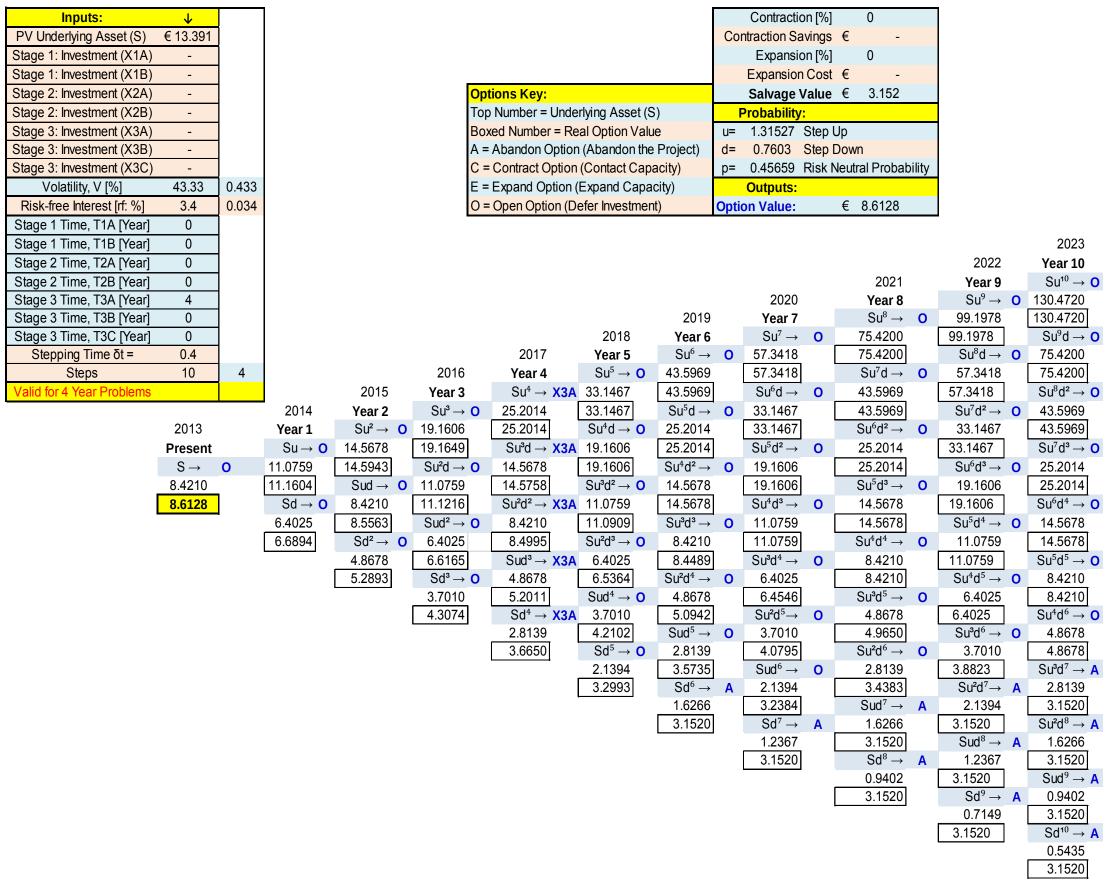

Figure 32. Abandon option value for a European production fab at T_{3A}.

Table 20 shows similar option values for the closed-form constructs and the binomial lattices. The real option values were added to the static NPV to obtain the total

NPV. For the American fab, the static NPV of $3.1717 billion was added to the real option closed-form NPV of $13.5690 billion to produce $16.7407 billion as illustrated in Table 21. For the European fab, the static NPV of minus €0.5883 billion was added to the closed-form real option NPV of €8.6095 billion to yield €8.0212 billion. Based on an exchange rate of $1.3487 per euro, the total NPV was $10.8182 billion.

Table 21 shows the hypothesis test results for two population means. The results revealed a *p* value of 0.0000. For 95% confidence, α was set to 0.05. Since $p < \alpha$, this indicated that the null hypothesis was rejected for both constructs. Finally, the OCC analysis indicated the probability of the null hypothesis type I error was 0.00%.

Table 21

Option to Abandon: Hypothesis Test for Two Population Means

	Mean NPV	Standard Deviation	Sample Size
American Fab CF	16.7407	2.177	46
American Fab BL	16.7217	2.177	46
European Fab CF	10.8182	2.471	46
European Fab BL	10.8226	2.471	46
Test Statistic Z CF		12.1974	
Test Statistic Z BL		12.1492	
95% Confidence Interval CF	[4.9708, 6.8742]		
95% Confidence Interval BL	[4.9474, 6.8508]		
p value CF and BL	0.0000, 0.0000		

Note. CF: Closed-form, BL: Binomial Lattice, Values listed are in $ billion
H_0: $\mu_1 \leq \mu_2$, $\alpha = 0.05$ (upper-tail)

Inferential models were created with multiple regressions to make option value predictions and to support the RQ4 hypotheses. Appendix F shows the regression models that were developed from the closed-form call on a put option. In addition, the option values obtained from the binomial lattice were based on the European put option. Diagnostic checking of the model involved the creation of residual plots to validate the normality assumption. Reliability performance parameters for the inference model are shown in Appendix G. A high *F* ratio indicated the inference model was significant. A check of the VIF value revealed that multicollinearity was not a problem. The 95% predictive interval ranged from $13.3129 billion to $13.7879 billion. A second inferential model was constructed to forecast insurance premiums, as illustrated in Appendix F. The reliability performance parameters listed in Appendix G exemplifies the inference model as being accurate. A check of the VIF value suggested multicollinearity was not a problem. The 95% predictive interval ranged from zero dollars to $425.544 million.

Construction of the European fab inference model began with a regression of the abandon option values as presented in Appendix F. The modeling performance parameters listed in Appendix G verify that the model was significant. A check of the VIF parameter points out that multicollinearity was not a problem. The 95% predictive interval ranged from €8.3907 billion to €8.8349 billion. A second inferential model was developed to predict insurance premiums for the European fab, as presented in Appendix F. The modeling performance parameters in Appendix G revealed the model was significant and multicollinearity was not a problem. The 95% confidence interval ranged from zero euros to €417.605 million.

The real option values listed in Table 22 supported hypothesis testing. A comparison of option values shows American 450mm wafer foundries could yield greater NPV values. Insurance premiums are also listed. Larger insurance premiums ensure higher salvage values in case the 450mm wafer foundry project fails. Respondents answering question Q11 forecasted a salvage value of $3.228 billion for the American foundry and $4.2511 billion for a European foundry. For American wafer fabs, the option NPV of $13.5504 billion plus the static NPV of $3.1717 billion will produce a total NPV of $16.7221 billion. For European wafer fabs, the option NPV of €8.6128 billion plus the static NPV of (€0.5883) billion yields a total NPV of €8.0245, or $10.8226 billion.

Table 22

Predictions to Abandon American and European 450mm Fab Projects

	American 450mm Wafer Fab		European 450mm Wafer Fab			
Insurance	Salvage Value	Option Value	Salvage Value		Option Value	
[$ Million]	[$ Billion]	[$ Billion]	[€ Billion]	[$ Billion]	[€ Billion]	[$ Billion]
100.00	2.8649	13.4742	2.6498	3.5738	8.4963	11.4590
178.04	3.2280	13.5504	2.9158	3.9325	8.5550	11.5381
200.00	3.3240	13.5724	2.9859	4.0271	8.5716	11.5605
254.30	3.5514	13.6279	3.1520	4.2511	8.6128	11.6161
300.00	3.7334	13.6744	3.2847	4.4301	8.6476	11.6630
400.00	4.1066	13.7820	3.5563	4.7964	8.7242	11.7663
500.00	4.4516	13.8913	3.8070	5.1345	8.8012	11.8702

Note. American fab inputs: S = 13.391 Bil, T_3 = 4y, r = 3.4%, and σ = 52%
European fab inputs: S = 8.421 Bil, T_3 = 4y, r = 3.4%, and σ = 43.33%, 1 euro = $1.3487

Research Question 5

Research questions RQ5 through RQ7 investigated optimal performance, sensitivity, and the option value impact for the American and European wafer foundries. Black-Scholes Equations 1 through 5 for the European call option and Equations 18 to 23 for the Greek sensitivity parameters were applied to analyze optimal performance. The dependent variables were analyzed using response surface methods (RSM). Predictive models were developed by varying one or two independent variables while other independent variables were held constant for each of the 46 runs.

The RSM process began with the construction of a Box-Behnken design (BBD) based on five independent Black-Scholes variables (S, X, T, σ, and r). Over 46 runs, the five variables were varied based on a combination of minimum, median, and maximum levels. For each combination, a Black-Scholes calculator was developed as described in Chapter 3 and was used to calculate the dependent variables: the option's call (C) value, put (P) value, delta (Δ), vega (ν), theta (θ), gamma (Γ), and rho (ρ). See Appendix E. Reliability of the RSM methods was verified by developing the BBD twice using Minitab 16 and Stat Ease Design Expert 8 software. The RSM results were compared and were found to be nearly identical. Residual plots were created to check the normality assumption. The purpose of research question RQ5 was to investigate delta (Δ) which is the first derivative ($\delta C/\delta S$). Delta is the sensitivity or rate of change for the European call (C) option value and the corresponding changes to the project's present value of future cash flows (S).

Figure 33 presents residual plots for the delta sensitivity parameter for an American 450mm wafer fab. Investigation for errors provided a rectification step to eliminate errors before continuing the RSM process with Minitab 16 and Design Expert. The residual plots illustrate that the Black-Scholes calculations for the dependent variable delta were free of errors. A review of the data points within the standardized residual plot show a straight line without significant outliers. The residual plots and histogram suggested a well-defined Gaussian distribution that validated the normality assumption. These qualities suggested that accurate generalizations could be made.

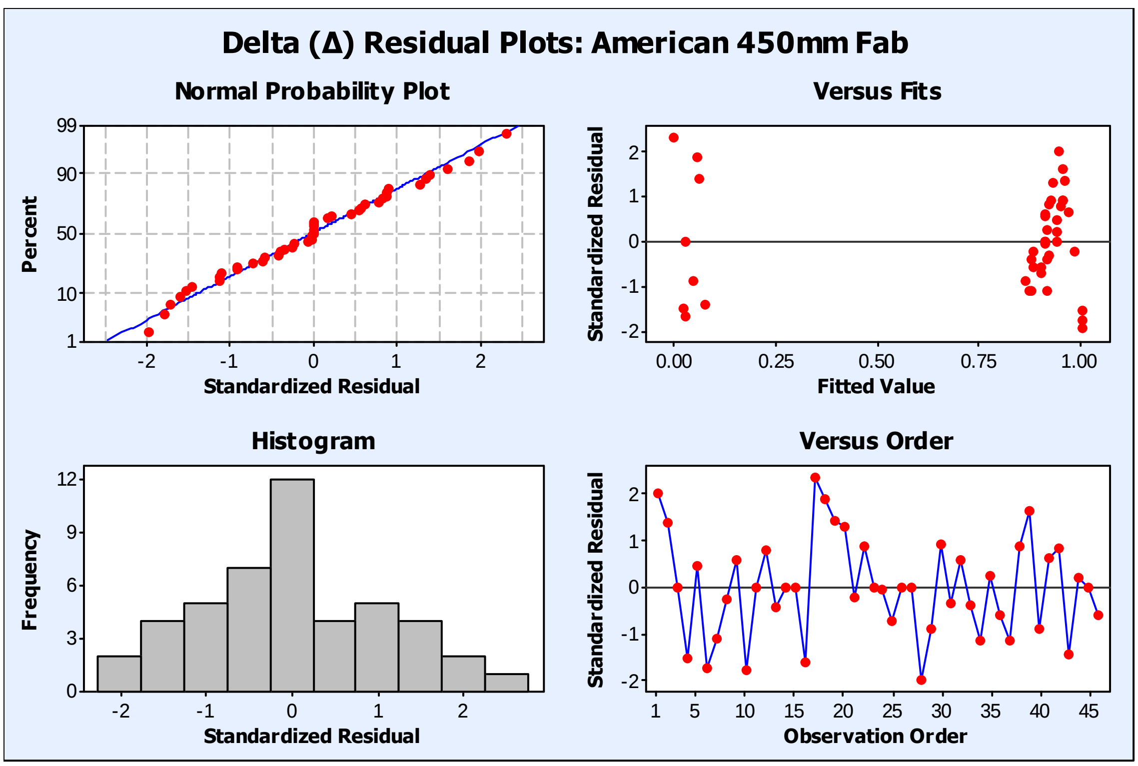

Figure 33. Delta residual plots for an American 450mm wafer fab.

Figure 34 illustrates normality with a straight line within the normal probability plot. The general shape depicted in the histogram exemplified an acceptable Gaussian distribution. Note the Box Behnken design utilized 46 runs.

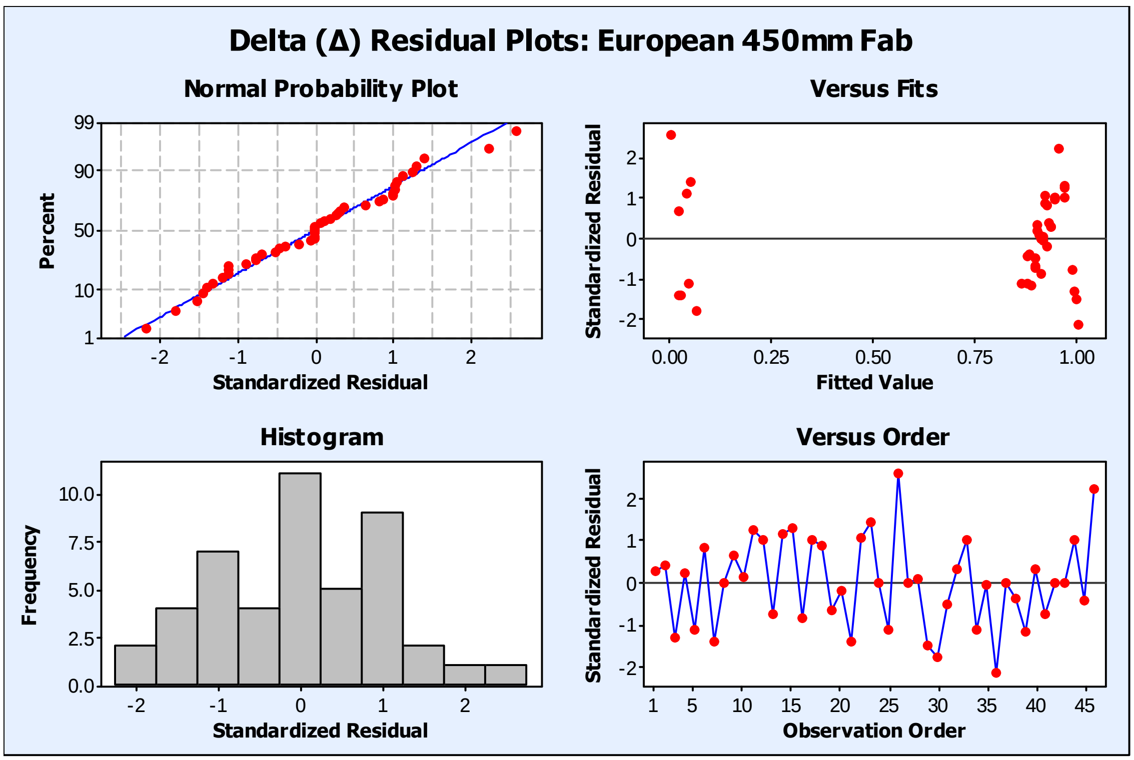

Figure 34. Delta residual plots for a European 450mm wafer fab.

Table 23 shows the relationship between delta (Δ) and the five independent Black-Scholes parameters for an American 450mm wafer fab. The correlation matrix shows the largest effect was the relationship between the call value *C* and the underlying asset *S,* which is the present value of all future cash flows. This correlation effect occurred since delta is the first derivative ($\delta C/\delta S$), which describes the rates of change between the option call value *C* and the present value of all future cash flows *S*.

Table 23

Correlation Matrix of Delta for an American 450mm Wafer Fab

	Δ	C	S	X	T	σ
C	.724*					
S	.818*	.983*				
X	-.062	-.089	.000			
T	-.003	.036	.000	.000		
σ	-.011	.024	.000	.000	.000	
r	.014	.019	.000	.000	.000	.000

Note. * $p < .0001$

The correlation matrix illustrates that the independent Black-Scholes variable *S* with respect to delta was significant. Moreover, the following independent variables such as the strike price *X*, or total investment in the project, the project lifetime *T*, volatility of cash flows with respect to the project lifetime σ, and the risk-free interest rate *r* were not significant.

Table 24 shows the relationship between delta (Δ) and the five independent Black-Scholes parameters for the European 450mm wafer fab. The correlation matrix shows the largest effect is the relationship between the call value *C* or the option value and the underlying asset *S*. The correlation matrix also illustrates the relationship between the following independent variables: *X*, *T*, σ, and *r* were not significant.

Table 24

Correlation Matrix of Delta for a European 450mm Wafer Fab

	Δ	C	S	X	T	σ
C	.724*					
S	.822*	.984*				
X	-.051	-.071	.000			
T	-.000	.031	.000	.000		
σ	-.006	.013	.000	.000	.000	
r	.020	.028	.000	.000	.000	.000

Note. * $p < .0001$

The contour plot illustrated in Figure 35 shows the dynamic interaction between the independent variables (*S*) and (*X*) and how they influenced the delta response. The optimal location for the delta mean is 0.9133 for American 450mm wafer fabs. The parabolic curves indicate that the inferential model utilized quadratic terms as presented in Appendix F.

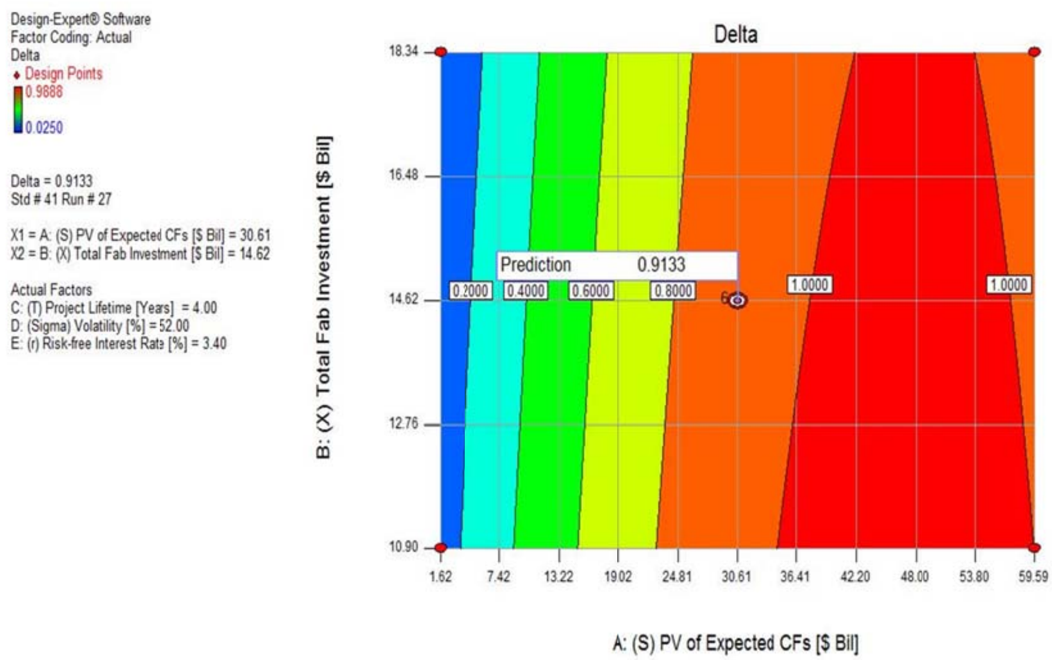

Figure 35. Delta response with factor effects (*X*) and (*S*) for an American fab.

Figure 36 illustrates the independent variables (*S*) and (*X*) and their effect on the dependent variable delta. The optimal location of the delta mean was found to be 0.9132 for a European 450mm wafer fab. According to Passarelli (2012), the delta rule of thumb approximates the probability that the project will likely be profitable; in other words, there is a 91.32% chance that the real option expires “in the money” (p. 28).

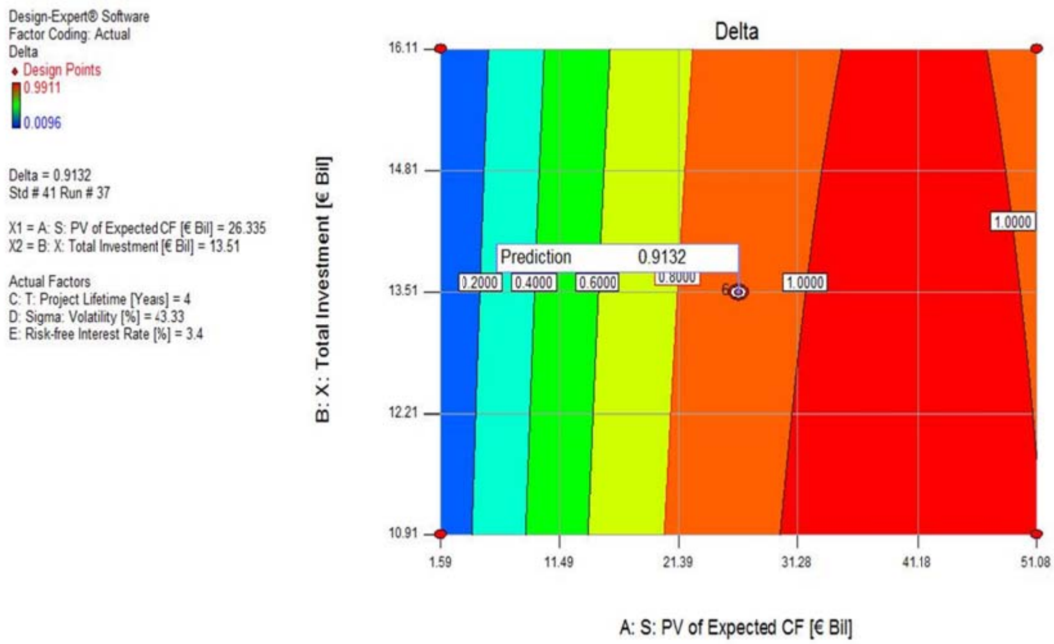

Figure 36. Delta response with factor effects (*X*) and (*S*) for a European fab.

The three-dimensional plot shown in Figure 37 illustrates the independent variables (*S*) and (*X*) and their effect on the dependent variable delta for an American 450mm wafer fab. The optimal delta location occurred at 0.9133. This curve suggested a 91.33% probability that the American wafer fab project will likely become profitable while operating at full-production capacity. These probabilities appear reasonable and are in line with the responses obtained from the survey. Americans answering questions Q17 and Q18 estimated the chance of success to ramp up production was 77.83% by 2019. American participants answering questions Q9 and Q10 anticipated the chance of success to develop a process recipe was 74.35% by 2017.

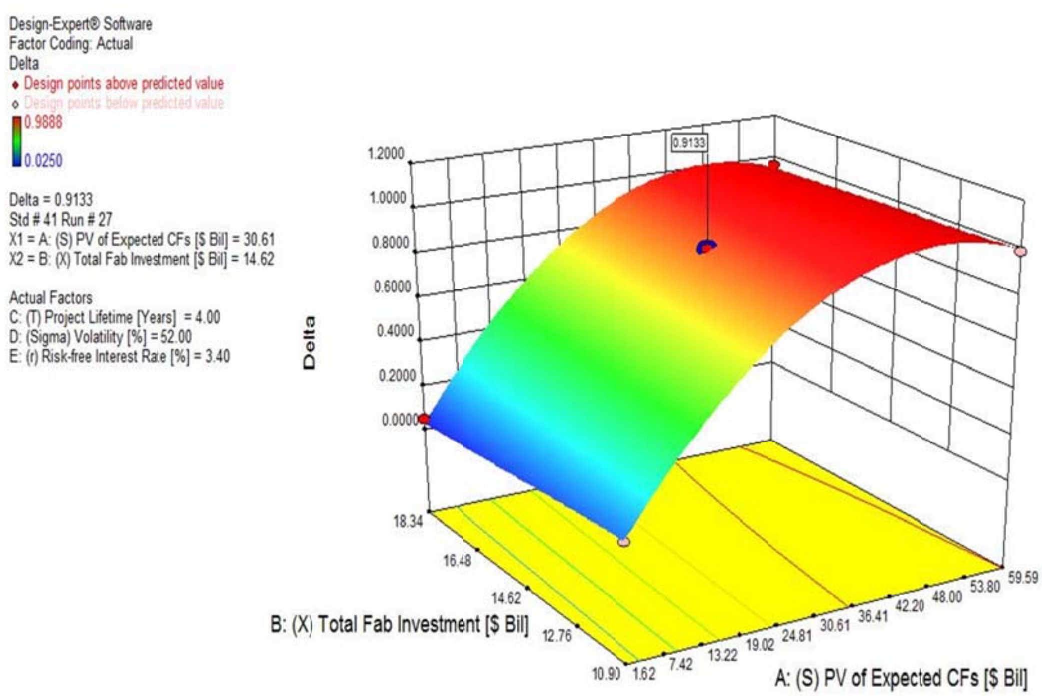

Figure 37. 3D Delta response with factor effects (*X*) and (*S*) for an American fab.

Figure 38 illustrates the independent variables (*S*) and (*X*) and their effect on delta for European foundries. The optimal location for delta occurs at 0.9132. The delta surface plot suggested a 91.32% chance that commercial European 450mm wafer foundries will be profitable while operating at full production capacity. Based on the survey results from the Europeans answering questions Q17 and Q18, there is a 76.74% probability to successfully ramp up production capacity by 2019. Based on the answers to Q9 and Q10, there is a 73.91% chance of success to develop a 450mm process recipe by 2017.

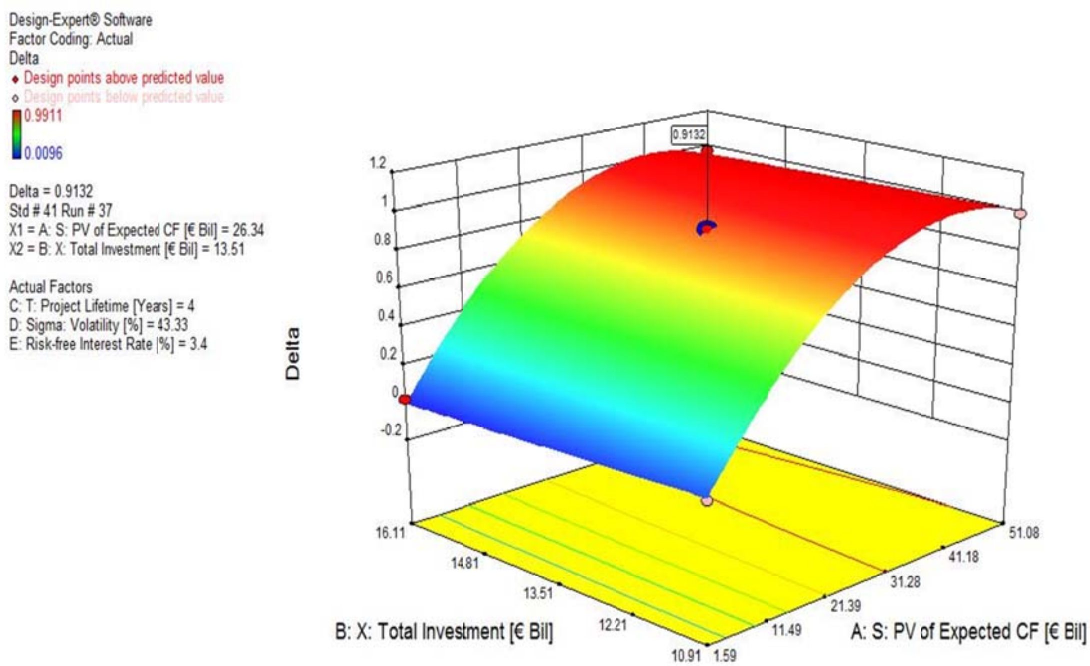

Figure 38. 3D Delta response with factor effects (*X*) and (*S*) for a European fab.

Table 25 shows the paired-difference hypothesis test results for the American and European foundries with n = 46 samples. The Z test statistic and confidence interval are also shown. Hypothesis testing was performed with 95% confidence with α set to 0.05. The hypothesis test yielded a *p* value of 0.4851. Since this *p* value was greater than α, the test indicated that the null hypothesis could not be rejected. In other words, the delta sensitivity parameter for the American wafer fab was not significantly different in comparison to delta for the European wafer foundry. The OCC analysis revealed the probability to reject the null hypothesis with a type II error was approximately 5%.

Table 25

Delta Parameter: Hypothesis Test for Two Population Means

	Mean	Standard Deviation	Sample Size
American 450mm Fab	0.9133	0.0148	46
European 450mm Fab	0.9132	0.0106	46
Test Statistic *Z*	0.0373		
95% Confidence Interval	[-0.0052, 0.0054]		
p value	0.4851		

Note. H_0: $\mu_1 \leq \mu_2$, $\alpha = 0.05$ (upper-tail)

Figure 39 exemplifies a power curve created for each hypothesis test. This power curve supported hypothesis testing for RQ5. Based on a sample size of $n = 46$ with a 95% confidence level, the low power of 0.06898 signified the null hypothesis could not be rejected. The difference of 0.0001 was calculated by subtracting the European wafer fab delta of 0.9132 from the American fab delta of 0.9133. The standard deviation difference of 0.004138 was calculated by subtracting the standard deviation delta of 0.0106135 for European wafer fab from the standard deviation delta of 0.014751 for the American fab.

The alternative hypothesis was set to greater than and the red dot indicated the power position on the power curve.

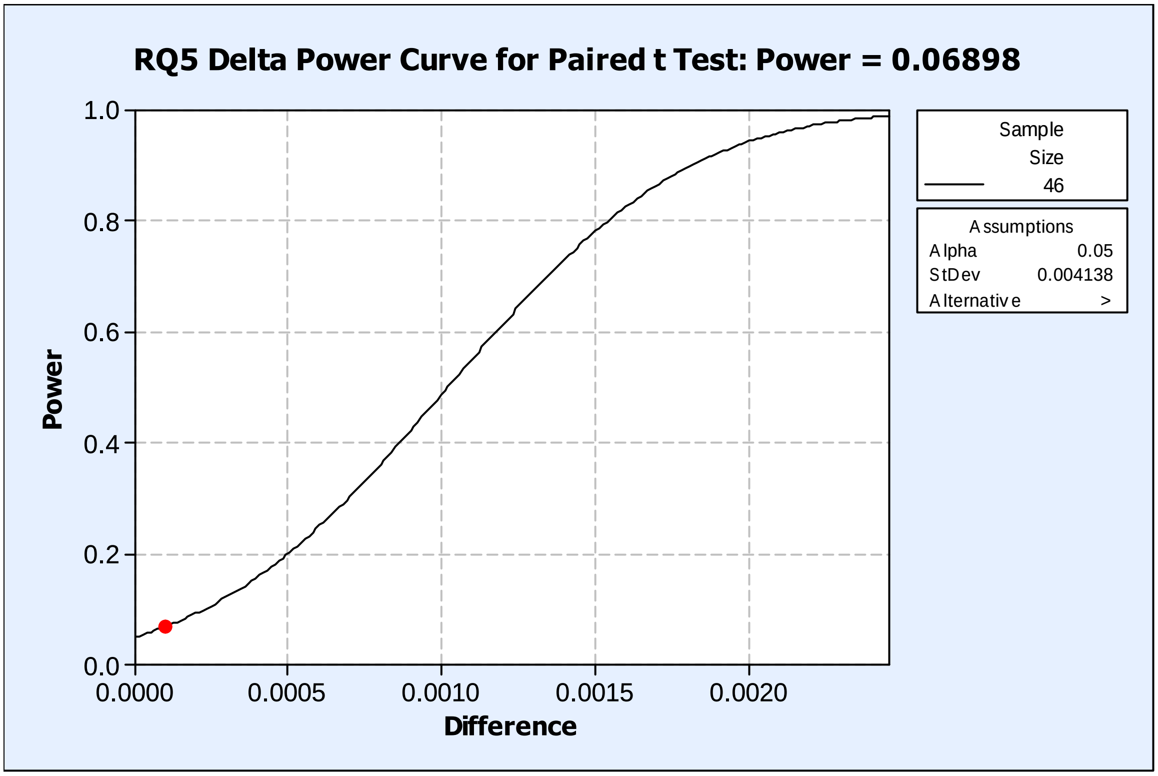

Figure 39. Power curve for the delta parameter using a paired *t* test.

Inferential models were developed to make revenue predictions to improve internal validity. Two regression models were created as illustrated in Appendix F. Performance parameters for the American wafer fab model were reviewed as presented in Appendix G. A check of the *F* ratio showed the model was significant and the VIF parameter revealed multicollinearity was not a problem. The 95% predictive interval ranged from 0.8805 to 0.9461. Reliability of the inferential model was checked by setting the predictor variables to: $S = 30.6095$, $X = 14.62$, $T = 4$, $\sigma = 52$, and $r = 3.4$. The model predicted a delta value of 0.9133; this same value was presented in Table 25.

A second inferential model was built for the European foundry, as shown in Appendix F. The modeling performance parameters listed in Appendix G show the model was significant and multicollinearity was not an issue. The 95% prediction interval ranged from 0.8896 to 0.9368. To investigate the model's ability to make inferences, the following inputs were set to: $S = 26.34$, $X = 13.51$, $T = 4$, $\sigma = 43.33$, and $r = 3.4$ and the model yielded a delta of 0.9132.

The inferential models created in Excel were linked to the underlying asset value (S) spreadsheets, as shown in Figures 23 and 24, to calculate annual revenue for a particular delta. A what-if analysis was performed with the Excel goal seek function to examine changes in annual revenue and the underlying asset value with respect to delta as listed in Table 26. For the American and European foundries, the predicted annual revenues of \$7.5359 billion and \$9.0660 billion were obtained. The underlying asset value of \$30.6097 billion was forecasted for American wafer fabs and \$35.5144 billion was forecasted for European wafer fabs.

Table 26

Delta Predictions for Annual Revenue and Asset Value

	American 450mm Wafer Fab		European 450mm Wafer Fab			
Delta	Annual Revenue	Asset Value (S)	Annual Revenue		Asset Value (S)	
	[$ Billion]	[$ Billion]	[€ Billion]	[$ Billion]	[€ Billion]	[$ Billion]
0.8900	7.2399	29.1683	6.4805	8.7403	25.1702	33.9470
0.9000	7.3635	29.7702	6.5824	8.8777	25.6605	34.6083
0.9132	7.5350	30.6053	6.7220	9.0660	26.3323	35.5144
0.9133	7.5359	30.6097	6.7240	9.0687	26.3420	35.5275
0.9200	7.6254	31.0455	6.7976	9.1679	26.6961	36.0050

Note. NA: not applicable; exchange rate: one euro = $1.3487, discount rate = 20%
Median operations cost: $1.25 billion American fab and €1.25 billion European fab

Two additional multiple regression models were developed for both wafer foundries as illustrated by Appendix F to investigate the significance of delta in terms of call value and the total NPV value. Construction of the regression models began by examining the normal plot of residuals and other parameters. Appendix G presents the modeling performance parameters. A high F ratio showed the model was significant and multicollinearity was not an issue. The 95% predictive interval ranged from $19.1706 billion to $20.7632 billion. Reliability of the inferential model to make predictions was checked by setting the predictor variables to: $S = 30.6095$, $X = 14.62$, $T = 4$, $\sigma = 52$, and $r = 3.4$. The American fab model found a call value of $19.9669 billion with a standard deviation of $0.3580 billion.

A similar model was developed for European wafer fabs, as shown in Appendix F. Modeling performance parameters are presented in Appendix G. These parameters indicated the model was significant and multicollinearity was not an issue. The 95% predictive interval ranged from €15.3332 billion to €16.5154 billion. Reliability of this inferential model to make predictions was checked by setting the predictor variables to: $S = 26.3420$, $X = 13.51$, $T = 4$, $\sigma = 43.33$, and $r = 3.4$, and this yielded a call value of €15.9299 billion. Table 27 lists the call value and NPV forecast for a few deltas. It is important to note that the American wafer fab delta of 0.9133 produced a greater total NPV value of $23.1388 billion in comparison to $20.6808 billion for a European wafer fab with a delta of 0.9132. This table accounts for the static NPV combined with a real option NPV to yield a larger NPV for American 450mm wafer fabs in comparison to European wafer fabs.

Table 27

Delta Predictions for Call Value and Total NPV

	American 450mm Wafer Fab		European 450mm Wafer Fab			
Delta	Call Value (C)	Total NPV	Call Value (C)		Total NPV	
	[$ Billion]	[$ Billion]	[€ Billion]	[$ Billion]	[€ Billion]	[$ Billion]
0.9000	19.2806	22.4523	15.3868	20.7522	14.7985	19.9587
0.9132	19.9635	23.1352	15.9222	21.4743	15.3339	20.6808
0.9133	19.9671	23.1388	15.9299	21.4847	15.3416	20.6912
0.9200	20.3260	23.4977	16.2145	21.8685	15.6262	21.0751

Note. NA: not applicable; exchange rate: one euro = $1.3487, discount rate = 20%
Median operations cost: $1.25 billion American fab and €1.25 billion European fab

Research Question 6

Research question RQ6 began as an investigation of the dependent variable vega with a review of residual plots, contour plots, three-dimensional plots, and hypothesis testing of two independent data pairs. The residual plots in Figure 40 illustrated a normal distribution; this validated the normality assumption for the American 450mm wafer fab, which indicated that valid inferences can be made.

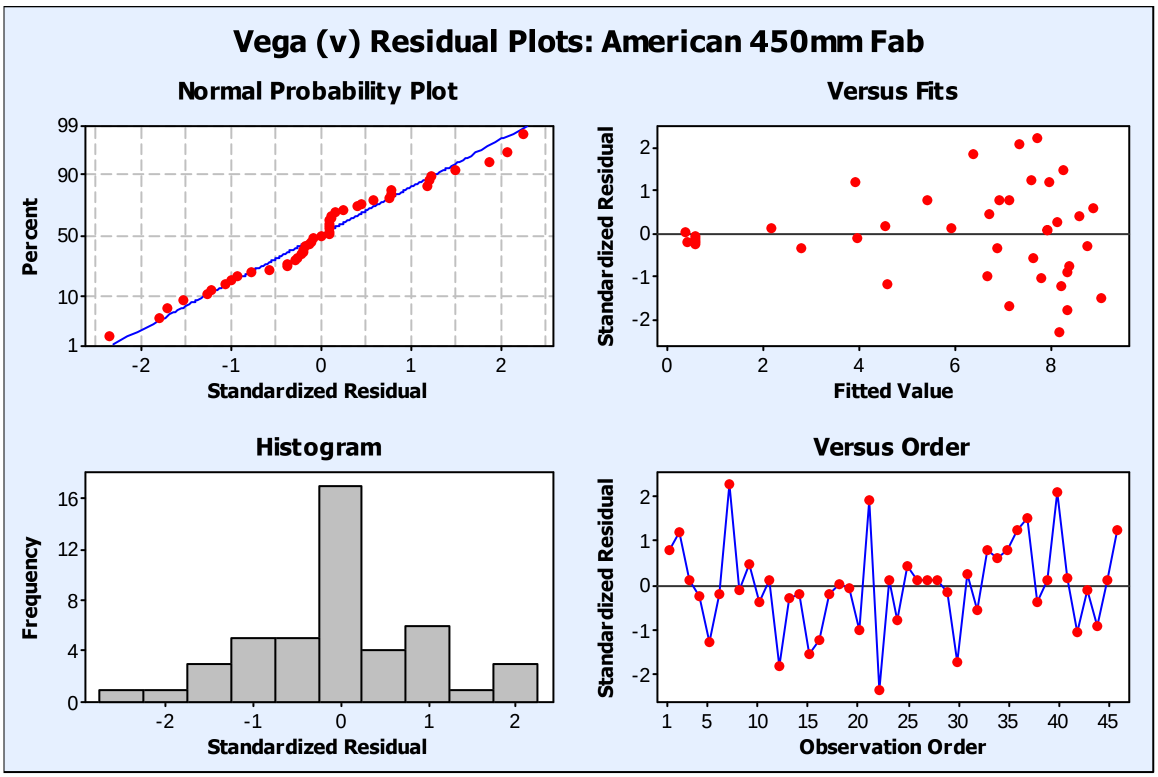

Figure 40. Vega residual plots for an American 450mm wafer fab.

Figure 41 illustrates a normal distribution for the dependent variable vega which is the first derivative or the rate of change for call value with respect to the implied project volatility. The histogram and normal probability plot for the European 450mm wafer fab shows a normal distribution with a symmetrical peak.

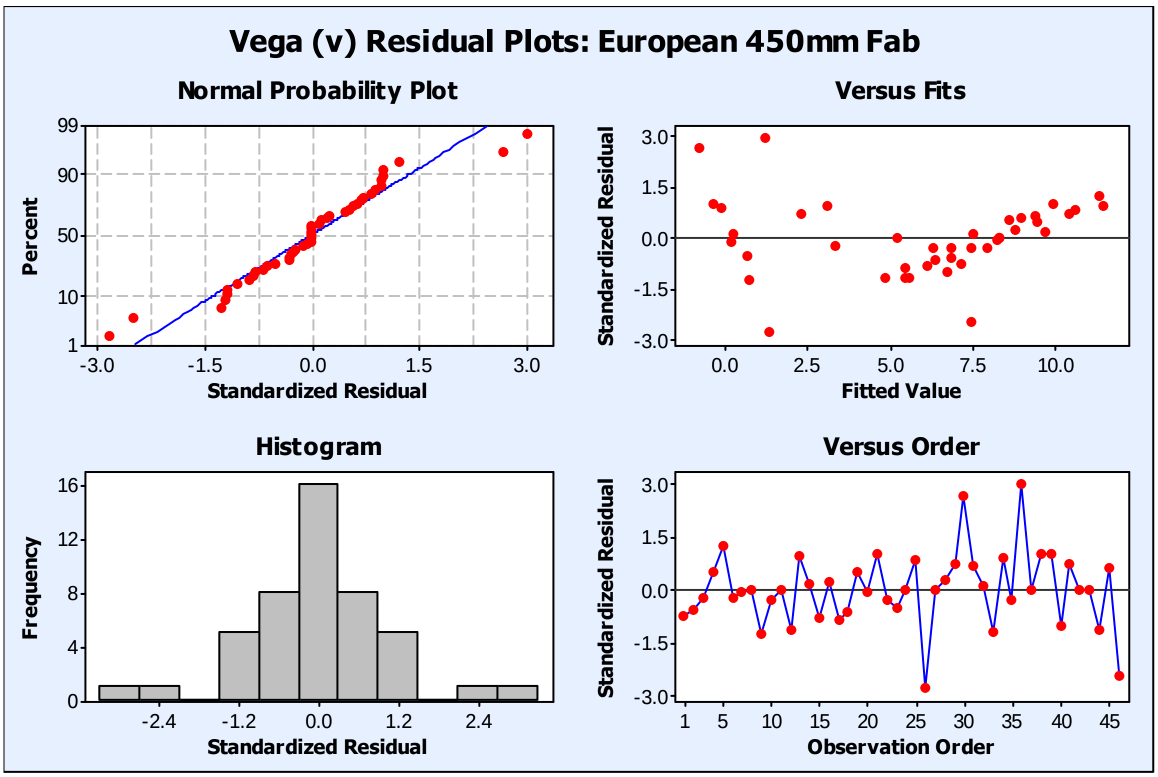

Figure 41. Vega residual plots for a European 450mm wafer fab.

An analysis of variance (ANOVA) presented in Table 28 summarizes the vega response and the modeling variation between the five Black-Scholes factors for the American 450mm fab. Similar ANOVA tables were created for each model using response surface methods. During the model development, the ANOVA revealed that quadratic factors were significant in comparison to linear and cubic factors. The ANOVA analysis indicated the most significant effects were from the underlying asset value (*S*) followed by the total fab investment (*X*).

Table 28

ANOVA Vega Summary for an American 450mm Wafer Foundry

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F_0	*p* value
Model	703.15	20	35.16	83.82	0.0001
(S) PV of Expected CF	138.98	1	138.98	331.34	0.0001
(X) Tot Fab Investment	120.93	1	120.93	288.30	0.0001
(T) Project Lifetime	25.36	1	25.36	60.47	0.0001
(σ) Volatility	11.46	1	11.46	27.32	0.0001
(r) Risk-free Interest Rate	10.73	1	10.73	25.58	0.0001
Quadratic Interactions	344.69	15			
Residual	10.49	5	0.42		
Total	713.64	45			

The contour plot illustrated in Figure 42 shows the dynamic variation from the independent variables, the total fab investment (*X*), and the present value of the expected cash flows (*S*) and their effect on the dependent variable vega. For an American 450mm wafer fab, the optimal vega response of 9.6697 was centrally located within the set of parabolic curves.

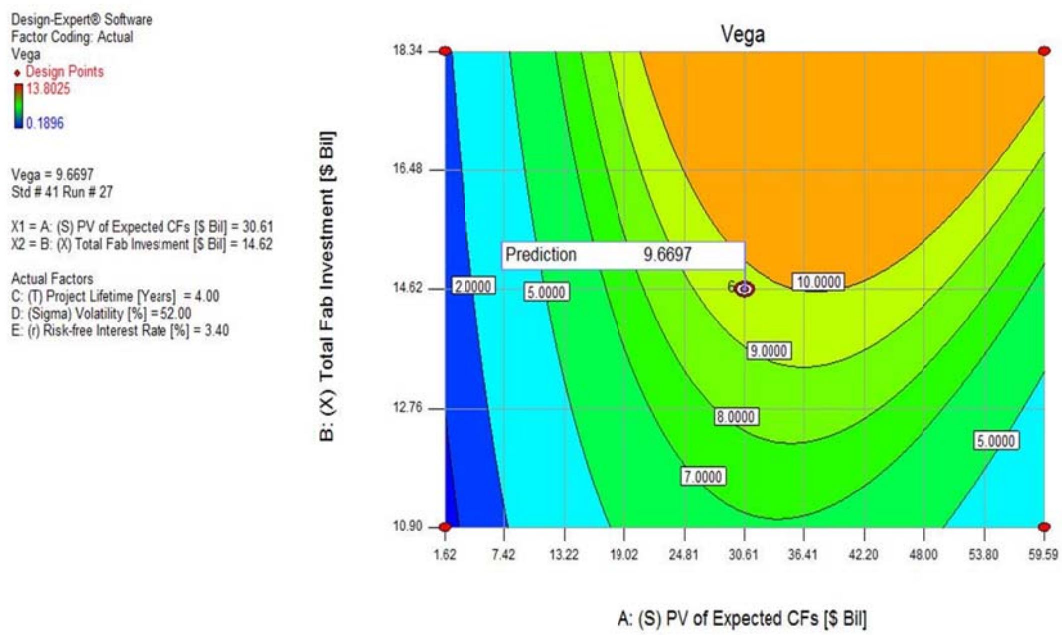

Figure 42. Vega response with factor effects (*X*) and (*S*) for an American fab.

Figure 43 shows the independent variables, the total fab investment (*X*), and the present value of the expected cash flows (*S*) and their effect on the dependent variable vega. The center of the contour plot revealed an optimal vega mean of 8.3277 for the European 450mm wafer foundry.

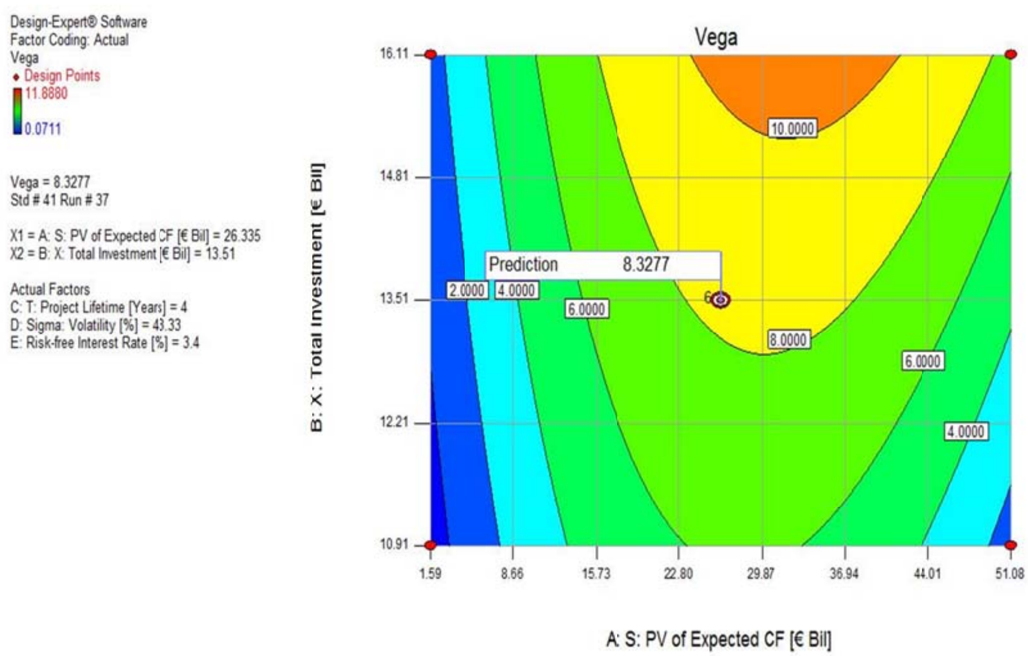

Figure 43. Vega response with factor effects (*X*) and (*S*) for a European fab.

The three-dimensional plot illustrated in Figure 44 shows the dynamics of the two independent variables, the total fab investment (*X*), and the present value of the expected cash flows (*S*) and how they affect the dependent variable vega. The flag marker at the center of the rising ridge shows the optimal vega mean at 9.6697 for the American 450mm wafer fab.

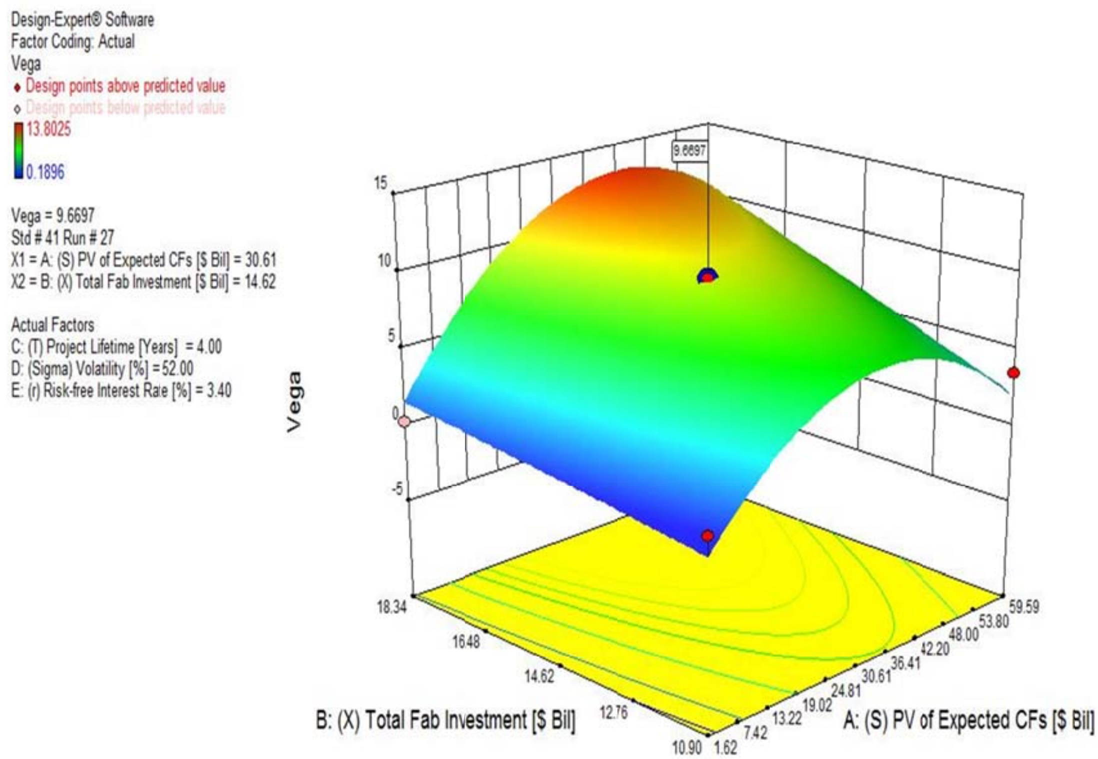

Figure 44. 3D Vega response with factor effects (*X*) and (*S*) for an American fab.

Figure 45 shows the dynamics of the independent variables, the total fab investment (*X*), and the present value of the expected cash flows (*S*) and their effect on vega. The difference between the previous response surface plot and this one is a steeper rising ridge as indicated by the vega flag marker positioned at 8.3277 for the European wafer foundry.

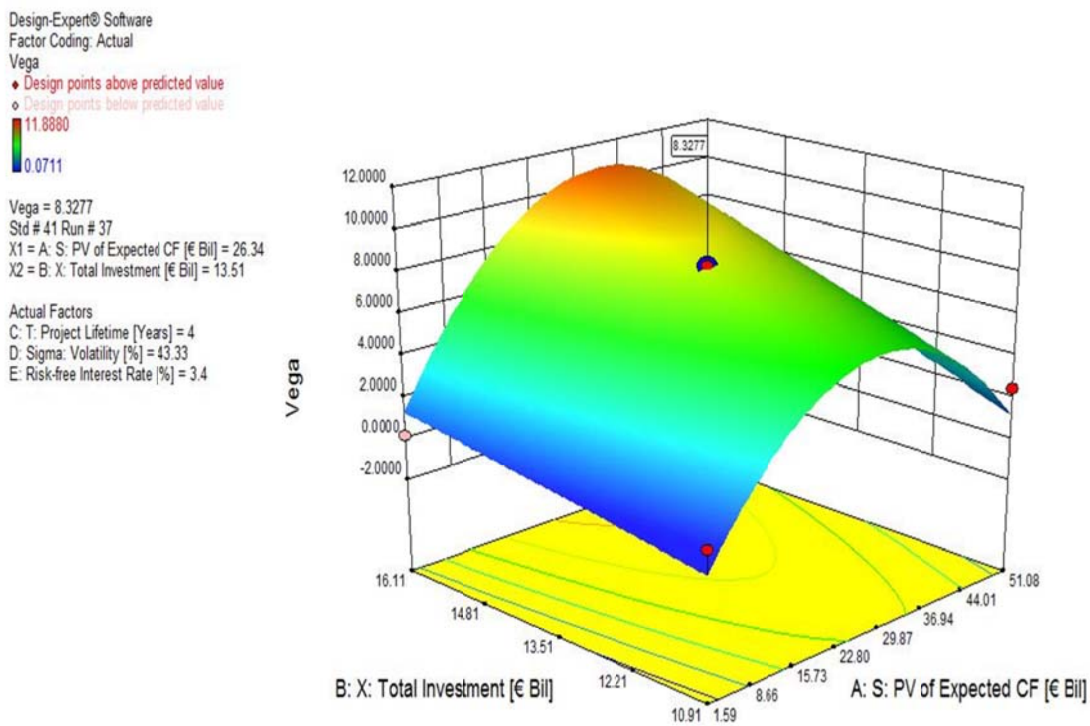

Figure 45. 3D Vega response with factor effects (*X*) and (*S*) for a European fab.

Table 29 shows the vega mean, the standard deviation, the *Z* test statistic, the confidence interval, and the hypothesis test results with $n = 46$ samples for the American and European wafer foundries. Hypothesis testing showed the p value was less than α

(0.05). This test indicated the null hypothesis was rejected. The OCC analysis revealed the probability of making a type I error was 0.00%. In conclusion, the higher vega value for the American fab was due to the higher volatility of 52% for the American fab in comparison to 43.33% for the European fab.

Table 29

Vega Sensitivity Parameter: Hypothesis Test for Two Population Means

	Mean	Standard Deviation	Sample Size
American 450mm Fab	9.6697	0.6477	46
European 450mm Fab	8.3277	0.5909	46
Test Statistic Z	10.3815		
95% Confidence Interval	[1.0886, 1.5954]		
p value	0.0000		

Note. H_0: $\mu_1 \leq \mu_2$, $\alpha = 0.05$ (upper-tail)

Two inference models were constructed to forecast annual revenue and the underlying asset value (*S*) using a spreadsheet as illustrated in Figures 23 and 24. Appendix F presents the two vega regression models. The modeling performance parameters for the American fab model suggested a good regression relationship as listed by Appendix G. A high *F* ratio showed the model was significant and multicollinearity was not a problem. The 95% predictive interval for vega ranged from 8.2290 to 11.1104. Reliability of the inferential model to make predictions was checked by setting the predictor variables to: $S = 30.6095$, $X = 14.62$, $T = 4$, $\sigma = 52$, and $r = 3.4$ to yield a vega of 9.6698, which was the same value as shown in the Table 29.

Modeling parameters for the European wafer fab model are presented in Appendix G. A high *F* ratio indicated the model was significant and the VIF value showed multicollinearity was not an issue. The 95% prediction interval for vega ranged from 7.0133 to 9.6421. Table 30 compares the annual revenue and the underlying asset value for several vega values. The vega forecast at 9.6697 for the American wafer fab predicted an annual revenue of $7.5358 billion with a $30.6092 billion underlying asset value. The vega forecast at 8.3277 for the European fab yielded an annual revenue of $9.0666 billion with an underlying asset value of $35.5176 billion. The Excel goal seek function could not calculate the high vega value at 9.6697 for the European wafer fab due to oscillations on both sides of the parabolic curve, as revealed in Figures 42 through 45.

Table 30

Vega Predictions for Annual Revenue and Asset Value

	American 450mm Wafer Fab		European 450mm Wafer Fab			
Vega	Annual Revenue	Asset Value (S)	Annual Revenue		Asset Value (S)	
	[$ Billion]	[$ Billion]	[€ Billion]	[$ Billion]	[€ Billion]	[$ Billion]
7.0000	4.7814	17.1964	5.0213	6.7722	18.1481	24.4765
7.5000	5.1434	18.9592	5.4935	7.4091	20.4204	27.5410
8.0000	5.5431	20.9056	6.1089	8.2391	23.3820	31.5353
8.3277	5.8331	22.3178	6.7225	9.0666	26.3347	35.5176
8.5000	5.9967	23.1144	7.6300	10.2906	30.7018	41.4075
9.6697	7.5358	30.6092	NA	NA	NA	NA

Note. NA: not applicable; exchange rate: one euro = $1.3487, discount rate = 20%
Median operations cost: $1.25 billion American fab and €1.25 billion European fab

To better understand the vega dynamics, the call value and the total NPV values were investigated with a second inference model. Appendix F shows the call value model. Table 31 presents the call values and the total NPV for both fabs. The total NPV value is the sum of the static NPV and the real option NPV. For the American wafer foundry, the total NPV is $23.1384 billion for a vega of 9.6697. For the European wafer foundry, the total NPV is €15.3358 billion, or $20.6834 billion for a vega of 8.3277.

Table 31

Vega Predictions for Call Value and Total NPV

	American 450mm Wafer Fab		European 450mm Wafer Fab			
Vega	Call Value (C)	Total NPV	Call Value (C)		Total NPV	
	[$ Billion]	[$ Billion]	[€ Billion]	[$ Billion]	[€ Billion]	[$ Billion]
7.0000	9.7741	12.9458	9.7919	13.2063	9.2036	12.4129
7.5000	11.0193	14.1910	11.4083	15.3864	10.8200	14.5929
8.0000	12.4274	15.5991	13.6138	18.3609	13.0255	17.5675
8.3277	13.4708	16.6425	15.9241	21.4768	15.3358	20.6834
8.5000	14.0675	17.2392	19.5448	26.3601	18.9565	25.5666
9.6697	19.9667	23.1384	NA	NA	NA	NA

Note. NA: not applicable; exchange rate: one euro = $1.3487, discount rate = 20%
Median operations cost: $1.25 billion American fab and €1.25 billion European fab

In summary, the total NPV of $23.1384 billion for an American wafer fab with a vega of 9.6697 is larger in comparison to the $20.6834 billion for a European wafer fab with a vega of 8.3277. The two predictions for call value and the total NPV support the RQ6 hypotheses. The model predicted the American 450mm wafer fabs will profitable with a greater total NPV when compared to next generation European fabs.

Research Question 7

Research question RQ7 compared the theta sensitivity parameter for the next generation American and European 450mm wafer foundries using response surface methods and hypothesis testing for two population means. RQ7 described the development of the inferential model and the predictions. For the American wafer fab, the theta in the Box Behnken design as illustrated in Figure 46 exemplified a normal distribution; therefore, the normality assumption was valid.

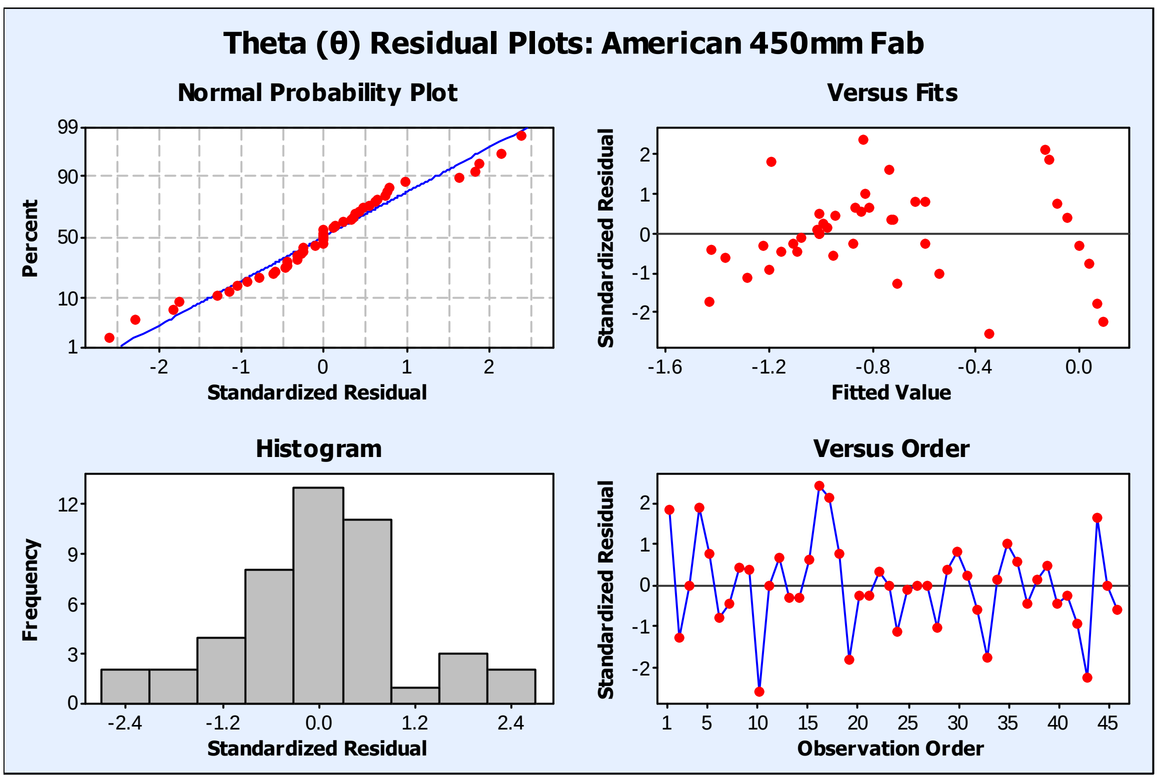

Figure 46. Theta residual plots for an American 450mm wafer fab.

The residual plot for theta in Figure 47 approximated a nearly normal distribution as depicted by the symmetrical theta response, the histogram, and the normal probability plots for European 450mm wafer fabs.

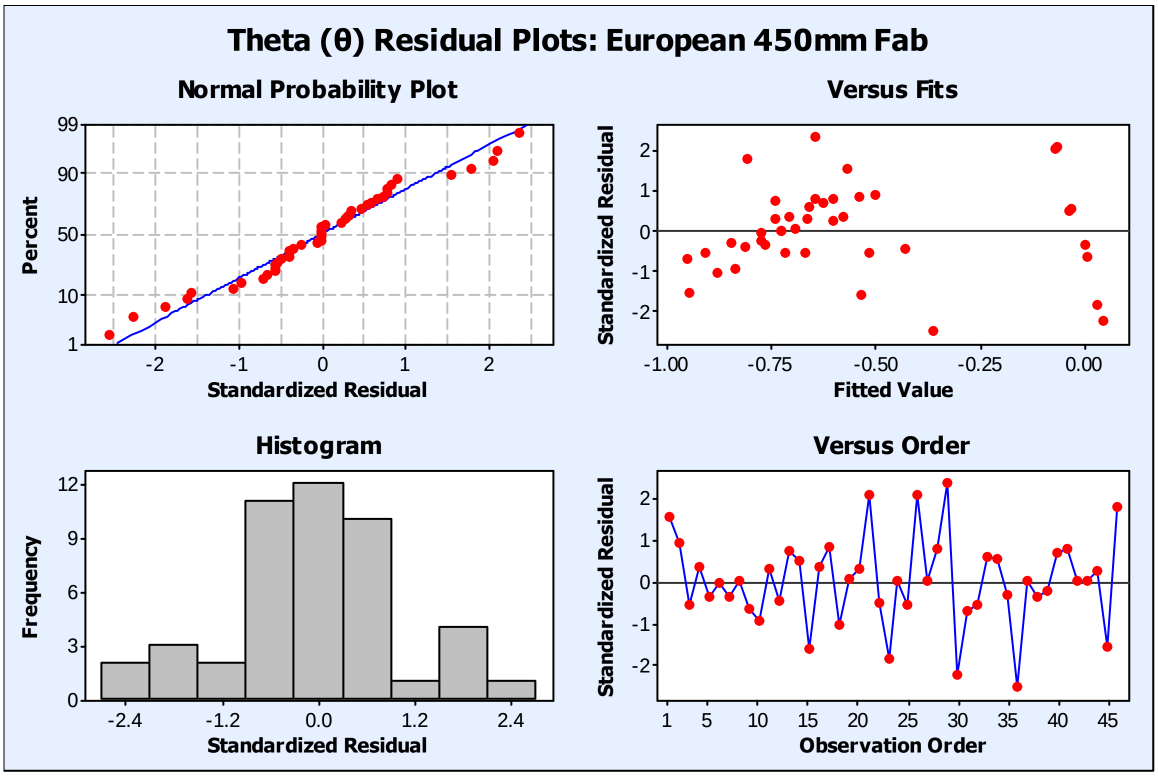

Figure 47. Theta residual plots for a European 450mm wafer fab.

Figure 48 depicts a contour plot with the theta mean of -0.9001 for American 450mm wafer fabs. This contour plot shows the theta response was dependent on two independent variables. These variables are the present value of the future cash flows (*S*) and the total investments (*X*) for the project.

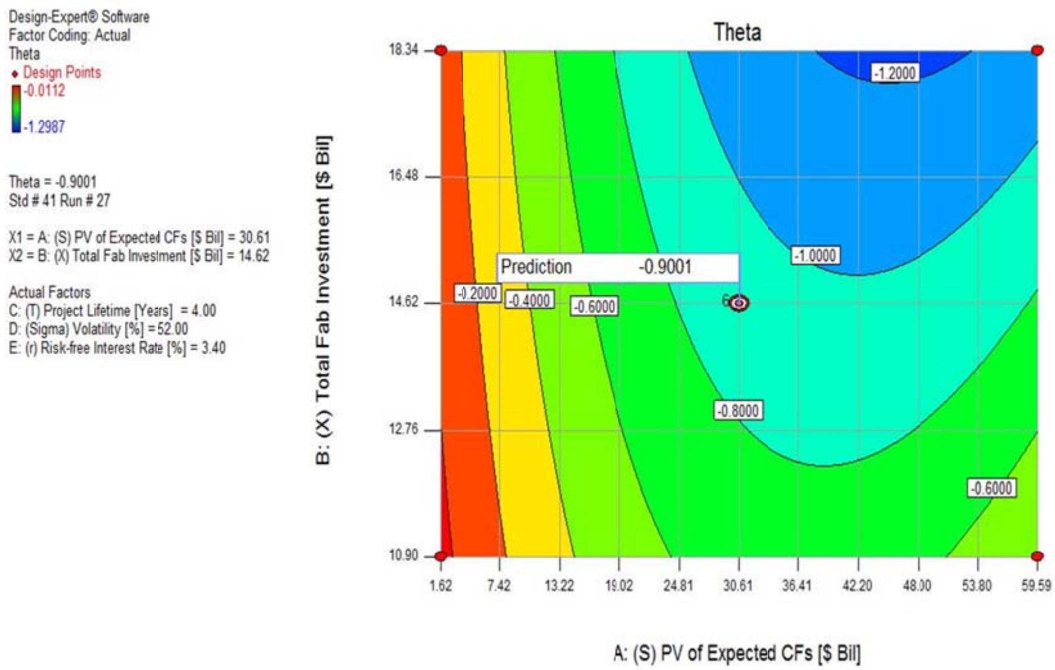

Figure 48. Theta response with factor effects (*X*) and (*S*) for an American fab.

Figure 49 shows a contour plot for an optimal theta of -0.7274 for the European 450mm wafer fabs. The two independent variables are the present value of the expected cash flows (*S*) and the total investments (*X*).

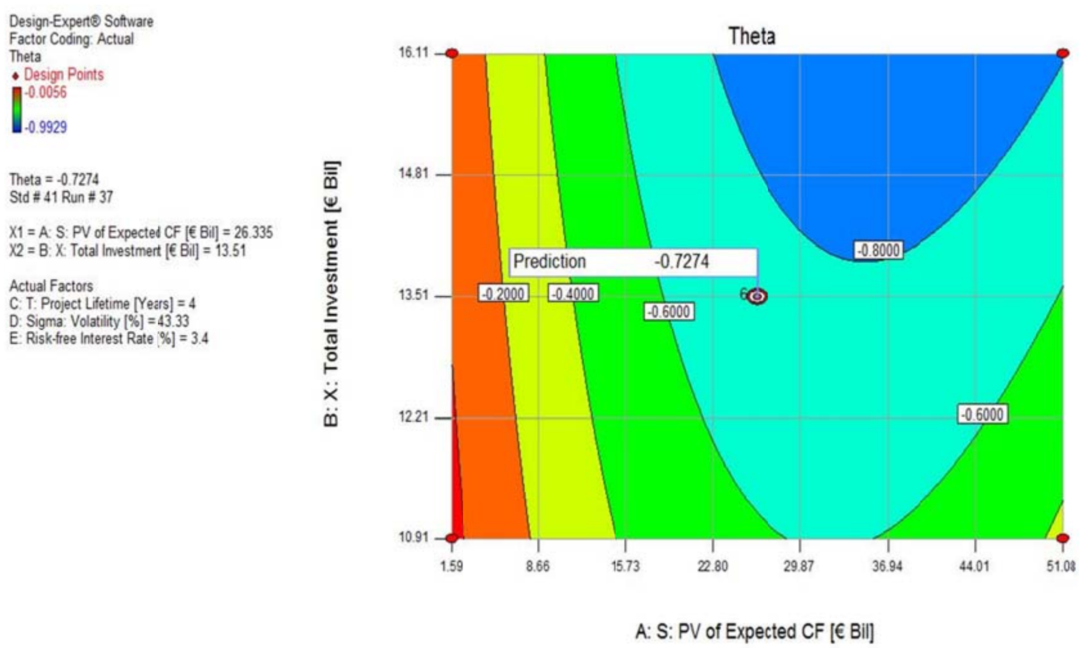

Figure 49. Theta response with factor effects (*X*) and (*S*) for a European fab.

The three-dimensional plot illustrated in Figure 50 shows the theta response from the following independent variables: the underlying asset value (*S*) and the total investment (*X*) for next generation American 450mm wafer fabs. Theta was located at the center of the response surface plot as indicated by the -0.9001 flag marker. As the present value of the expected cash flows increases, the theta value becomes more negative, as illustrated by the blue parabolic region at the lower right.

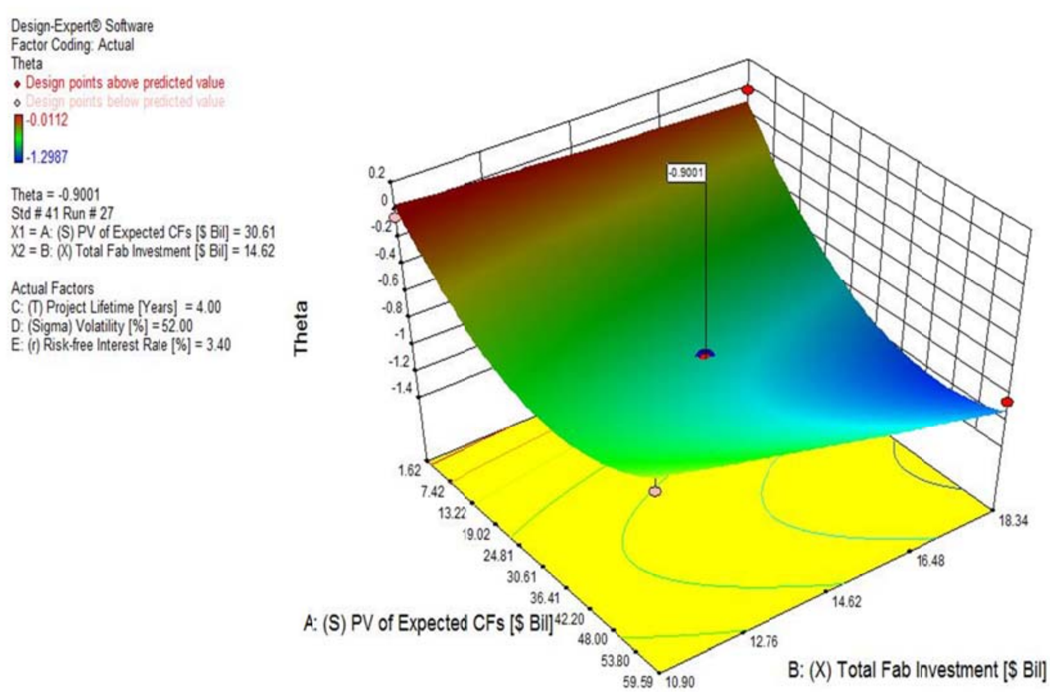

Figure 50. 3D Theta response with factor effects (*X*) and (*S*) for an American fab.

Figure 51 shows a three-dimensional surface plot for the following independent variables: the underlying asset value (*S*), the total investment (*X*), and the dependent variable theta. For next generation European 450mm wafer fabs, the optimal location for theta was located at -0.7274. This theta value for European wafer fabs is larger in comparison to the -0.9001 theta for American wafer fabs. Comparison of Figures 50 and 51 reveals a smaller theta corresponds to greater NPV for American wafer foundries.

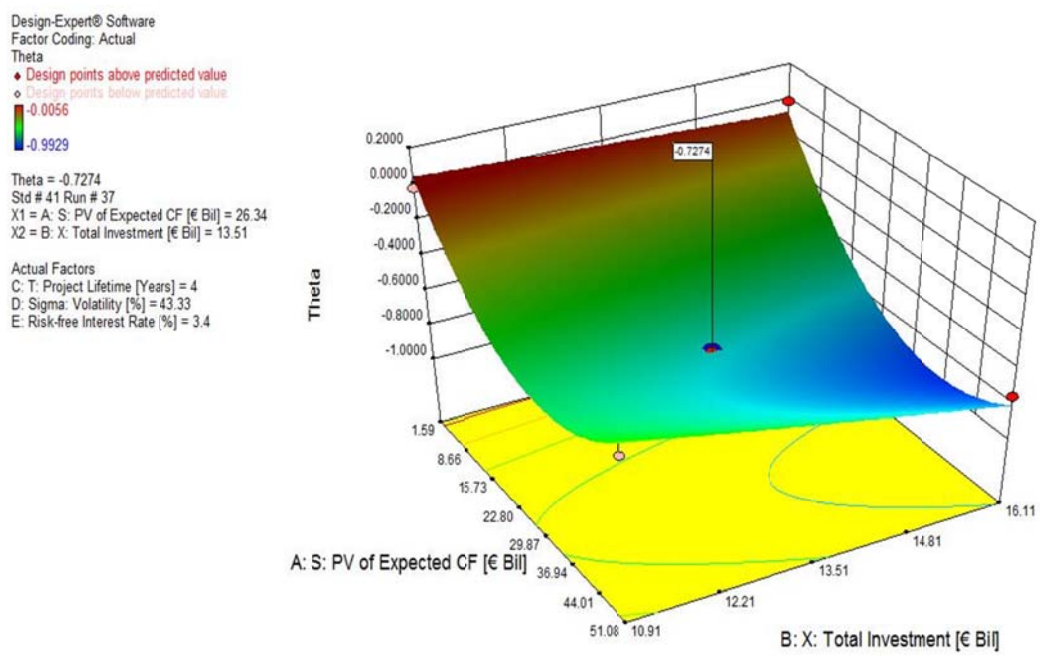

Figure 51. 3D theta response with factor effects (X) and (S) for a European fab.

Table 32 shows the hypothesis test results for American and European wafer fabs with $n = 46$ samples. For 95% confidence with α set to 0.05, the p value was found to be 1.0000. Since the p value was greater than α, the null hypothesis could not be rejected. The OCC analysis showed the probability to accept the null hypothesis type II error was approximately 0%.

Table 32

Theta Sensitivity Parameter: Hypothesis Test for Two Population Means

	Mean	Standard Deviation	Sample Size
American 450mm Fab	-0.9001	0.0552	46
European 450mm Fab	-0.7274	0.0402	46
Test Statistic Z	-17.1528		
95% Confidence Interval	[-0.1924, -0.1530]		
p value	1.0000		

Note. H_0: $\mu_1 \leq \mu_2$, $\alpha = 0.05$ (upper-tail)

Inference models were developed to make predictions for the underlying asset value and the annual revenue for various theta values. These inference models are shown in Appendix F. Reliability parameters for these theta models are presented in Appendix G. A high F ratio value for the American theta model revealed the prediction capability was significant. Also, there was no issue with multicollinearity. The 95% prediction interval ranged from -1.0229 to -0.7773. Reliability of the inferential model was checked by setting the predictor variables to: $S = 30.6095$, $X = 14.62$, $T = 4$, $\sigma = 52$, and $r = 3.4$. With these inputs, the model predicted a theta value of -0.9001, and this was the same value as presented in the Table 32.

For the European fab model, the 95% prediction interval for theta ranged from -0.8168 to -0.6380. Since both inference models were created using Microsoft Excel 2010, the goal seek function was applied to determine the annual revenue and the underlying asset value for a few theta values. The results are presented in Table 33. For a theta value of -0.9001, the annual revenue forecast was $7.5359 billion for the American wafer fab. The corresponding underlying asset value was $30.6097 billion. For a theta value of -0.7274, the annual revenue forecast was $9.0673 billion for the European wafer fab. The corresponding underlying asset value was $35.5208 billion. Based on these two parameters, the inference model appears to support the RQ7 hypothesis.

Table 33

Theta Predictions for Annual Revenue and Asset Value

	American 450mm Wafer Fab		European 450mm Wafer Fab			
Theta	Annual Revenue	Asset Value (S)	Annual Revenue		Asset Value (S)	
	[$ Billion]	[$ Billion]	[€ Billion]	[$ Billion]	[€ Billion]	[$ Billion]
-0.9001	7.5359	30.6097	NA	NA	NA	NA
-0.7700	5.9836	23.0506	7.8550	10.5940	31.7845	42.8678
-0.7500	5.7978	22.1459	7.1895	9.6965	28.5820	38.5485
-0.7274	5.5982	21.1739	6.7230	9.0673	26.3371	35.5208

Note. Exchange rate: one euro per $1.3487, discount rate = 20%
Median operations cost: $1.25 billion American fab and €1.25 billion European fab

To better understand the theta dynamics, the call value and the total NPV values were investigated with a second inference model for both foundries. Appendix F shows the call value model. Table 34 presents the total NPV values for the American wafer fab. The total NPV value is the sum of the static NPV plus the real option NPV. For the smaller theta of -0.9901, the total NPV will likely be $23.1388 billion for American wafer fabs. For the larger theta value of -0.7274, the call value prediction for the European wafer fab was €15.9260 billion. Combining this real option NPV with the static

NPV of negative €0.5883 billion yields a total NPV of €15.3377 billion, or $20.6860 billion. In conclusion, the findings revealed smaller theta values will yield larger NPV.

Table 34

Theta Predictions for Call Value and Total NPV

	American 450mm Wafer Fab		European 450mm Wafer Fab			
Theta	Call Value (C)	Total NPV	Call Value (C)		Total NPV	
	[$ Billion]	[$ Billion]	[€ Billion]	[$ Billion]	[€ Billion]	[$ Billion]
-0.9001	19.9671	23.1388	NA	NA	NA	NA
-0.7700	14.0195	17.1912	20.4801	27.6215	19.8918	26.8281
-0.7500	13.3428	16.5145	17.7569	23.9487	17.1686	23.1553
-0.7274	12.6242	15.7959	15.9260	21.4794	15.3377	20.6860

Note. NA: not applicable; exchange rate: one euro = $1.3487, discount rate = 20%
Median operations cost: $1.25 billion American fab and €1.25 billion European fab

Summary

Research question RQ1 began with a real option to expand production capacity. The first construct was made using an American call option. The second construct was created with binomial lattices using Microsoft Excel 2010. The solutions from both constructs were found to be similar as production capacity was increased in 10% increments from 110% to 150%. The NPV for both the American and European wafer fabs was compared at 130% capacity. Hypothesis testing revealed the null hypothesis was rejected. A pair of inferential models supported this hypothesis with a prediction that the NPV will likely be greater for American foundries using the expand capacity option.

Research question RQ2 began with the construction of a real option to contract production capacity. The first construct was created using an American put option. The second construct was built using binomial lattices. Findings from both constructs were similar as production capacity decreased in 10% decrements from 90% to 50%. The NPV for both the American and European wafer fabs was compared at 70% capacity. Hypothesis testing showed the null hypothesis was rejected. A pair of inferential models supported this hypothesis. In summary, the findings reveal that NPV will likely be greater for American wafer fabs using the contract capacity option.

Research question RQ3 began with the creation of a real option to defer the EUV lithography investment $X_{2\mathrm{A}}$. Two constructs were developed based on the European compound call on a call option. Hypothesis testing showed the null hypothesis was rejected. Two inferential models supported this hypothesis, because the NPV will likely be greater for American foundries using the deferred investment option.

Research question RQ4 began with the construction of a real option to abandon the 450mm wafer-foundry project in case of failure at time T_{3A}. The first abandon option construct was built with compound call on put option equations while the second was built with binomial lattices. Findings from both constructs were similar. Hypothesis testing showed the null hypothesis was rejected. A pair of inferential models supported this hypothesis. The findings showed NPV will likely be greater for American wafer fabs using the abandon option.

Research question RQ5 began with an investigation of the delta sensitivity parameter. A European call option and response surface methods were used. The delta value obtained from both the American and European wafer fabs were almost identical. With similar values, hypothesis testing showed the null hypothesis could not be rejected. Inferential models forecasted that NPV will likely be greater for American foundries.

Research question RQ6 studied the vega sensitivity parameter. European call option equations and response surface methods were utilized. The vega obtained from both fabs was compared. Hypothesis testing showed the null hypothesis was rejected. Inferential models verified the call value and NPV were greater for American wafer foundries. As a result, this evidence supported hypothesis testing.

Research question RQ7 investigated the theta sensitivity parameter. The theta value was found to be larger for the European wafer fab. A pair of inferential models found smaller theta values yielded greater NPV for American 450mm wafer fabs.

Research questions RQ1, RQ2, RQ3, RQ4, and RQ6 were rejected, while the null hypothesis for RQ5 and RQ7 could not be rejected. For RQ5, despite the nearly identical deltas, the inference model forecasted the NPV for the American 450mm wafer fabs will be greater. The null hypothesis for RQ7 was not rejected since the theta value was larger for the European wafer fab. Despite the larger theta for the European fab, the inference model predicted greater NPV for American 450mm wafer fabs.

This study found smaller theta values yield larger NPV values. Emery, Guo, and Su (2008) used a European call option to investigate the theta dynamics; they claimed theta was not well understood due to a lack of research (p. 60). Madhumathi and Parthasarathy (2010) stated theta is negative and value decreases as project time approaches maturity or completion (pp. 16-17). Based on a comparison of NPV values with two different thetas, the finding that smaller thetas produce greater NPV may be useful to other researchers. Based on the evidence presented in Figure 51 and Table 34, it appears the RQ7 hypothesis statement was written in error.

Based on the data for RQ1 to RQ7, the conclusion is that American 450mm wafer fabs are expected to yield higher NPV values. The NPV findings in this study support the competitive strategy theory described by Chevalier-Roignant and Trigeorgis (2011). Another finding disclosed in this study was that European 450mm wafer fabs are expected to have greater capacity in comparison to American foundries. Chevalier-Roignant and Trigeorgis (2011) stated firms with substantial fixed costs are likely to produce high-volume products and can take advantage of steeper learning curves, which are characteristic of the cost leadership strategy (pp. 70-71). A review of the NPV data concluded American 450mm wafer fabs will most likely choose a differentiation business strategy to produce higher-priced premium products. American 450mm wafer-foundry companies have a first-mover advantage because they were the first to invest and begin construction of giant wafer-foundry complexes and to collaborate with the development of the revolutionary EUV lithography process. Chevalier-Roignant and Trigeorgis (2011) explained that the differentiation strategy was based on brand recognition and building higher-quality products (pp. 71-72). This study has shown that American wafer fabs have the potential to generate higher NPV values using several real options. Since the incumbents have first-mover advantages, it is likely management operating American wafer foundries will choose the differentiation business strategy. Based on competitive forces from the incumbents, this pressure will likely influence the followers like European fab management to select the cost leadership business strategy.

Chapter 5 summarizes specific findings using descriptive statistics and generalizations made from predictive modeling. Implications from these findings will be discussed. The concluding topics include limitations of the study, recommendations, implications for social change, and finally, a conclusion.

Chapter 5: Discussion, Positive Social Change, and Conclusions

In this chapter, I discuss the financial and business findings for American and European 450mm wafer foundries, state the implications of advanced semiconductor technology, and describe positive social change starting in 2020. I recommend topics for future research studies and summarize this quantitative study with a conclusion.

The 2011 ITRS executive summary identified a need for flexible financial models for next generation foundries spanning from R&D to commercialization (pp. 14, 30). Moreover, the literature review showed a lack of finance literature on future 450mm wafer-foundry models based on flexible options with an embedded sensitivity analysis. Although the 2011 ITRS executive summary stated the IEM was revised, this model lacked flexible decision making capabilities. In this study, flexible real option models with sensitivity parameters were developed to emulate wise investment decision making for future 450mm wafer-foundry complexes.

The purpose of this quantitative study was to compare NPV for future American and European 450mm wafer foundries using real option models spanning from R&D to commercialization to expand capacity, to contract capacity, to defer the EUV lithography investment, or to abandon the project. In this study, independent variable data were collected and entered into two constructs. The first construct was designed using closed-form equations. The second construct was designed using binomial lattices. From questionnaire data, dependent variables and the mean NPV values were calculated. Hypothesis testing was performed on seven research questions. Inference models were developed from response surface methods and Microsoft Excel 2010 to support hypothesis testing. In conclusion, the NPV findings from seven research questions revealed American 450mm wafer foundries are expected to generate greater NPV in comparison to European foundries.

In this study, I began with the selection of a quantitative method because it provided a postpositivist worldview and reductionism that encouraged the researcher to narrow in on a topic with one reality and to identify specific variables to investigate. Independent variables derived from the Black-Scholes theory were investigated. These included the underlying asset value (S), investment cost (X), volatility (σ), the risk free interest rate (r), and lifetime (T). The dependent variables included the call value (C), put value (P), and the five sensitivity parameters delta (Δ), vega (ν), theta (θ), gamma (Γ), and rho (ρ). With the purpose to solve seven research questions, a survey instrument comprised of closed-ended questions was constructed to collect data from participants in America and Europe. Descriptive statistics were performed on the questionnaire data and compared using graphical plots. Data were applied to four real option models to determine NPV. Hypothesis testing was performed using a paired-difference test. Inference models were constructed with second-order multiple regressions to make predictions and to support hypothesis testing.

A second finding was the validation of Moore's second law as presented by Rupp and Selberherr (2011). This verification was based on a comparison of the theoretical value calculated from the Moore's second law equation with data collected from two populations. Validity was improved with a summation of individual investments and a comparison to a total investment value.

The findings from the seven research questions in this study indicate American 450mm wafer foundries will likely generate larger NPV. The null hypothesis findings for RQ1, RQ2, RQ3, RQ4, and RQ6 were rejected, while the null hypothesis findings for RQ5 and RQ7 could not be rejected. In this study, I found the original hypothesis statement for RQ7 was written in error. Based on the evidence, as a means to sustain competitive advantage, there is a greater likelihood that American fab management will select the differentiation strategy. This strategy selection by the incumbent will likely force followers like the Europeans to choose the cost leadership strategy. This strategy selection by the leader and follower are in line with the theoretical framework presented by Chevalier-Roignant and Trigeorgis (2011, pp. 70-73). In this study, I was able to accomplish the objective of developing real options that can be used by managers to make wise investment decisions to conserve limited financial resources for 450mm wafer foundries.

Interpretation of the Findings

The purpose of this study was to compare future NPV from American and European 450mm wafer foundries with several real options based on the Black-Scholes framework, to test the hypotheses, and to make forecasts with inferential models. For each of the seven research questions, the model findings indicated greater NPV would be obtained from future American 450mm wafer foundries in comparison to European wafer foundries, as summarized in Table 35. The total NPV values are the sum of the static NPV plus the real option NPV.

Table 35

Actual Outcome

	America	Total NPV	Europe	Total NPV
RQ1: NPV Option to Expand	Greater	19.4326	Lower	12.5283
RQ2: NPV Option to Contract	Greater	16.5992	Lower	10.6066
RQ3: NPV Option to Defer	Greater	12.9896	Lower	6.1903
RQ4: NPV Option to Abandon	Greater	16.7217	Lower	10.8226
RQ5: Delta (Δ)	Same	23.1388	Same	20.6808
RQ6: Vega (ν)	Greater	23.1384	Lower	20.6834
RQ7: Theta (θ)	Lower	23.1388	Greater	20.6860
Differentiation Strategy	X			
Cost Leadership Strategy			X	

Note. All NPV values in $Billion

These NPV findings correlate with the expectations as presented in Chapter 3, Table 3. These greater NPV values imply the American fab leaders will likely take competitive advantages with the differentiation business strategy. This action will likely force the competitor, the European follower, to react by taking the cost leadership strategy. Similar to the game positioning strategy described by Chevalier-Roignant and Trigeorgis (2011), American wafer fabs like Intel will likely select the differentiation strategy to increase brand recognition by producing advanced, high-quality microprocessors fabricated with leading-edge technology nodes. This differentiation strategy would allow Intel to charge higher prices for their premium microprocessors, while high volume production to sustain market leadership most likely will be less of a concern. The European 450mm wafer fabs will likely take the cost leadership business strategy to produce high volume, low cost commodity products to increase Europe's global market share. The goal of achieving higher capacity was one of the findings in this study. Electronics Leaders Group (2014) described Europe's national competitive strategy, as advocated by the Vice-President of the European Commission, Neelie Kroes, with the 10/100/20 European Initiative (pp. 6-12). The future plan is to capture 20% global market share by 2020 by manufacturing smart commodity semiconductor devices that support the future Internet of Things. In summary, these real option valuations and their dynamic relationship to competitive business strategies within the semiconductor industry extends current scholarly knowledge that was not found in peer-reviewed articles, as described in the Chapter 2 literature review. Moreover, these NPV findings may provide external validity to other researchers interested in conceptual game theories such as Porter's competitive advantage strategy and the Nash equilibrium.

The study began by applying the Black-Scholes theory to examine five independent variables as described in Chapter 2. In the process of determining the future NPV using four real options, this study has validated Moore's second law, the exponential growth equation to predict the total investment cost of a wafer foundry in the future or the past as presented by Rupp and Selberherr (2011, pp. 1-2). Individual investments were summed and compared to a total investment and a theoretical value, as described in Chapter 3. The sum of the individual investments on the left side of the equation: $X_{1A} + X_{1B} + X_{2A} + X_{2B} + X_{3A} + X_{3B} + X_{3C} = X$ was compared to the total investment on the right side of the equation, as illustrated by Figure 5. Based on the survey, Table 36 presents a summary of separate investments and timing information.

Table 36

Individual Investments and Timing for Decision-making

	American [$]	Year	European [€]	European [$]	Year
X1A: Fab Construction	5.304	3Q 2014	4.326	5.834	1Q 2015
X1B: R&D Funding	5.195	3Q 2014	4.655	6.278	1Q 2015
X2A: Pilot EUV Lithography	0.275	3Q 2015	0.264	0.356	2Q 2015
X2B: Pilot Wafer Process Tools	0.607	3Q 2015	0.626	0.844	3Q 2015
Process Recipe Developed		3Q 2016			1Q 2017
X3A: Production EUV Tools	1.110	1Q 2017	1.195	1.612	1Q 2017
X3B: Production Process Tools	3.413	2Q 2017	3.032	4.089	3Q 2016
X3C: Production EHS Facilities	0.491	2Q 2017	0.455	0.614	3Q 2016
X: Sum of Individual Investments	16.395	3Q 2018	14.553	19.627	1Q 2019
X: Predicted Total	14.643	3Q 2018	13.208	17.814	1Q 2019
X: Theoretical Moore's 2nd Law	16.100	2019	11.937	16.100	2019

Note. All Investments are in Billions, Exchange rate is 1 euro per $1.3487

For the American 450mm wafer fabs, the summation of the individual investments obtained from answers to Q3, Q5, Q6, Q8, Q14, Q15, and Q16 equated to $16.395 billion. For European wafer fabs, the investment sum was €14.553 billion, or $19.627 billion. These summations were compared to the theoretical value using Moore's second law equation, as illustrated in Figure 8. These values were also compared to the total foundry cost collected from participant responses to question Q19. The Americans answering Q19 estimated American wafer fabs will cost $14.643 billion. The Europeans answering Q19 estimated Europeans wafer fabs will cost €13.208 billion, or $17.814 billion. Americans answering question Q17 estimated commercialization will likely begin by the third quarter of 2018. The Europeans predicted wafer fabs built in Europe will likely reach commercialization by 2019. These dates agree with the G450C consortium forecast by Akiki et al. (2013, p. 365).

Figure 8 illustrates the theoretical investment will be $16.1 billion in 2019. For American wafer fabs, the sum of individual investments was calculated to be $16.395 billion; this yielded an error difference of 1.80%. For the second method, participants estimated a total investment of $14.643 billion. The error difference between the summation of single investments and the total investment was 10.69%. For European wafer fabs, the sum of individual investments was calculated to be $19.627 billion. From the survey data from Q19, the total investment was $17.814 billion. Both were higher than the theoretical value of $16.1 billion for 2019. The error between the two total investment cost methods for the European fab was 9.24%. These findings appear to be valid since the European 450mm wafer foundries are anticipated to manufacture with a greater capacity rate of 40,217 WSPM, as indicated by the average reply to question Q1. Larger European investments are expected to acquire more wafer-processing tools in comparison to the smaller American fabs with 37,717 WSPM. The literature review performed in Chapter 2 did not find peer-reviewed literature studies that had examined the total cost of a 450mm wafer foundry or studies that had validated Moore's second law. In summary, this total investment cost prediction for 450mm wafer foundries in 2019 verifies Moore's second law, and this will likely be useful to stakeholders.

The second Black-Scholes independent variable investigated was the underlying asset value (*S*), which was derived from the present value of future cash flows as shown in Figures 23 and 24. This independent variable calculation depended on several findings from questions Q22, the forecasted operational lifetime of the 450mm wafer foundry; Q20, the best-case annual revenue; Q21, the worst-case annual revenue; and Q23, the operations cost or annual running cost. With a discount rate of 20%, the underlying asset value was calculated at $13.391 billion for American wafer fabs and €8.4213 billion, or $11.3578 billion, for European wafer fabs. In this study, I found that the operational costs will likely be greater for European wafer fabs. The estimated annual running cost for an American wafer fab is $1.25 billion, while operations in European wafer fabs are expected to be €1.25 billion, or $1.69 billion per year. European wafer fabs are expected to operate with greater annual operating costs; this corresponds to larger production capacity. At a lower discount rate of 10%, the best-case underlying asset value (*S*) for the European wafer fab increases to €51.0814 billion, or $68.893 billion. This European forecast exceeds the best-case expectations for an American wafer fab at $59.595 billion. Again this financial information may be useful to stakeholders.

The third Black-Scholes independent variable investigated was volatility (σ). Data collected from survey participants entered into Equation 5 revealed the American wafer fab project had a larger volatility at 52% in comparison to the European wafer fab volatility at 43.33%. These volatilities appear valid because the Americans took the lead with a first-mover advantage to build 450mm wafer foundries; therefore, they assumed greater risk in their investments. The Europeans, as followers, are learning from the

Americans to develop their 450mm wafer foundries. This learning effect should enable the Europeans to make better investment decisions. Learning tends to reduce volatility.

The fourth Black-Scholes independent variable examined was the project lifetime (T) using the lifetime equation: $T = T_{3D} – T_{1A}$. Answers to question Q17 suggested commercialization is likely to begin in 2019 for both foundries. The expected optimal start date to begin fab construction is likely to occur by 2015. In this study, I found 4-years will be needed to construct an operational wafer foundry. According to the findings in this study, the lifespan of American wafer fabs is likely to be 18 years while European wafer fabs are expected to operate for almost 17 years. This lifetime information was not available in peer-reviewed literature; therefore, it may useful to industry stakeholders.

The last Black-Scholes independent variable examined was the risk free interest rate (r). This variable was calculated by taking the average of the risk free interest rate from 1.5% to 5.3% over the last 10 years in accordance with the U.S. Department of the Treasury. The average risk free interest rate of 3.4% was applied to the seven research questions for both the American and European wafer fabs. This interest rate was interpreted to be realistic. Since the interest rate is low, this independent variable is likely to have a small effect on the Greek sensitivity parameter rho and on real option values, in accordance with Madhumathi and Parthasarathy (2010, p. 18).

The first two research questions in this study examined the use of real options to determine the optimal production capacity in wafer fabs. This information is useful to determine how many 450mm wafer foundries may be built in Europe. Based on the near future (2020 to 2025) production capacity forecast for Europe, the Electronics Leaders

Group (2014) foresaw future capacity demand of 250,000 WSPM based on 300mm wafers (pp. 6-12). A 450mm wafer is 2.25 times larger than a 300mm wafer; this economy of scale implies that Europe will likely need to build two or three 450mm wafer foundries. Likely foundry locations are in Brussels, Dresden, and Grenoble. In this study, I found that European respondents expect 450mm wafer fabs will likely have a capacity of 40,217 WSPM in Europe. This manufacturing output is equivalent to 300mm wafer fabs with a 90,488 WSPM capacity rate. Likewise, the Americans are constructing three 450mm wafer foundries; these are Intel's D1X in Oregon, Intel's Fab 42 in Arizona, and the G450C consortium fab in New York.

Limitations of the Study

Several limitations existed in this study. To mitigate as many limitations as possible, proactive attempts were made to reduce threats to validity. To increase external validity and to improve the process to make generalizations, I investigated participants from two different populations. Two groups of 46 Americans and 46 Europeans were examined. Data collection was performed with two closed-ended survey instruments as illustrated in Appendix D. The only difference between the two instruments was currency. Generalizations about a couple of time frames in this study were compared to the recent findings reported by Akiki et al. (2013). In conclusion, the time frames listed in this study are reasonable. Threats to internal validity were mitigated by selecting participants using random selection. In this study, I excluded unqualified participants from backend operations, such as package assembly and semiconductor IC test houses. Mutual acceptance after a brief participant selection process ensured reliable data were collected from knowledgeable participants. Moreover, data sets were carefully examined for outliers, and those data sets with excessive outliers were discarded. Construct validity was mitigated with the development of two constructs for the first four research questions. Several assumptions stated by Black and Scholes (1973) were applied in this study (pp. 640-641). The closed-form construct based on Black-Scholes equations and the binomial constructs provided similar findings; therefore, validity for the real option NPV was substantiated.

One limitation for this study was not having developed a static NPV valuation using the capital asset pricing model (CAPM) and the neglect of considering corporate taxes and other liabilities. Another limitation was the cash flow analysis. Growth rate was not utilized in order to keep the cash flow analysis simple. Likewise, simplicity was maintained with a 20% discount rate approximation instead of using a realistic one obtained from a financial analysis. Had the appropriate discount rate and growth rate been researched, the accuracy of annual revenue and NPV projections could have been improved. The third limitation was that the findings obtained by response surface methods were not compared with Monte Carlo simulations. Reliable generalizations were made with the creation of second-order regression models to support hypothesis testing, to determine the total NPV, and to validate the expected business strategy outcome. The threat of statistical conclusion was mitigated with the use of rigorous descriptive statistics as presented in Tables 4 and 5. The standard errors for each parameter were found to be low. The Anderson-Darling test showed the data represented a normal distribution; therefore, reliable inferences could be made.

A limitation for RQ1 and RQ2 was an assumption made that the production capacity followed a linear function. These assumptions of linear functions neglected other nonlinear variables such as the critical mass of knowledgeable employees, EHS facility capabilities, currency exchange rate, limited electricity, raw materials, and other confounding variables. One limitation was not having performed a profit and loss sensitivity analysis to determine the boundary conditions for minimum and maximum capacity. Another limitation was not fully examining the theta sensitivity parameter prior to developing the RQ7 hypothesis statement. The correct hypothesis statement should have been written as H_A7: θ(America) < θ(Europe).

A final limitation was not having developed in-depth knowledge of competitive game theories for preemptive leader and follower investments using the Cournot-Nash equilibrium theory and the dynamic relationship with real options. Future researchers may want to explore real option competitive game theories and the dynamics of future 450mm wafer foundries to improve investment decision making models to conserve financial resources and to increase market share.

Recommendations for Further Study

This study was unique because there was a lack of financial studies on 450mm semiconductor wafer fabs that develop wise decision making real option models, Greek sensitivity parameters, and response surface methods to develop business predictions. Similar financial studies are needed since they would contribute to conserving limited financial resources for next generation wafer fabs to impact the world with low-cost, advanced semiconductor products that will drive the future Internet of Everything.

Studies to compare NPV from future 450mm wafer fabs to be built in Taiwan or South Korea with those in America or Europe are recommended. A study on 450mm wafer foundries in Asia will be valuable if it applies the same Black-Scholes framework to develop similar real options using closed-form or lattice models to make comparisons to American or European foundries. This study would provide external validity.

Financial studies on 450mm wafer foundries are needed because gaps still exist in the literature. An important study most shareholders in the semiconductor industry would value would be one which investigates the return on investment (ROI) for a typical 450mm wafer foundry. The findings from that study would support policy makers and investors with job creation and innovation and would encourage suppliers to continue developing 450mm wafer-processing tools.

Studies that examine rainbow options where volatility changes with respect to time or switch options where value changes by switching to smaller technology nodes to produce advanced semiconductor products in 450mm wafer fabs are recommended. NPV could be considered using Greek sensitivity parameters such as gamma, rho, and xi. Mun (2006) described the sixth Greek sensitivity parameter known as xi as being the first derivative ($\delta C/\delta X$), in other words, the rate of change for call value with respect to the investment cost (pp. 227, 231). Other financial parameters which influence 450mm wafer fab profitability such as the effect of government support, tax havens, and cyclical global supply and demand should be examined. Another study to consider is how 450mm wafer foundries will affect existing 300mm wafer foundry profitability and business strategies. Future researchers could examine gaming strategies to encourage management of 300mm wafer fabs to select alternative survival strategies such as manufacturing niche products, mergers and acquisitions, or new business opportunities like LED fabs, photovoltaic fabs, or 3D IC fabs. In conclusion, it would be beneficial if this paper sparks interest in developing financial studies about 450mm semiconductor wafer foundries.

Implications for Social Change

Conserving financial resources with wise investment decision making using real options is likely to be the key to building and operating giant 450mm semiconductor wafer foundries. These next generation semiconductors fabs are expected to increase economy of scale by 2.25 times, to reduce manufacturing cost by 30%, and to produce advanced semiconductor devices that will likely drive the Internet of Everything (IoE). Overall, this era should have a significant effect on several levels of society.

New opportunities to manufacture low-cost, advanced semiconductors in the near future will likely have a significant impact on government policy, in particular a science, technology, and innovation policy based on information and communication technology (ICT) in America and Europe. President Obama and the European Commission Vice-President Neelie Kroes have recognized the need to renew the economy with the creation of new jobs and innovation. Appendix C presents their speeches. Following America's lead, Neelie Kroes has launched an ambitious goal for Europe to recapture its lost semiconductor market share after several decades of decline. The January 2014 SEMI EU 10/100/20 Factsheet quoted Neelie Kroes on May 23rd, 2013, as stating, "I want to double our chip production to around 20% of global production. It's a realistic goal if we channel our investments properly" (p. 3). This 10/100/20 initiative has three objectives:

to provide €10 billion for research and development, to make €100 billion investments in semiconductor manufacturing, and to obtain 20% global semiconductor market share by 2020 (p. 2). European investments will be available for the 450mm wafer transition, to continue manufacturing products in 300mm wafer fabs, and to expand nanotechnology manufacturing. Georgoutsakou (2014) outlined the SEMI Europe Advocacy roadmap to implement the EU 10/100/20 initiative (p. 1). This roadmap specifies a plan and time frame to double global market share by 2020 with a goal to capture 60% market share of smart semiconductors and 20% semiconductor market share of mobile wireless products that are expected to drive the Internet of Things. Bui, Castellani, Vangelista, Zanella, and Zorzi (2014) recognized that semiconductors like sensors and actuators can develop ICT to monitor, control, and reduce cost with an efficient synergy of smart government, smart grid, smart utilities, traffic and waste management, smart parking, smart buildings as well as preserve heritage buildings. Daniel and Doran (2014) predicted that ICT and geomantic applications such as GPS and augmented reality devices combined with big data analytics will be the foundation for decision making in future smart cities (pp. 57, 62-71). Hancke, Hancke Jr., and Silva (2013) described many types of semiconductor sensors such as near field communication (NFC) and radio frequency identification (RFID) to construct wireless sensors to develop many types of smart city applications to control electricity, transportation, and water and to monitor smart buildings, health care, seismic activity, and the weather (pp. 393-415).

At the organizational level, advanced low-cost semiconductors from future 450mm wafer foundries are expected to drive IoE applications with smart cities, smart infrastructures, smart grids, and smart buildings. Responsive organizations that recognize new opportunities with novel semiconductor innovations most likely will become competitive as they develop new business strategies and applications. Abdelwahab, Guizani, Hamdaoui, and Rayes (2014) stated that Cisco Systems predicts the IoE market will generate an NPV of $14 trillion (p. 276). These researchers outlined many opportunities for future semiconductors communicating with GPS to monitor the environment, healthcare, animal behavior, agricultural watering needs, spacecraft crews, in-flight aircraft performance, energy consumption in smart homes and smart buildings, the supply and distribution of energy in smart grids, traffic status, and oil and gas in pipelines (pp. 277-278). Kristian (2013) anticipated the IoE will connect automobiles, people, places, processes, machines, and things that will communicate together in smart clouds (pp. 695-697). Dlodlo, Foko, Mathaba, and Mvelase (2012) predicted by 2020, there will be 50 billion things, machines, and infrastructure sensors, each made with semiconductors like microprocessors, memories, image sensors, actuators, RFID tags, biometric chips, NFC chips in digital wallets, chip antennas, chips embedded in smart fabrics, and chips embedded in humans to monitor vital signs or to track people and things with the internet (pp. 244-256). Jalali (2013) foresaw future semiconductors will be needed to build several types of smart infrastructure comprised of a network of sensors to monitor and manage fleets, smart cities, smart grids, and waste operations using management applications such as a dashboard to monitor remote situations where big data flows require analytic software to make fast, wise decisions (pp. 210-213).

At the family level, many types of advanced, low-cost semiconductors manufactured in 450mm wafer foundries will be needed to build smart homes, safe autonomous vehicles, and autonomous robots. These novel semiconductor innovations will communicate with the IoE to retrieve and provide information and they are expected to bring about positive social change for families around the globe. Demestichas et al. (2013) foresaw semiconductors by 2020 will be used to design cognitive networks for self-driving automobiles to recognize patterns, learn, and develop autonomous behavior to safely drive (pp. 91-92). Ferreras (2014) expects future autonomous vehicles aided by GPS will communicate with other vehicles, with smart parking structures, with smart infrastructure cloud services to monitor real time traffic conditions, perform stochastic analysis to adapt by finding optimal routes to transport people and goods (pp. 54-55). Barolli et al. (2013) foresaw RFID semiconductors will enable autonomous humanoid robots to communicate together as they assist the elderly (pp. 589-591).

At the individual level, a wide variety of advanced, low-cost semiconductors manufactured in 450mm wafer foundries will likely be used in smart fabrics or wearable products. Future semiconductors designed for the healthcare applications are expected to screen blood and DNA, detect viruses and cancers, distribute time released medications, restore vision and hearing, and guide physicians wearing wearable computers with augmented reality (AR) to improve surgical procedures. Wei (2014) provided a brief segmented market study on future semiconductors embedded in wearable products such as military and firefighter jackets with environmental and vital sign sensors, outdoor activity trackers, smart watches, and wearable computers that stream AR information from the IoE (pp. 54-56). Balasubramaniam and Kangasharju (2013) anticipated nanotechnology biosensor chips embedded in the human body most likely will transmit medical data such as electrocardio pulses or other information about pathogens or allergens (pp. 62-63). Kaku (2011) predicted wearable sensor chips embedded in fabrics will monitor the human body for vital signs while other chips will screen blood for many types of cancers (pp. 21, 35-36, 136-137). Kaiho et al. (2009) described how retinal prosthesis chips will likely restore vision to the blind (p. 1).

The key to building these 450mm semiconductor foundries will depend on wise investment decision making as stated by the European Commission Vice-President Neelie Kroes. In this study, the Black-Scholes theoretical framework was applied to develop several real option models to enable fab management to make wise investment decisions for 450mm semiconductor wafer foundries. A structured quantitative survey was constructed based on the Black-Scholes framework, and empirical data were collected to make inferences about NPV, future annual revenues, and optimal capacity. It is recommended that similar real options should be employed by fab management to facilitate wise investment decision making prior to building and operating future 450mm wafer foundries. Wise decision making is important to conserve financial resources in giant 450mm wafer foundries to manufacture low-cost semiconductor products that will likely drive the IoE business by 2020 and make a significant impact on global humanity.

Conclusions

Since the invention of the transistor in 1947, the semiconductor industry has continued to miniaturize transistors every 18 months in accordance with Moore’s law.

The goal of miniaturization is to pack more transistors into the same area to reduce cost, to improve performance, and to increase speed and energy efficiency. Cost can be reduced further by increasing the size of silicon wafers to increase the economy of scale. The latest transition to 450mm (18") wafers provides 2.25 times more area than 300mm (12") wafers, and this economy of scale can reduce cost by 30%. However, processing larger wafers requires the construction of larger foundries to accommodate larger wafer-processing tools. Cost can be reduced further if managers apply wise investment decision making tools based on real option models; this has been the focus of this study.

This quantitative study presents ideas at the forefront of semiconductor wafer fab technology and modern finance. This study may be the first to compare NPV for future American and European 450mm wafer fabs using real options developed from the Black-Scholes option pricing theory. Real option models were developed to enable wise investment decision making, to optimize production capacity, to examine the impact of deferring the EUV lithography investment, and to mitigate risk with an abandon option. Real option models can conserve financial resources from fab conception through commercialization. In this study, I integrated real options, investigated Greek sensitivity parameters, and applied response surface methods specifically with the Box-Behnken design as a new approach to forecast and improve wafer-foundry performance.

Regarding the technical feasibility to build 450mm future wafer foundries, Singer (2014) stated there were "no technical barriers seen for 450mm" (p. 11). Singer interviewed Paul Farrar, the general manager of the G450C consortium's 450mm pilot fab in New York, and stated excellent results were obtained from 34 operational wafer-processing tools, which include: CMP, CVD, electroplate, etchers, furnaces, lithography, metrology, PVD, and wet cleans. Akiki et al. (2013) concluded that the 450mm wafer transition will be a profitable opportunity for the semiconductor industry (p. 366).

In this study, the results predict American 450mm wafer fabs will likely cost $14.6 billion, while the higher-capacity European wafer fabs will likely cost $17.8 billion. Both fabs are expected to reach commercialization by 2019. I found American 450mm wafer fabs will likely achieve greater NPV and American fab management will likely choose a differentiation business strategy while the Europeans will likely select the cost leadership strategy for their high-production-capacity wafer fabs. By 2020, abundant low-cost semiconductor devices produced from these 450mm wafer fabs are expected to drive the Internet of Everything. With an expected 50 billion Internet connections, people will likely be connected to autonomous vehicles, to infrastructure places, and to things. Semiconductors should unlock human potentials with smart homes, advanced medical diagnostics to detect cancers and other diseases, to restore vision and hearing, to improve energy efficiency, and to allow communications with autonomous robot teams to perform a variety of tasks. Wise investment decision making based on real options can conserve limited financial resources for 450mm wafer foundries to manufacture advanced low-cost semiconductor technology that should improve the quality of life for global humanity.

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Appendix A: Acronyms Applied in This Study

200mm	8” or 200mm diameter wafers used in small wafer fabs
300mm	12” or 300mm diameter wafers currently used in wafer fabs
300mm Prime	300mm fab program to improve production efficiency
3D IC	Three-dimensional Integrated Circuit
450mm	18” or 450mm diameter wafers to be used in future fabs
AMHS	Automated Material Handling System
AR	Augmented Reality, real time information superimposed on a real world environment
CMP	Chemical-mechanical Planarization
CVD	Chemical vapor deposition, a deposition method for crystalline materials
EHS / ESH	Environmental, Health and Safety facilities management
EUV	Extreme Ultraviolet lithography source, $\lambda = 13.5$ nanometers
Fab	Wafer fabrication facility or foundry that makes semiconductors
IC	Integrated Circuit semiconductor, an electronic device chip
ICT	Information and Communication Technology
IEM	Industry Economic Model, a traditional demand-supply model
IoE	Internet of Everything connects future smart cities, smart infrastructure, smart buildings, and smart grids with things
IoT	Internet of Things connects people, robots, machines, wearable computers, mobile devices, self-driving vehicles, and things
ITRS	International Technology Roadmap for Semiconductors

M2M	Machine to Machine communications, robot to robot via the Internet
NFC	Near Field Communication chips support short range bidirectional communication for digital payments and wallets
nm	Nanometers
NPV	Net Present Value
PVD	Physical vapor deposition, a deposition method for metals
R&D	Research and Development
RFID	Radio Frequency Identification Device technology contain readers and tags to support unidirectional communication
RSM	Response surface method/ methodology
SEMI	Semiconductor Equipment and Materials International, a consortia
SEMICON	SEMI conference
WSPM	Wafer Starts per Month is the production capacity rate for a fab

Appendix B: Semiconductor Fab Videos

Uploaded by channelintel on Nov 7, 2007 Fab 32 - Intel's first high-volume 45nm chip factory. Available from http://www.youtube.com/watch?v=4FLBtQC0F0c&feature=related

Uploaded by NewsFromTheShed on Nov 13, 2010 Intel Factory Tour - 32nm Manufacturing Technique. Available from http://www.youtube.com/watch?v=SeGqCl3YAaQ&feature=related

Uploaded by ElectroIQ on May 18, 2011 Major IC makers are on 450mm wafers, says ISMI. Available from http://www.youtube.com/watch?v=Z0ZI0oT0-KU

Uploaded by frgmstr on Apr 18, 2011 GLOBALFOUNDRIES - Building Fab 8 – HardOCP. Available from http://www.youtube.com/watch?v=Izea72ojj3s&feature=fvwrel

Uploaded by TheNanoCollege on Jul 12, 2013 G450C General Manager Paul Farrar outlines 450mm transition progress to massive SEMICON West crowd. Available from http://www.youtube.com/watch?v=j4eLkp0hBQQ

Uploaded by Sarah Garland on Feb 18, 2014 D1X Construction. Available from http://www.youtube.com/watch?v=pJ9LOkEftgc

Uploaded by channelintel on May 25, 2012 Intel: The Making of a Chip with 22nm/3D Transistors. Available from http://www.youtube.com/watch?v=d9SWNLZvA8g&feature=related

Uploaded by GFOUNDRIESDresden on Jul 20, 2011, GLOBALFOUNDRIES - A new foundry leader. Available from http://www.youtube.com/watch?v=7CWCunlViDk&feature=related

Uploaded by jeannotdriedonkx on Nov 7, 2009, ASML: Chip making goes vacuum with EUV. Available from http://www.youtube.com/watch?v=XLNsYecX_2Q

Uploaded by jeannotdriedonkx on Jul 22, 2009, ASML and Carl Zeiss - Two Companies, one business. Available from http://www.youtube.com/watch?v=WbukKUi3vHw

Uploaded by ChannelCymer on May 4, 2012, How An EUV Light Source Works. Available from http://www.youtube.com/watch?v=8xJEs3a-1QU&feature=related

Appendix C: Social Change Videos

Uploaded by ABC15 Arizona on Jan 25, 2012 President Obama's speech at Intel. Available from http://www.youtube.com/watch?v=nXkSMzTYlvA

Uploaded by ABC15 Arizona on Feb 18, 2011 Intel announces $5 billion facility planned for Chandler. Available from http://www.youtube.com/watch?v=ICF7XJPQquE

Uploaded by TheNanoCollege on May 8, 2012 President Obama: The College of Nanoscale Science and Engineering is a Model for the Nation. Available from http://www.youtube.com/watch?v=lCoTdwCWkrI

Uploaded by Neelie Kroes on Nov 14, 2012 Europe needs research and innovation. Available from http://www.youtube.com/watch?v=2O4GWWqZtR4

Uploaded by Cisco on Dec 10, 2012 Cisco Commercial | Tomorrow Starts Here (:60). Available from http://www.youtube.com/watch?v=BJSjbttGaVM&list=PLFT-9JpKjRTBO06vEUTM7I91AZ7_-I8XI

Uploaded by channelintel on Feb 28, 2013 Internet of Everything Economy HD. Available from http://www.youtube.com/watch?v=M578lU2TGeI

Uploaded by AndrewatEML on Apr 26, 2013 What is the Internet of Everything? Available from http://www.youtube.com/watch?v=5FSmkKXNxq8

Uploaded by Cisco on Oct 31, 2013, Internet of Everything | Powering Tomorrow's Possibilities. Available from http://www.youtube.com/watch?v=YFbqoOZB6Vo&list=PLFT-9JpKjRTBO06vEUTM7I91AZ7_-I8XI

Uploaded by Thinking on Mar 1, 2013 What is The Internet of Things? Available from http://www.youtube.com/watch?v=LVlT4sX6uVs

Uploaded Cisco on Nov 29, 2012, The Internet of Everything: Relevant and Valuable Connections Will Change the World. Available from http://www.youtube.com/watch?v=bVNJfUOBzJE&list=PLFT-9JpKjRTBO06vEUTM7I91AZ7_-I8XI

Uploaded Cisco on Feb 5, 2013, Connecting the Unconnected Through the IoE. Available from http://www.youtube.com/watch?v=llVJD1hih28&list=PLFT-9JpKjRTBO06vEUTM7I91AZ7_-I8XI

Uploaded by Sebastian Lange on Feb 21, 2013, The Internet of Things Architecture, IoT-A. Available from http://www.youtube.com/watch?v=nEVatZruJ7k

Uploaded by nttccwaza on Jun 12, 2013, 2025 The Future of ICT. Available from http://www.youtube.com/watch?v=GpJ36KzHJG4

Uploaded by Alstom on Jan 2, 2013, Architecture of a Smart Grid. Available from http://www.youtube.com/watch?v=PIATMO0c9xQ

Uploaded by Siemens on Dec 22, 2010, Siemens - Electromobility - Into the mobile future with energy. Available from http://www.youtube.com/watch?v=Yp6Rf_wS02c

Uploaded by gizmag on Oct 5, 2009, Honda's self-balancing U3-X electric unicycle. Available from http://www.youtube.com/watch?v=5LduYhx5lDY

Uploaded by Playstation Game Trailers (UK) on Oct 27, 2013, Kara : a PS3 new technology. Available from http://www.youtube.com/watch?v=lhoYLp8CtXI

Uploaded by TIA NOW on Sep 11, 2013, Future of the Network Documentary, Part 1 - M2M and the Internet of Things: Brace for Impact. Available from http://www.youtube.com/watch?v=L24j08q_zVo

Uploaded by Supecx Documentaries (UK) on Jan 24, 2014, America Building Robots Army for Future | New Documentary. Available from http://www.youtube.com/watch?v=Ci7EFmO260E

Uploaded by Google on Mar 28, 2012, Self-Driving Car Test: Steve Mahan. Available from http://www.youtube.com/watch?v=cdgQpa1pUUE

Uploaded by Google Self-Driving Car Project on May 27, 2014, A Ride in the Google Self Driving Car. Available from http://www.youtube.com/watch?v=TsaES--OTzM

Uploaded by Google Self-Driving Car Project on May 27, 2014, Behind the Google Self Driving Car Project. Available from http://www.youtube.com/watch?v=cdeXlrq-tNw

Appendix D: Survey Instruments

American Survey

Survey Part I: Construction of a Pilot 450mm Semiconductor Wafer Foundry

Instructions: Based on your wafer foundry perspective to transition to pilot 450mm semiconductor wafer foundries; please check one box per question.

1. To construct an average 450mm production wafer fab, please estimate what the optimal capacity measured in wafer starts per month [WSPM] should be?

≤15,000	20,000	25,000	30,000	35,000	40,000	45,000	50,000	55,000	>60,000

2. What will be the best time [Year] to start construction of a 450mm wafer fab, this includes: clean-room ballrooms, the facility (utility) yards, and the office complex?

2010	2011	2012	2013	2014	2015	2016	2017	2018	2019

3. Please predict what the expected R&D funding [$ Billions] will be to assist tool and equipment suppliers to speed-up development of EUV lithography and wafer-processing tools?

≤$1B	$2B	$3B	$4B	$5B	$6B	$7B	$8B	$9B	≥$10B

4. Please estimate when [Year] EUV lithography will be available to install into a pilot 450mm wafer fab; this includes scanners, photoresist chemistries, and a set of reticles?

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022

5. Please predict what the expected fab construction cost [$ Billions] will be to construct a 450mm semiconductor wafer fab complex, this includes the cleanrooms, facilities support, utility yards, and offices? Please exclude the cost for wafer-processing tools.

≤$1B	$2B	$3B	$4B	$5B	$6B	$7B	$8B	$9B	≥$10B

6. Please estimate the total EUV lithography cost-of-ownership for a pilot 450mm wafer fab; this includes the purchase of scanners, energy consumption, photoresist, and reticles?

≤$50M	$100M	$150M	$200M	$250M	$300M	$350M	$400M	$450M	≥$500M

7. What year will the wafer-processing toolset be available for a pilot 450mm wafer fab?

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022

8. Please predict the cost of a wafer-processing toolset for a pilot 450mm wafer fab?

$100M	$200M	$300M	$400M	$500M	$600M	$700M	$800M	$900M	≥$1B

9. Please predict the year when the main process recipe will be ready for production in a 450mm wafer fab?

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022

10. Please estimate the probability of success to construct a pilot 450mm wafer fab complex, to install and qualify alpha and beta wafer-processing tools with EUV lithography and to develop a process recipe?

0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%

11. Please predict the value of the pilot 450mm wafer fab after completion, in other words the salvage value?

≤$2B	$2.5B	$3B	$3.5B	$4B	$4.5B	$5B	$5.5B	$6B	$6.5B	≥$7B

Survey Part II: Ramp-up of a Full Capacity Production 450mm Wafer Foundry

Instructions: Based on your prior expert wafer foundry perspective, for the transition to production 450mm semiconductor wafer foundries; please check one box per question.

12. Please estimate when production EUV lithography will be ready, this includes scanners, photoresist, and mask sets to support full-scale 450mm wafer-processing?

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022

13. Please estimate when the entire wafer-processing toolset will become available to start full-scale production in a 450mm wafer fab?

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022

14. Please estimate the total cost for all production EUV lithography scanner tools, reticle sets, and photoresist chemistry to operate at full capacity in a 450mm wafer fab?

≤$200M	$400M	$600M	$800M	$1B	$1.2B	$1.4B	$1.6B	$1.8B	≥$2B

15. Please estimate the total cost of a wafer-processing toolset capable of operating at full capacity in a production 450mm wafer fab?

≤$0.5B	$1B	$1.5B	$2B	$2.5B	$3B	$3.5B	$4B	$4.5B	≥$5B

16. Please estimate the total cost of EHS-facilities support and operations to ramp-up production in an average 450mm wafer fab at full-production capacity?

≤$100M	$200M	$300M	$400M	$500M	$600M	$700M	$800M	$900M	≥$1B

17. Please estimate when a production 450mm wafer fab will operate at full capacity?

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022

18. Please estimate the probability of success to ramp-up production in 450mm wafer fab; this includes installation and qualification of EUV lithography and wafer-processing tools, EHS/ ESH facilities support, and operations?

0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%

19. Please forecast the total investment [$ Billions] cost for an average 450mm wafer foundry?

$7.4B	$8.4B	$9.6B	$10.9B	$12.4B	$14.1B	$16.1B	$18.3B	$20.9B	≥$23.8B

20. Please predict the best-case future annual revenue that could be generated once an average 450mm wafer fab begins operation at full-production capacity?

≤$1B	$2B	$3B	$4B	$5B	$6B	$7B	$8B	$9B	≥$10B

21. Please predict the worst-case future annual revenue that could be generated once an average 450mm wafer fab begins operation at full-production capacity?

≤$1B	$2B	$3B	$4B	$5B	$6B	$7B	$8B	$9B	≥$10B

22. Please predict the expected lifespan or end of life [Years] for a production 450mm wafer foundry?

≤10	12	14	16	18	20	22	24	26	28	≥30

23. Please forecast the annual commercial operations cost to run an average 450mm wafer fab at full-production capacity?

≤$250M	$500M	$750M	$1B	$1.25B	$1.5B	$1.75B	$2B	$2.25B	≥$2.5B

European Survey

Survey Part I: Construction of a Pilot 450mm Semiconductor Wafer Foundry

Instructions: Based on your wafer foundry perspective to transition to pilot 450mm semiconductor wafer foundries; please check one box per question.

1. To construct an average 450mm production wafer fab, please estimate what the optimal capacity measured in wafer starts per month [WSPM] should be?

≤15,000	20,000	25,000	30,000	35,000	40,000	45,000	50,000	55,000	≥60,000

2. What will be the best time [Year] to start construction of a 450mm wafer fab, this includes: clean-room ballrooms, the facility (utility) yards, and the office complex?

2010	2011	2012	2013	2014	2015	2016	2017	2018	2019

3. Please predict what the expected R&D funding [€ Billions] will be to assist tool and equipment suppliers to speed-up development of EUV lithography and wafer-processing tools?

≤€1B	€2B	€3B	€4B	€5B	€6B	€7B	€8B	€9B	≥€10B

4. Please estimate when [Year] EUV lithography will be available to install into a pilot 450mm wafer fab; this includes scanners, photoresist chemistries, and a set of reticles?

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022

5. Please predict what the expected fab construction cost [€ Billions] will be to construct a 450mm semiconductor wafer fab complex, this includes the cleanrooms, facilities support, utility yards, and offices? Please exclude the cost for wafer-processing tools.

≤€1B	€2B	€3B	€4B	€5B	€6B	€7B	€8B	€9B	≥€10B

6. Please estimate the total EUV lithography cost-of-ownership for a pilot 450mm wafer fab; this includes the purchase of scanners, energy consumption, photoresist, and reticles?

<€50M	€100M	€150M	€200M	€250M	€300M	€350M	€400M	€450M	≥€500M

7. What year will the wafer-processing toolset be available for a pilot 450mm wafer fab?

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022

8. Please predict the cost of a wafer-processing toolset for a pilot 450mm wafer fab?

€100M	€200M	€300M	€400M	€500M	€600M	€700M	€800M	€900M	≥€1B

9. Please predict the year when the main process recipe will be ready for production in a 450mm wafer fab?

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022

10. Please estimate the probability of success to construct a pilot 450mm wafer fab complex, to install and qualify alpha and beta wafer-processing tools with EUV lithography and to develop a process recipe?

0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%

11. Please predict the value of the pilot 450mm wafer fab after completion, in other words the salvage value?

≤€2B	€2.5B	€3B	€3.5B	€4B	€4.5B	€5B	€5.5B	€6B	€6.5B	≥€7B

Survey Part II: Ramp-up of a Full Capacity Production 450mm Wafer Foundry

Instructions: Based on your prior expert wafer foundry perspective, for the transition to production 450mm semiconductor wafer foundries; please check one box per question.

12. Please estimate when production EUV lithography will be ready, this includes scanners, photoresist, and mask sets to support full-scale 450mm wafer-processing?

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022

13. Please estimate when the entire wafer-processing toolset will become available to start full-scale production in a 450mm wafer fab?

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022

14. Please estimate the total cost for all production EUV lithography scanner tools, reticle sets, and photoresist chemistry to operate at full capacity in a 450mm wafer fab?

≤€200M	€400M	€600M	€800M	€1B	€1.2B	€1.4B	€1.6B	€1.8B	≥€2B

15. Please estimate the total cost of a wafer-processing toolset capable of operating at full capacity in a production 450mm wafer fab?

≤€0.5B	€1B	€1.5B	€2B	€2.5B	€3B	€3.5B	€4B	€4.5B	≥€5B

16. Please estimate the total cost of EHS-facilities support and operations to ramp-up production in an average 450mm wafer fab at full-production capacity?

€100M	€200M	€300M	€400M	€500M	€600M	€700M	€800M	€900M	≥€1B

17. Please estimate when a production 450mm wafer fab will operate at full capacity?

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022

18. Please estimate the probability of success to ramp-up production in 450mm wafer fab; this includes installation and qualification of EUV lithography and wafer-processing tools, EHS/ ESH facilities support, and operations?

0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%

19. Please forecast the total investment [€ Billions] cost for an average 450mm wafer foundry?

€7.4B	€8.4B	€9.6B	€10.9B	€12.4B	€14.1B	€16.1B	€18.3B	€20.9B	≥€23.8B

20. Please predict the best-case future annual revenue that could be generated once an average 450mm wafer fab begins operation at full-production capacity?

≤€1B	€2B	€3B	€4B	€5B	€6B	€7B	€8B	€9B	≥€10B

21. Please predict the worst-case future annual revenue that could be generated once an average 450mm wafer fab begins operation at full-production capacity?

≤€1B	€2B	€3B	€4B	€5B	€6B	€7B	€8B	€9B	≥€10B

22. Please predict the expected lifespan or end of life [Years] for a production 450mm wafer foundry?

≤10	12	14	16	18	20	22	24	26	28	≥30

23. Please forecast the annual commercial operations cost to run an average 450mm wafer fab at full-production capacity?

≤€250M	€500M	€750M	€1B	€1.25B	€1.5B	€1.75B	€2B	€2.25B	≥€2.5B

Appendix E: Response Surface Methods

RQ1 Box-Behnken Design for an American 450mm Fab

Random Order	Run #	(S) PV CF [$ Billions]	(XE) Invest [$ Billions]	(Tʒ) Lifetime [Years]	(r) Interest [%]	(σ) Volatility [%]	(C) Call [$ Billions]	(P) Put [$ Billions]	Delta Δ	Gamma Γ	Rho ρ	Theta θ	Vega ν
40	1	13.391	2.5072	4	5.3	52.0	18.2888	11.4319	0.9891	0.0018	7.1830	-0.1400	0.6891
4	2	25.158	2.5072	4	3.4	52.0	35.6443	22.9819	0.9964	0.0003	8.0192	-0.0864	0.2812
29	3	13.391	1.5043	3	3.4	43.1	16.0979	12.0346	0.9994	0.0002	4.0386	-0.0489	0.0429
9	4	13.391	0.5014	4	3.4	43.1	14.3210	12.9536	0.9999	0.0000	1.7382	-0.0151	0.0063
26	5	25.158	1.5043	4	1.5	52.0	31.3593	23.7453	0.9990	0.0002	5.3459	-0.0265	0.0991
12	6	13.391	2.5072	4	3.4	60.9	18.3069	11.3807	0.9808	0.0027	6.8993	-0.1481	1.1755
45	7	13.391	1.5043	4	3.4	52.0	16.2609	12.0999	0.9961	0.0007	4.9148	-0.0591	0.2672
37	8	13.391	0.5014	4	1.5	52.0	14.3237	12.9214	0.9995	0.0001	1.8346	-0.0096	0.0423
25	9	1.624	1.5043	4	1.5	52.0	1.6880	0.7062	0.7881	0.2624	1.9048	-0.0778	1.0866
16	10	25.158	1.5043	5	3.4	52.0	31.5167	23.8884	0.9978	0.0002	5.7470	-0.0457	0.1278
7	11	13.391	1.5043	3	5.3	52.0	16.2218	12.1150	0.9982	0.0003	3.7399	-0.0754	0.1078
39	12	13.391	0.5014	4	5.3	52.0	14.3706	12.9862	0.9996	0.0000	1.5815	-0.0223	0.0208
18	13	13.391	1.5043	4	5.3	43.1	16.2599	12.1778	0.9988	0.0002	4.7712	-0.0673	0.0760
10	14	13.391	2.5072	4	3.4	43.1	18.0410	11.2342	0.9936	0.0015	8.2522	-0.0944	0.4499
3	15	1.624	2.5072	4	3.4	52.0	1.7414	0.4926	0.6210	0.2779	1.7939	-0.0967	1.2529
1	16	1.624	0.5014	4	3.4	52.0	1.6475	1.2645	0.9586	0.1162	0.9277	-0.0358	0.4298
38	17	13.391	2.5072	4	1.5	52.0	18.0546	11.1412	0.9850	0.0026	8.1274	0.0945	0.9856
46	18	13.391	1.5043	4	3.4	52.0	16.2609	12.0999	0.9961	0.0007	4.9148	-0.0591	0.2672
15	19	1.624	1.5043	5	3.4	52.0	1.7221	0.8211	0.8229	0.2294	2.1561	-0.0744	1.1485
2	20	25.158	0.5014	4	3.4	52.0	27.2553	24.7182	0.9997	0.0000	1.6631	-0.0138	-0.0050
21	21	13.391	0.5014	3	3.4	52.0	14.3150	12.9387	0.9998	0.0000	1.3445	-0.0161	0.0105
8	22	13.391	1.5043	5	5.3	52.0	16.4214	12.2635	0.9951	0.0006	5.2303	-0.0721	0.3208
19	23	13.391	1.5043	4	1.5	60.9	16.2774	12.0424	0.9920	0.0012	4.8905	-0.0603	0.5506
31	24	13.391	1.5043	3	3.4	60.9	16.2362	12.0597	0.9956	0.0008	3.7828	-0.0702	0.2696
22	25	13.391	2.5072	3	3.4	52.0	18.0108	11.1735	0.9916	0.0018	6.2845	-0.1151	0.5062
42	26	13.391	1.5043	4	3.4	52.0	16.2609	12.0999	0.9961	0.0007	4.9148	-0.0591	0.2672
20	27	13.391	1.5043	4	5.3	60.9	16.4012	12.2166	0.9937	0.0009	4.2885	-0.0864	0.3889
13	28	1.624	1.5043	3	3.4	52.0	1.6622	0.6530	0.7948	0.2907	1.5498	-0.0954	0.8976
24	29	13.391	2.5072	5	3.4	52.0	18.3135	11.4095	0.9837	0.0024	8.6929	-0.1175	1.1223
35	30	1.624	1.5043	4	3.4	60.9	1.7293	0.8353	0.8163	0.2206	1.6691	-0.0939	1.0467
34	31	25.158	1.5043	4	3.4	43.1	31.4071	24.8417	0.9993	0.0001	5.0954	-0.0426	-0.0137
5	32	13.391	1.5043	3	1.5	52.0	16.1019	11.9650	0.9976	0.0006	4.1630	-0.0349	0.1625
44	33	13.391	1.5043	4	3.4	52.0	16.2609	12.0999	0.9961	0.0007	4.9148	-0.0591	0.2672
32	34	13.391	1.5043	5	3.4	60.9	16.4285	12.2073	0.9908	0.0012	5.1700	-0.0750	0.6548
33	35	1.624	1.5043	4	3.4	43.1	1.6596	0.6510	0.8051	0.2971	2.1087	-0.0721	1.0058
6	36	13.391	1.5043	5	1.5	52.0	16.2635	12.0468	0.9933	0.0011	6.1906	-0.0456	0.5205
43	37	13.391	1.5043	4	3.4	52.0	16.2609	12.0999	0.9961	0.0007	4.9148	-0.0591	0.2672
23	38	13.391	0.5014	5	3.4	52.0	14.3755	12.9669	0.9991	0.0001	2.0329	0.0171	0.0623
27	39	1.624	1.5043	4	5.3	52.0	1.7013	0.7778	0.8325	0.2514	1.8638	-0.0892	0.9926
41	40	13.391	1.5043	4	3.4	52.0	16.2609	12.0999	0.9961	0.0007	4.9148	-0.0591	0.2672
17	41	13.391	1.5043	4	1.5	43.1	16.0982	11.9826	0.9982	0.0004	5.5173	0.0284	0.1428
14	42	25.158	1.5043	3	3.4	52.0	31.3736	23.7976	0.9994	0.0000	3.9412	-0.0453	0.0073
30	43	13.391	1.5043	5	3.4	43.1	16.2596	12.1332	0.9975	0.0005	6.0832	-0.0496	0.1902
11	44	13.391	0.5014	4	3.4	60.9	14.3742	12.9598	0.9988	0.0002	1.6356	-0.0200	0.0805
36	45	25.158	1.5043	4	3.4	60.9	31.4936	23.8531	0.9975	0.0001	4.6781	-0.0541	0.1879
28	46	25.158	1.5043	4	5.3	52.0	31.5349	23.9328	0.9983	0.0000	4.5403	-0.0609	0.0108

RQ1 Box-Behnken Design for a European 450mm Fab

Random Order	Run #	(S) PV CF [€ Billions]	(XE) Invest [€ Billions]	(T3) Lifetime [Years]	(r) Interest [%]	(σ) Volatility [%]	(C) Call [€ Billions]	(P) Put [€ Billions]	Delta Δ	Gamma Γ	Rho ρ	Theta θ	Vega ν
1	1	1.595	0.4682	4	3.4	43.33	1.6081	1.2266	0.9735	0.1369	0.9815	-0.0285	0.3713
39	2	8.421	0.4682	4	5.3	43.33	8.9268	8.0432	0.9996	0.0001	1.4938	-0.0208	0.0192
42	3	8.421	1.4045	4	3.4	43.33	9.8775	7.2132	0.9947	0.0019	4.6299	-0.0525	0.2422
38	4	8.421	2.3408	4	1.5	43.33	10.7439	6.3167	0.9753	0.0077	7.5464	-0.0801	0.9570
37	5	8.421	0.4682	4	1.5	43.33	8.8855	7.9821	0.9993	0.0002	1.7248	-0.0084	0.0359
32	6	8.421	1.4045	5	3.4	47.33	9.9954	7.2824	0.9901	0.0027	5.2382	-0.0578	0.4677
11	7	8.421	0.4682	4	3.4	47.33	8.9175	8.0151	0.9991	0.0003	1.5848	-0.0161	0.0449
30	8	8.421	1.4045	5	3.4	39.33	9.9096	7.2534	0.9949	0.0018	5.5972	-0.0483	0.2593
17	9	8.421	1.4045	4	1.5	39.33	9.7818	7.1121	0.9954	0.0018	5.0604	-0.0293	0.2103
8	10	8.421	1.4045	5	5.3	43.33	10.0175	7.3650	0.9943	0.0017	5.0102	-0.0654	0.2830
20	11	8.421	1.4045	4	5.3	47.33	9.9681	7.3075	0.9940	0.0019	4.2269	-0.0719	0.2689
25	12	1.595	1.4045	4	1.5	43.33	1.6292	0.6249	0.7996	0.3187	2.0912	-0.0626	1.0120
2	13	15.247	0.4682	4	3.4	43.33	16.3795	14.8383	0.9999	-0.0001	1.6220	-0.0139	0.0027
19	14	8.421	1.4045	4	1.5	47.33	9.8511	7.1362	0.9908	0.0029	4.8007	-0.0413	0.3945
3	15	1.595	2.3408	4	3.4	43.33	1.6604	0.3972	0.5787	0.3289	1.8756	-0.0818	1.2162
6	16	8.421	1.4045	5	1.5	43.33	9.8763	7.1584	0.9905	0.0029	5.8754	-0.0373	0.4550
10	17	8.421	2.3408	4	3.4	39.33	10.7997	6.4277	0.9850	0.0054	7.4314	-0.0939	0.6251
7	18	8.421	1.4045	3	5.3	43.33	9.8553	7.2295	0.9975	0.0011	3.5005	-0.0695	0.1059
24	19	8.421	2.3408	5	3.4	43.33	10.9664	6.5597	0.9756	0.0068	8.2320	-0.1020	1.0621
34	20	15.247	1.4045	4	3.4	39.33	18.6295	14.0222	0.9996	0.0001	4.8603	-0.0428	0.0302
23	21	8.421	0.4682	5	3.4	43.33	8.9301	8.0289	0.9991	0.0003	1.9111	-0.0152	0.0508
18	22	8.421	1.4045	4	5.3	39.33	9.9126	7.2919	0.9974	0.0010	4.4144	-0.0647	0.1265
27	23	1.595	1.4045	4	5.3	43.33	1.6399	0.7036	0.8512	0.3056	2.0493	-0.0766	0.9136
41	24	8.421	1.4045	4	3.4	43.33	9.8775	7.2132	0.9947	0.0019	4.6299	-0.0525	0.2422
13	25	1.595	1.4045	3	3.4	43.33	1.6192	0.5908	0.8134	0.3447	1.6724	-0.0778	0.8149
21	26	8.421	0.4682	3	3.4	43.33	8.8823	7.9987	0.9998	0.0001	1.2591	-0.0150	0.0102
4	27	15.247	2.3408	4	3.4	43.33	20.9096	13.2213	0.9964	0.0007	7.8465	-0.0820	0.2834
12	28	8.421	2.3408	4	3.4	47.33	10.9034	6.4919	0.9749	0.0071	6.8334	-0.1157	0.9735
46	29	8.421	1.4045	4	3.4	43.33	9.8775	7.2132	0.9947	0.0019	4.6299	-0.0525	0.2422
31	30	8.421	1.4045	3	3.4	47.33	9.8316	7.1676	0.9953	0.0018	3.6254	-0.0559	0.1879
5	31	8.421	1.4045	3	1.5	43.33	9.7533	7.0894	0.9961	0.0016	3.8810	-0.0308	0.1580
40	32	8.421	2.3408	4	5.3	43.33	10.9503	6.5883	0.9838	0.0053	6.7490	-0.1258	0.6709
26	33	15.247	1.4045	4	1.5	43.33	18.5610	13.9290	0.9990	0.0002	5.1885	-0.0243	0.0892
9	34	8.421	0.4682	4	3.4	39.33	8.8967	8.0129	0.9998	0.0001	1.6199	-0.0145	0.0139
28	35	15.247	1.4045	4	5.3	43.33	18.7235	14.1122	0.9992	0.0000	4.4692	-0.0613	0.0391
29	36	8.421	1.4045	3	3.4	39.33	9.7784	7.1571	0.9981	0.0009	3.7347	-0.0476	0.0812
45	37	8.421	1.4045	4	3.4	43.33	9.8775	7.2132	0.9947	0.0019	4.6299	-0.0525	0.2422
33	38	1.595	1.4045	4	3.4	39.33	1.6247	0.6265	0.8266	0.3324	2.1764	-0.0644	0.9341
22	39	8.421	2.3408	3	3.4	43.33	10.7275	6.3521	0.9856	0.0055	5.8162	-0.1034	0.5186
43	40	8.421	1.4045	4	3.4	43.33	9.8775	7.2132	0.9947	0.0019	4.6299	-0.0525	0.2422
36	41	15.247	1.4045	4	3.4	47.33	18.6633	14.0247	0.9985	0.0003	4.7545	-0.0468	0.1085
44	42	8.421	1.4045	4	3.4	43.33	9.8775	7.2132	0.9947	0.0019	4.6299	-0.0525	0.2422
15	43	1.595	1.4045	5	3.4	43.33	1.6586	0.7309	0.8351	0.2853	2.4123	-0.0634	1.0847
16	44	15.247	1.4045	5	3.4	43.33	18.7074	14.0683	0.9984	0.0002	5.7246	-0.0441	0.1200
14	45	15.247	1.4045	3	3.4	43.33	18.5843	13.9796	0.9997	0.0001	3.7806	-0.0444	0.0224
35	46	1.595	1.4045	4	3.4	47.33	1.6512	0.7035	0.8251	0.2933	1.9695	-0.0751	0.9867

RQ2 Box-Behnken Design for an American 450mm Fab

Random Order	Run #	(S) PV CF [$ Billions]	(Xs) Invest [$ Billions]	(T3) Lifetime [Years]	(r) Interest [%]	(σ) Volatility [%]	(C) Call [$ Billions]	(P) Put [$ Billions]	Delta Δ	Gamma Γ	Rho ρ	Theta θ	Vega ν
14	1	25.158	1.5043	3	3.4	52.0	25.1592	0.0015	-0.0002	0.0000	-0.0207	-0.0025	0.0310
28	2	25.158	1.5043	4	5.3	52.0	25.1638	0.0041	-0.0004	0.0001	-0.0613	-0.0040	0.0739
46	3	13.391	1.5043	4	3.4	52.0	13.4275	0.0233	-0.0036	0.0007	-0.2951	-0.0158	0.2812
36	4	25.158	1.5043	4	3.4	60.9	25.1806	0.0194	-0.0015	0.0001	-0.2257	-0.0157	0.2318
37	5	13.391	0.5014	4	1.5	52.0	13.3912	0.0029	-0.0005	0.0001	-0.0425	-0.0028	0.0455
32	6	13.391	1.5043	5	3.4	60.9	13.5065	0.0916	-0.0087	0.0013	-1.0047	-0.0357	0.6986
34	7	25.158	1.5043	4	3.4	43.1	25.1587	0.0008	-0.0001	0.0000	-0.0157	-0.0010	0.0212
16	8	25.158	1.5043	5	3.4	52.0	25.1742	0.0123	-0.0010	0.0001	-0.1935	-0.0084	0.1873
2	9	25.158	0.5014	4	3.4	52.0	25.1580	0.0004	0.0000	0.0000	-0.0068	-0.0005	0.0087
45	10	13.391	1.5043	4	3.4	52.0	13.4275	0.0233	-0.0036	0.0007	-0.2951	-0.0158	0.2812
33	11	1.624	1.5043	4	3.4	43.1	2.1781	0.3427	-0.1911	0.3623	-3.1868	-0.0317	1.0911
22	12	13.391	2.5072	3	3.4	52.0	13.5848	0.0479	-0.0084	0.0019	-0.4669	-0.0401	0.5237
7	13	13.391	1.5043	3	5.3	52.0	13.4016	0.0079	-0.0016	0.0004	-0.0940	-0.0084	0.1160
20	14	13.391	1.5043	4	5.3	60.9	13.4618	0.0472	-0.0056	0.0010	-0.4893	-0.0257	0.4234
26	15	25.158	1.5043	4	1.5	52.0	25.1674	0.0071	-0.0007	0.0001	-0.1025	-0.0073	0.1175
43	16	13.391	1.5043	4	3.4	52.0	13.4275	0.0233	-0.0036	0.0007	-0.2951	-0.0158	0.2812
21	17	13.391	0.5014	3	3.4	52.0	13.3910	0.0006	-0.0001	0.0000	-0.0094	-0.0010	0.0122
30	18	13.391	1.5043	5	3.4	43.1	13.4058	0.0124	-0.0023	0.0005	-0.2240	-0.0073	0.2051
29	19	13.391	1.5043	3	3.4	43.1	13.3935	0.0021	-0.0006	0.0002	-0.0332	-0.0028	0.0448
17	20	13.391	1.5043	4	1.5	43.1	13.4030	0.0084	-0.0018	0.0005	-0.1378	-0.0073	0.1456
39	21	13.391	0.5014	4	5.3	52.0	13.3911	0.0016	-0.0003	0.0001	-0.0250	-0.0015	0.0280
6	22	13.391	1.5043	5	1.5	52.0	13.4713	0.0527	-0.0065	0.0011	-0.7009	-0.0256	0.5335
44	23	13.391	1.5043	4	3.4	52.0	13.4275	0.0233	-0.0036	0.0007	-0.2951	-0.0158	0.2812
10	24	13.391	2.5072	4	3.4	43.1	13.5403	0.0329	-0.0064	0.0015	-0.4648	-0.0215	0.4726
27	25	1.624	1.5043	4	5.3	52.0	2.2128	0.3837	-0.1689	0.3453	-2.9657	-0.0348	1.1400
8	26	13.391	1.5043	5	5.3	52.0	13.4418	0.0314	-0.0042	0.0008	-0.4411	-0.0141	0.3618
40	27	13.391	2.5072	4	5.3	52.0	13.6330	0.0758	-0.0108	0.0021	-0.8144	-0.0386	0.7599
13	28	1.624	1.5043	3	3.4	52.0	2.2167	0.3915	-0.2044	0.3395	-2.4802	-0.0548	0.9568
23	29	13.391	0.5014	5	3.4	52.0	13.3916	0.0047	-0.0007	0.0002	-0.0751	-0.0032	0.0713
41	30	13.391	1.5043	4	3.4	52.0	13.4275	0.0233	-0.0036	0.0007	-0.2951	-0.0158	0.2812
31	31	13.391	1.5043	3	3.4	60.9	13.4353	0.0282	-0.0042	0.0008	-0.2601	-0.0254	0.2793
1	32	1.624	0.5014	4	3.4	52.0	1.7297	0.0818	-0.0424	0.1367	-0.7643	-0.0236	0.4630
38	33	13.391	2.5072	4	1.5	52.0	13.7243	0.1129	-0.0150	0.0027	-1.1765	-0.0605	0.9989
42	34	13.391	1.5043	4	3.4	52.0	13.4275	0.0233	-0.0036	0.0007	-0.2951	-0.0158	0.2812
9	35	13.391	0.5014	4	3.4	43.1	13.3910	0.0003	-0.0001	0.0000	-0.0074	-0.0004	0.0085
19	36	13.391	1.5043	4	1.5	60.9	13.4913	0.0694	-0.0078	0.0013	-0.6895	-0.0402	0.5615
15	37	1.624	1.5043	5	3.4	52.0	2.2851	0.4861	-0.1846	0.3020	-3.8470	-0.0412	1.2948
4	38	25.158	2.5072	4	3.4	52.0	25.2553	0.0252	-0.0023	0.0003	-0.3207	-0.0204	0.3561
18	39	13.391	1.5043	4	5.3	43.1	13.3978	0.0045	-0.0010	0.0003	-0.0712	-0.0037	0.0866
5	40	13.391	1.5043	3	1.5	52.0	13.4069	0.0123	-0.0024	0.0006	-0.1399	-0.0136	0.1648
25	41	1.624	1.5043	4	1.5	52.0	2.3082	0.5050	-0.2142	0.2900	-3.4254	-0.0608	1.1329
24	42	13.391	2.5072	5	3.4	52.0	13.7457	0.1430	-0.0162	0.0026	-1.5855	-0.0514	1.1959
3	43	1.624	2.5072	4	3.4	52.0	3.3192	1.1433	-0.4314	0.3500	-1.9070	-0.0339	0.7709
35	44	1.624	1.5043	4	3.4	60.9	2.3295	0.5446	-0.1921	0.2778	-3.1561	-0.0612	1.1560
11	45	13.391	0.5014	4	3.4	60.9	13.3919	0.0074	-0.0010	0.0002	-0.0859	-0.0060	0.0883
12	46	13.391	2.5072	4	3.4	60.9	13.8111	0.1865	-0.0190	0.0028	-1.5404	-0.0798	1.2209

RQ2 Box-Behnken Design for a European 450mm Fab

Random Order	Run #	(S) PV CF [€ Billions]	(Xs) Invest [€ Billions]	(T3) Lifetime [Years]	(r) Interest [%]	(σ) Volatility [%]	(C) Call [€ Billions]	(P) Put [€ Billions]	Delta Δ	Gamma Γ	Rho ρ	Theta θ	Vega ν
27	1	1.595	1.4045	4	5.3	43.33	2.0529	0.2456	-0.1430	0.4097	-2.6447	-0.0210	1.0345
11	2	8.421	0.4682	4	3.4	47.33	8.4212	0.0029	-0.0009	0.0003	-0.0473	-0.0024	0.0470
10	3	8.421	2.3408	4	3.4	39.33	8.6411	0.0514	-0.0156	0.0058	-0.7121	-0.0259	0.6505
14	4	15.247	1.4045	3	3.4	43.33	15.2477	0.0011	-0.0003	0.0001	-0.0180	-0.0016	0.0254
8	5	8.421	1.4045	5	5.3	43.33	8.4580	0.0222	-0.0057	0.0018	-0.3686	-0.0089	0.2960
45	6	8.421	1.4045	4	3.4	43.33	8.4526	0.0183	-0.0053	0.0019	-0.2705	-0.0110	0.2457
32	7	8.421	1.4045	5	3.4	47.33	8.4878	0.0473	-0.0099	0.0028	-0.6654	-0.0184	0.4833
36	8	15.247	1.4045	4	3.4	47.33	15.2571	0.0074	-0.0013	0.0003	-0.1122	-0.0062	0.1207
41	9	8.421	1.4045	4	3.4	43.33	8.4526	0.0183	0.0053	0.0019	-0.2705	-0.0110	0.2457
5	10	8.421	1.4045	3	1.5	43.33	8.4334	0.0111	-0.0039	0.0017	-0.1460	-0.0107	0.1584
34	11	15.247	1.4045	4	3.4	39.33	15.2479	0.0015	-0.0003	0.0001	-0.0300	-0.0015	0.0363
9	12	8.421	0.4682	4	3.4	39.33	8.4210	0.0006	-0.0002	0.0001	-0.0144	-0.0006	0.0145
30	13	8.421	1.4045	5	3.4	39.33	8.4518	0.0176	-0.0051	0.0018	-0.3232	-0.0082	0.2645
22	14	8.421	2.3408	3	3.4	43.33	8.6366	0.0458	-0.0148	0.0057	-0.5045	-0.0327	0.5326
31	15	8.421	1.4045	3	3.4	47.33	8.4456	0.0150	-0.0047	0.0018	-0.1779	-0.0129	0.1896
12	16	8.421	2.3408	4	3.4	47.33	8.7576	0.1183	-0.0262	0.0076	-1.2173	-0.0496	1.0128
13	17	1.595	1.4045	3	3.4	43.33	2.0597	0.2634	-0.1829	0.3982	-2.2153	-0.0372	0.8628
25	18	1.595	1.4045	4	1.5	43.33	2.1378	0.3548	-0.2008	0.3494	-3.1112	-0.0452	1.0503
3	19	1.595	2.3408	4	3.4	43.33	3.1383	0.9475	-0.5227	0.3912	-1.8912	-0.0306	0.8616
46	20	8.421	1.4045	4	3.4	43.33	8.4526	0.0183	-0.0053	0.0019	-0.2705	-0.0110	0.2457
7	21	8.421	1.4045	3	5.3	43.33	8.4291	0.0066	-0.0025	0.0011	-0.0932	-0.0061	0.1070
20	22	8.421	1.4045	4	5.3	47.33	8.4599	0.0232	-0.0060	0.0020	-0.3118	-0.0123	0.2776
15	23	1.595	1.4045	5	3.4	43.33	2.1141	0.3283	-0.1665	0.3667	-3.4889	-0.0286	1.2078
16	24	15.247	1.4045	5	3.4	43.33	15.2573	0.0078	-0.0013	0.0003	-0.1444	-0.0050	0.1384
4	25	15.247	2.3408	4	3.4	43.33	15.3310	0.0189	-0.0034	0.0008	-0.2798	-0.0142	0.3057
40	26	8.421	2.3408	4	5.3	43.33	8.6534	0.0646	-0.0174	0.0060	-0.7930	-0.0287	0.7231
37	27	8.421	0.4682	4	1.5	43.33	8.4210	0.0021	-0.0007	0.0003	-0.0372	-0.0018	0.0365
21	28	8.421	0.4682	3	3.4	43.33	8.4210	0.0005	-0.0002	0.0001	-0.0091	-0.0007	0.0104
1	29	1.595	0.4682	4	3.4	43.33	1.6134	0.0411	-0.0260	0.1596	-0.6669	-0.0159	0.3988
29	30	8.421	1.4045	3	3.4	39.33	8.4271	0.0044	-0.0019	0.0009	-0.0700	-0.0046	0.0816
39	31	8.421	0.4682	4	5.3	43.33	8.4210	0.0010	-0.0004	0.0001	-0.0204	-0.0009	0.0208
26	32	15.247	1.4045	4	1.5	43.33	15.2536	0.0049	-0.0010	0.0002	-0.0840	-0.0047	0.0930
33	33	1.595	1.4045	4	3.4	39.33	2.0560	0.2568	0.1688	0.4023	-2.8511	-0.0254	1.0092
38	34	8.421	2.3408	4	1.5	43.33	8.7431	0.1013	-0.0250	0.0078	-1.1648	-0.0479	0.9659
17	35	8.421	1.4045	4	1.5	39.33	8.4409	0.0139	-0.0046	0.0018	-0.2284	-0.0095	0.2112
42	36	8.421	1.4045	4	3.4	43.33	8.4526	0.0183	-0.0053	0.0019	-0.2705	-0.0110	0.2457
44	37	8.421	1.4045	4	3.4	43.33	8.4526	0.0183	-0.0053	0.0019	-0.2705	-0.0110	0.2457
24	38	8.421	2.3408	5	3.4	43.33	8.7566	0.1193	-0.0259	0.0074	-1.4980	-0.0385	1.1233
28	39	15.247	1.4045	4	5.3	43.33	15.2507	0.0025	-0.0005	0.0001	-0.0460	-0.0023	0.0540
18	40	8.421	1.4045	4	5.3	39.33	8.4327	0.0007	-0.0026	0.0011	-0.1158	-0.0047	0.1262
6	41	8.421	1.4045	5	1.5	43.33	8.4838	0.0407	-0.0096	0.0029	-0.6243	-0.0180	0.4600
43	42	8.421	1.4045	4	3.4	43.33	8.4526	0.0183	-0.0053	0.0019	-0.2705	-0.0110	0.2457
35	43	1.595	1.4045	4	3.4	47.33	2.1239	0.3404	-0.1763	0.3596	-2.8848	-0.0391	1.0753
19	44	8.421	1.4045	4	1.5	47.33	8.4808	0.0380	-0.0092	0.0029	-0.4791	-0.0217	0.3977
2	45	15.247	0.4682	4	3.4	43.33	15.2470	0.0002	0.0000	0.0000	-0.0048	-0.0003	0.0057
23	46	8.421	0.4682	5	3.4	43.33	8.4212	0.0030	-0.0009	0.0003	-0.0604	-0.0019	0.0540

RQ3 Box-Behnken Design for an American 450mm Fab

Random Order	Run #	(S) PV CF [$ Billions]	(X3) Invest [$ Billions]	(T2A) Lifetime [Years]	(r) Interest [%]	(σ) Volatility [%]	(C) Call [$ Billions]	Delta Δ	Gamma Γ	Rho ρ	Theta θ	Vega ν
23	1	13.391	4.0153	5	3.4	52.0	10.4179	0.9560	0.0056	14.1202	-0.0326	3.0255
32	2	13.391	5.0153	5	3.4	60.9	10.2625	0.9345	0.0065	13.3428	-0.0426	4.1577
27	3	1.624	5.0153	4	5.3	52.0	0.3670	0.4540	0.2098	2.1175	-0.0289	1.5277
28	4	25.158	5.0153	4	5.3	52.0	21.5880	0.9840	0.0012	18.5715	-0.0169	2.4606
9	5	13.391	4.0153	4	3.4	43.1	10.1518	0.9674	0.0053	16.3608	-0.0161	2.3749
3	6	1.624	6.0153	4	3.4	52.0	0.2758	0.3639	0.1989	1.8072	-0.0258	1.4492
1	7	1.624	4.0153	4	3.4	52.0	0.3977	0.4834	0.2125	2.2040	-0.0303	1.5311
38	8	13.391	6.0153	4	1.5	52.0	9.0590	0.9058	0.0102	17.9919	-0.0281	5.4734
45	9	13.391	5.0153	4	3.4	52.0	9.8677	0.9392	0.0071	15.8325	-0.0249	3.9212
8	10	13.391	5.0153	5	5.3	52.0	10.1893	0.9482	0.0063	14.8786	-0.0347	3.4577
33	11	1.624	5.0153	4	3.4	43.1	0.1998	0.3105	0.2286	1.7455	-0.0236	1.3528
20	12	13.391	5.0153	4	5.3	60.9	10.4744	0.9448	0.0057	12.6866	-0.0302	3.6327
42	13	13.391	5.0153	4	3.4	52.0	9.8677	0.9392	0.0071	15.8325	-0.0249	3.9212
18	14	13.391	5.0153	4	5.3	43.1	9.8795	0.9594	0.0064	17.3860	-0.0199	2.8463
12	15	13.391	6.0153	4	3.4	60.9	9.8277	0.9190	0.0077	14.4843	-0.0331	4.8890
29	16	13.391	5.0153	3	3.4	43.1	9.5223	0.9500	0.0073	18.4683	-0.0128	3.3723
24	17	13.391	6.0153	5	3.4	52.0	9.4264	0.9188	0.0090	17.0921	-0.0401	4.9027
16	18	25.158	5.0153	5	3.4	52.0	21.2394	0.9794	0.0014	20.1941	-0.0246	3.0438
5	19	13.391	5.0153	3	1.5	52.0	9.5390	0.9291	0.0081	16.6648	-0.0143	4.4312
41	20	13.391	5.0153	4	3.4	52.0	9.8677	0.9392	0.0071	15.8325	-0.0249	3.9212
39	21	13.391	4.0153	4	5.3	52.0	10.6511	0.9651	0.0045	13.2196	-0.0224	2.5146
44	22	13.391	5.0153	4	3.4	52.0	9.8677	0.9392	0.0071	15.8325	-0.0249	3.9212
36	23	25.158	5.0153	4	3.4	60.9	21.5172	0.9745	0.0015	17.5531	-0.0201	3.6435
37	24	13.391	4.0153	4	1.5	52.0	10.1138	0.9485	0.0063	15.0630	-0.0210	3.4372
10	25	13.391	6.0153	4	3.4	43.1	8.9759	0.9282	0.0099	20.2814	-0.0220	4.4692
26	26	25.158	5.0153	4	1.5	52.0	20.8221	0.9752	0.0020	21.7785	-0.0128	3.5641
2	27	25.158	4.0153	4	3.4	52.0	21.8781	0.9871	0.0011	17.2575	-0.0132	2.0483
13	28	1.624	5.0153	3	3.4	52.0	0.2973	0.4024	0.2213	1.9349	-0.0337	1.4585
4	29	25.158	6.0153	4	3.4	52.0	20.5998	0.9720	0.0019	22.6700	-0.0167	3.9436
30	30	13.391	5.0153	5	3.4	43.1	9.5616	0.9473	0.0078	18.5475	-0.0294	3.5018
46	31	13.391	5.0153	4	3.4	52.0	9.8677	0.9392	0.0071	15.8325	-0.0249	3.9212
14	32	25.158	5.0153	3	3.4	52.0	21.2079	0.9803	0.0013	19.9936	-0.0103	2.9375
43	33	13.391	5.0153	4	3.4	52.0	9.8677	0.9392	0.0071	15.8325	-0.0249	3.9212
22	34	13.391	6.0153	3	3.4	52.0	9.3700	0.9217	0.0087	17.1279	-0.0185	4.7814
17	35	13.391	5.0153	4	1.5	43.1	9.1743	0.9363	0.0090	19.7073	-0.0183	4.0699
31	36	13.391	5.0153	3	3.4	60.9	10.2009	0.9370	0.0063	13.3816	-0.0208	4.0413
15	37	1.624	5.0153	5	3.4	52.0	0.3541	0.4309	0.1981	2.0403	-0.0249	1.5391
40	38	13.391	6.0153	4	5.3	52.0	9.7109	0.9329	0.0078	16.2935	-0.0275	4.2412
11	39	13.391	4.0153	4	3.4	60.9	10.6686	0.9522	0.0051	12.0763	-0.0275	3.2397
6	40	13.391	5.0153	5	1.5	52.0	9.5897	0.9259	0.0084	16.6633	-0.0390	4.5694
7	41	13.391	5.0153	3	5.3	52.0	10.1382	0.9505	0.0061	14.8609	-0.0186	3.3439
25	42	1.624	5.0153	4	1.5	52.0	0.2912	0.3805	0.2027	1.8673	-0.0269	1.4660
19	43	13.391	5.0153	4	1.5	60.9	9.9648	0.9253	0.0072	14.1302	-0.0309	4.5965
35	44	1.624	5.0153	4	3.4	60.9	0.4640	0.5083	0.1797	2.0594	-0.0309	1.5412
21	45	13.391	4.0153	3	3.4	52.0	10.3734	0.9586	0.0053	14.0539	-0.0144	2.8979
34	46	25.158	5.0153	4	3.4	43.1	20.9975	0.9875	0.0014	22.6055	-0.0110	1.9868

RQ3 Box-Behnken Design for a European 450mm Fab

Random Order	Run #	(S) PV CF [€ Billions]	(X3) Invest [€ Billions]	(T2A) Lifetime [Years]	(r) Interest [%]	(σ) Volatility [%]	(C) Call [€ Billions]	Delta Δ	Gamma Γ	Rho ρ	Theta θ	Vega ν
34	1	15.247	4.6815	4	3.4	39.33	11.4312	0.9717	0.0046	19.8617	-0.0131	2.4090
19	2	8.421	4.6815	4	1.5	47.33	5.0310	0.8709	0.0226	13.4242	-0.0296	4.2979
18	3	8.421	4.6815	4	5.3	39.33	5.2632	0.9184	0.0193	14.4421	-0.0237	3.0857
1	4	1.595	3.6815	4	3.4	43.33	0.2851	0.4146	0.2561	2.1468	-0.0269	1.4630
8	5	8.421	4.6815	5	5.3	43.33	5.4199	0.9104	0.0186	13.3225	-0.0341	3.3115
4	6	15.247	5.6815	4	3.4	43.33	10.9259	0.9495	0.0066	20.8703	-0.0178	3.8687
32	7	8.421	4.6815	5	3.4	47.33	5.3150	0.8889	0.0199	12.8676	-0.0387	3.8731
9	8	8.421	3.6815	4	3.4	39.33	5.5274	0.9360	0.0160	13.7084	-0.0197	2.5580
5	9	8.421	4.6815	3	1.5	43.33	4.8369	0.8750	0.0240	14.4964	-0.0179	4.2148
27	10	1.595	4.6815	4	5.3	43.33	0.2497	0.3737	0.2475	1.9850	-0.0251	1.4275
17	11	8.421	4.6815	4	1.5	39.33	4.6898	0.8753	0.0264	15.6690	-0.0246	4.1959
36	12	15.247	4.6815	4	3.4	47.33	11.6559	0.9607	0.0049	17.5213	-0.0177	3.1551
25	13	1.595	4.6815	4	1.5	43.33	0.1812	0.2908	0.2251	1.6194	-0.0222	1.2889
29	14	8.421	4.6815	3	3.4	39.33	4.9620	0.9012	0.0221	15.0835	-0.0169	3.5677
10	15	8.421	5.6815	4	3.4	39.33	4.5059	0.8582	0.0286	15.9464	-0.0279	4.5888
22	16	8.421	5.6815	3	3.4	43.33	4.6643	0.8591	0.0259	14.7739	-0.0221	4.5790
35	17	1.595	4.6815	4	3.4	47.33	0.2699	0.3801	0.2272	1.9254	-0.0258	1.4372
40	18	8.421	5.6815	4	5.3	43.33	4.9666	0.8798	0.0232	14.2978	-0.0291	4.0962
21	19	8.421	3.6815	3	3.4	43.33	5.6152	0.9316	0.0152	12.6953	-0.0156	2.7036
41	20	8.421	4.6815	4	3.4	43.33	5.1300	0.8936	0.0213	13.9805	-0.0265	3.7508
38	21	8.421	5.6815	4	1.5	43.33	4.4065	0.8300	0.0294	15.1129	-0.0312	5.1702
37	22	8.421	3.6815	4	1.5	43.33	5.3856	0.9132	0.0184	13.3998	-0.0224	3.2235
45	23	8.421	4.6815	4	3.4	43.33	5.1300	0.8936	0.0213	13.9805	-0.0265	3.7508
20	24	8.421	4.6815	4	5.3	47.33	5.5226	0.9086	0.0175	12.4094	-0.0281	3.3581
12	25	8.421	5.6815	4	3.4	47.33	4.8756	0.8567	0.0240	13.6707	-0.0321	4.6227
7	26	8.421	4.6815	3	5.3	43.33	5.3673	0.9146	0.0178	13.3675	-0.0200	3.2025
16	27	15.247	4.6815	5	3.4	43.33	11.5553	0.9646	0.0048	18.7132	-0.0242	2.8950
43	28	8.421	4.6815	4	3.4	43.33	5.1300	0.8936	0.0213	13.9805	-0.0265	3.7508
28	29	15.247	4.6815	4	5.3	43.33	11.8784	0.9732	0.0039	17.3499	0.0168	2.3019
31	30	8.421	4.6815	3	3.4	47.33	5.2568	0.8934	0.0195	12.9432	-0.0208	3.7647
2	31	15.247	3.6815	4	3.4	43.33	12.1950	0.9797	0.0031	16.0075	-0.0129	1.8222
39	32	8.421	3.6815	4	5.3	43.33	5.8696	0.9431	0.0133	12.0445	-0.0225	2.3351
42	33	8.421	4.6815	4	3.4	43.33	5.1300	0.8936	0.0213	13.9805	-0.0265	3.7508
3	34	1.595	5.6815	4	3.4	43.33	0.1650	0.2691	0.2158	1.5186	-0.0208	1.2451
15	35	1.595	4.6815	5	3.4	43.33	0.2361	0.3469	0.2286	1.8728	-0.0215	1.4167
23	36	8.421	3.6815	5	3.4	43.33	5.6606	0.9270	0.0159	12.6998	-0.0317	2.8296
44	37	8.421	4.6815	4	3.4	43.33	5.1300	0.8936	0.0213	13.9805	-0.0265	3.7508
46	38	8.421	4.6815	4	3.4	43.33	5.1300	0.8936	0.0213	13.9805	-0.0265	3.7508
24	39	8.421	5.6815	5	3.4	43.33	4.7250	0.8543	0.0262	14.6619	-0.0399	4.6807
6	40	8.421	4.6815	5	1.5	43.33	4.8920	0.8695	0.0244	-0.0388	-0.0388	4.3357
30	41	8.421	4.6815	5	3.4	39.33	5.0108	0.8960	0.0229	15.0339	-0.0337	3.6920
33	42	1.595	4.6815	4	3.4	39.33	0.1611	0.2791	0.2440	1.6296	-0.0213	1.2609
11	43	8.421	3.6815	4	3.4	47.33	5.7474	0.9246	0.0152	11.8363	-0.0249	2.8996
13	44	1.595	4.6815	3	3.4	43.33	0.1879	0.3143	0.2521	1.7132	-0.0283	1.3026
14	45	15.247	4.6815	3	3.4	43.33	11.5234	0.9665	0.0047	18.5678	-0.0106	2.7805
26	46	15.247	4.6815	4	1.5	43.33	11.1681	0.9566	0.0058	20.0366	-0.0138	3.4194

RQ4 Box-Behnken Design for an American 450mm Fab

Random Order	Run #	(S) PV CF [$ Billions]	(Sv) Salvage [$ Billions]	(T3) Lifetime [Years]	(r) Interest [%]	(σ) Volatility [%]	(C) Call [$ Billions]	(P) Put [$ Millions]	Delta Δ	Gamma Γ	Rho ρ	Theta θ	Vega ν
30	1	13.391	3.228	5	3.4	43.1	13.5016	115.9600	-0.0173	0.0033	-1.5931	-0.0441	1.2739
36	2	25.158	3.228	4	3.4	60.9	25.2889	133.1300	-0.0084	0.0007	-1.2685	-0.0761	1.1415
8	3	13.391	3.228	5	5.3	52.0	13.5853	209.7700	-0.0231	0.0037	-2.2550	-0.0613	1.6381
15	4	1.624	3.228	5	3.4	52.0	3.3944	1792.5300	-0.5726	0.3361	-3.1449	-0.0292	0.9737
12	5	13.391	4.228	4	3.4	60.9	13.9997	586.7100	-0.0500	0.0065	-4.3199	-0.1735	2.7621
25	6	1.624	3.228	4	1.5	52.0	3.4544	1816.8100	-0.5407	0.3066	-4.5552	-0.0488	1.0136
6	7	13.391	3.228	5	1.5	52.0	13.6779	314.2300	-0.0315	0.0046	-3.2970	-0.1000	2.1133
32	8	13.391	3.228	5	3.4	60.9	13.8449	442.3200	-0.0342	0.0043	-3.7528	-0.1117	2.2540
34	9	25.158	3.228	4	3.4	43.1	25.1675	13.1900	-0.0016	0.0002	-0.2075	-0.0121	0.2570
35	10	1.624	3.228	4	3.4	60.9	3.4664	1836.3600	-0.4901	0.3230	-2.4162	-0.0390	0.7915
23	11	13.391	2.228	5	3.4	52.0	13.4906	104.1900	-0.0123	0.0021	-1.1717	-0.0409	0.9400
7	12	13.391	3.228	3	5.3	52.0	13.4759	85.8600	-0.0144	0.0030	-0.7707	-0.0592	0.8397
3	13	1.624	4.228	4	3.4	52.0	4.2683	2651.4900	-0.8503	0.3118	-3.8343	-0.0312	0.9811
11	14	13.391	2.228	4	3.4	60.9	13.5208	138.4200	-0.0147	0.0023	-1.1985	-0.0649	0.9861
5	15	13.391	3.228	3	1.5	52.0	13.5099	120.8600	-0.0191	0.0038	-1.0838	-0.0877	1.0745
31	16	13.391	3.228	3	3.4	60.9	13.5728	205.0800	-0.0250	0.0042	-1.4889	-0.1207	1.3557
20	17	13.391	3.228	4	5.3	60.9	13.6649	280.3800	-0.0276	0.0040	-2.2470	-0.0996	1.6995
18	18	13.391	3.228	4	5.3	43.1	13.4480	57.7800	-0.0107	0.0025	-0.7247	-0.0307	0.7474
39	19	13.391	2.228	4	5.3	52.0	13.4399	52.8500	-0.0079	0.0016	-0.5765	-0.0296	0.5735
26	20	25.158	3.228	4	1.5	52.0	25.2040	66.4400	-0.0055	0.0006	-0.7928	-0.0482	0.7876
1	21	1.624	2.228	4	3.4	52.0	2.5826	912.0400	-0.3542	0.3548	-3.0660	-0.0382	0.9794
22	22	13.391	4.228	3	3.4	52.0	13.5897	230.5900	-0.0336	0.0062	-1.8368	-0.1287	1.7253
44	23	13.391	3.228	4	3.4	52.0	13.5504	178.0400	-0.0227	0.0039	-1.7656	-0.0787	1.4420
41	24	13.391	3.228	4	3.4	52.0	13.5504	178.0400	-0.0227	0.0039	-1.7656	-0.0787	1.4420
10	25	13.391	4.228	4	3.4	43.1	13.5463	175.8500	-0.0283	0.0057	-1.9944	-0.0763	1.7309
33	26	1.624	3.228	4	3.4	43.1	3.2860	1668.8000	-0.8078	0.3599	-3.3121	-0.0296	1.0729
14	27	25.158	3.228	3	3.4	52.0	25.1751	21.3800	-0.0024	0.0003	0.2368	-0.0248	0.3176
2	28	25.158	2.228	4	3.4	52.0	25.1704	16.7400	-0.0016	0.0002	-0.2166	-0.0146	0.2526
46	29	13.391	3.228	4	3.4	52.0	13.5504	178.0400	-0.0227	0.0039	-1.7656	-0.0787	1.4420
28	30	25.158	3.228	4	5.3	52.0	25.1868	42.1300	-0.0037	0.0004	-0.5076	-0.0292	0.5521
37	31	13.391	2.228	4	1.5	52.0	13.4643	79.4600	-0.0110	0.0021	-0.8642	-0.0467	0.7681
42	32	13.391	3.228	4	3.4	52.0	13.5504	178.0400	-0.0227	0.0039	-1.7656	-0.0787	1.4420
4	33	25.158	4.228	4	3.4	52.0	25.2749	119.2500	-0.0093	0.0010	-1.3034	-0.0704	1.2539
45	34	13.391	3.228	4	3.4	52.0	13.5504	178.0400	-0.0227	0.0039	-1.7656	-0.0787	1.4420
38	35	13.391	4.228	4	1.5	52.0	13.8224	424.4100	-0.0466	0.0070	-3.8333	-0.1553	2.6101
29	36	13.391	3.228	3	3.4	43.1	13.4142	36.6200	-0.0083	0.0022	-0.4265	-0.0323	0.5174
13	37	1.624	3.228	3	3.4	52.0	3.3304	1717.1800	-0.7186	0.3355	-2.4855	-0.0477	0.8758
40	38	13.391	4.228	4	5.3	52.0	13.7014	303.6500	-0.0362	0.0059	-2.6195	-0.1016	2.0973
16	39	25.158	3.228	5	3.4	52.0	25.2463	94.9900	-0.0066	0.0006	-1.2154	-0.0458	1.0400
21	40	13.391	2.228	3	3.4	52.0	13.4113	31.4400	-0.0058	0.0013	-0.3135	-0.0288	0.3735
43	41	13.391	3.228	4	3.4	52.0	13.5504	178.0400	-0.0227	0.0039	-1.7656	-0.0787	1.4420
9	42	13.391	2.228	4	3.4	43.1	13.4054	21.0600	-0.0042	0.0011	-0.3051	-0.0151	0.3280
17	43	13.391	3.228	4	1.5	43.1	13.4827	93.5500	-0.0161	0.0035	-1.1909	-0.0533	1.0717
19	44	13.391	3.228	4	1.5	60.9	13.7585	379.0200	-0.0344	0.0047	-3.0083	-0.1436	2.0351
24	45	13.391	4.228	5	3.4	52.0	13.8908	479.3000	-0.0454	0.0063	-4.6111	-0.1164	2.8410
27	46	1.624	3.228	4	5.3	52.0	3.3059	1706.1100	-0.7343	0.3666	-2.7594	-0.0310	1.0398

RQ4 Box-Behnken Design for a European 450mm Fab

Random Order	Run #	(S) PV CF [€ Billions]	(Sv) Salvage [€ Billions]	(T3) Lifetime [Years]	(r) Interest [%]	(σ) Volatility [%]	(C) Call [€ Billions]	(P) Put [€ Millions]	Delta Δ	Gamma Γ	Rho ρ	Theta θ	Vega ν
20	1	8.421	3.152	4	5.3	47.33	8.6454	213.3400	-0.0445	0.0123	-2.0154	-0.0668	1.5804
19	2	8.421	3.152	4	1.5	47.33	8.7400	306.1400	-0.0584	0.0147	-2.8850	-0.1058	1.9717
16	3	15.247	3.152	5	3.4	43.33	15.3316	83.8900	-0.0116	0.0021	-1.2104	-0.0364	1.0310
34	4	15.247	3.152	4	3.4	39.33	15.2658	26.8600	-0.0053	0.0013	-0.4114	-0.0192	0.4611
41	5	8.421	3.152	4	3.4	43.33	8.6128	188.5500	-0.0439	0.0130	-2.0001	-0.0679	1.5674
21	6	8.421	2.152	3	3.4	43.33	8.4458	31.2600	-0.0106	0.0043	-0.3558	-0.0249	0.4007
33	7	1.595	3.152	4	3.4	39.33	3.1788	1586.4600	-0.8767	0.3598	-3.1630	-0.0234	1.0232
23	8	8.421	2.152	5	3.4	43.33	8.5024	90.6800	-0.0206	0.0062	-1.1562	-0.0324	0.9289
10	9	8.421	4.152	4	3.4	39.33	8.8180	313.4700	-0.0755	0.0223	-3.2229	-0.0908	2.4040
27	10	1.595	3.152	4	5.3	43.33	3.1583	1572.0000	-0.9015	0.3851	-2.7715	-0.0206	1.0583
30	11	8.421	3.152	5	3.4	39.33	8.6084	181.9000	-0.0421	0.0125	-2.3568	-0.0504	1.6893
32	12	8.421	3.152	5	3.4	47.33	8.7702	337.1500	-0.0564	0.0133	-3.4590	-0.0783	2.1514
37	13	8.421	2.152	4	1.5	43.33	8.4928	74.2200	-0.0193	0.0063	-0.8833	-0.0389	0.7798
15	14	1.595	3.152	5	3.4	43.33	3.2306	1654.3800	-0.7399	0.3561	-3.4328	-0.0247	1.1078
44	15	8.421	3.152	4	3.4	43.33	8.6128	188.5500	-0.0439	0.0130	-2.0001	-0.0679	1.5674
28	16	15.247	3.152	4	5.3	43.33	15.2803	38.5600	-0.0067	0.0014	-0.5126	-0.0236	0.5616
31	17	8.421	3.152	3	3.4	47.33	8.5832	169.0600	-0.0424	0.0132	-1.4491	-0.0878	1.3210
8	18	8.421	3.152	5	5.3	43.33	8.6360	204.7600	-0.0423	0.0117	-2.3452	-0.0482	1.6865
22	19	8.421	4.152	3	3.4	43.33	8.7339	297.5400	-0.0756	0.0231	-2.4281	-0.1228	2.0813
29	20	8.421	3.152	3	3.4	39.33	8.4957	79.3900	-0.0272	0.0109	-0.8576	-0.0498	0.9078
46	21	8.421	3.152	4	3.4	43.33	8.6128	188.5500	-0.0439	0.0130	-2.0001	-0.0679	1.5674
18	22	8.421	3.152	4	5.3	39.33	8.5148	104.5600	-0.0301	0.0107	-1.2006	-0.0394	1.1247
13	23	1.595	3.152	3	3.4	43.33	3.1904	1596.0700	-0.8599	0.3447	-2.5425	-0.0334	0.8613
45	24	8.421	3.152	4	3.4	43.33	8.6128	188.5500	-0.0439	0.0130	-2.0001	-0.0679	1.5674
5	25	8.421	3.152	3	1.5	43.33	8.5465	144.2200	-0.0406	0.0137	-1.4011	-0.0849	1.2725
40	26	8.421	4.152	4	5.3	43.33	8.7708	348.6900	-0.0754	0.0209	-3.1770	-0.0877	2.3960
26	27	15.247	3.152	4	1.5	43.33	15.3011	64.1100	-0.0103	0.0020	-0.8622	-0.0418	0.8310
17	28	8.421	3.152	4	1.5	39.33	8.5663	164.2000	-0.0431	0.0138	-1.9856	-0.0685	1.5439
7	29	8.421	3.152	3	5.3	43.33	8.5080	100.3300	-0.0303	0.0111	-0.9379	-0.0549	0.9889
35	30	1.595	3.152	4	3.4	47.33	3.2466	1667.2100	-0.7157	0.3462	-2.8534	-0.0330	0.9672
12	31	8.421	4.152	4	3.4	47.33	8.9327	519.8500	-0.0910	0.0213	-4.1734	-0.1260	2.7291
4	32	15.247	4.152	4	3.4	43.33	15.3709	126.3400	-0.0190	0.0035	-1.5111	-0.0633	1.4077
3	33	1.595	4.152	4	3.4	43.33	4.1520	2553.9200	-0.9952	0.2906	-2.3386	-0.0087	0.5268
42	34	8.421	3.152	4	3.4	43.33	8.6128	188.5500	-0.0439	0.0130	-2.0001	-0.0679	1.5674
36	35	15.247	3.152	4	3.4	47.33	15.3291	81.8400	-0.0116	0.0021	-0.9747	-0.0464	0.9243
25	36	1.595	3.152	4	1.5	43.33	3.2878	1686.9400	-0.6802	0.3213	-3.2170	-0.0372	0.9096
43	37	8.421	3.152	4	3.4	43.33	8.6128	188.5500	-0.0439	0.0130	-2.0001	-0.0679	1.5674
6	38	8.421	3.152	5	1.5	43.33	8.7526	317.2900	-0.0586	0.0145	-3.6361	-0.0850	2.2142
1	39	1.595	2.152	4	3.4	43.33	2.4049	791.2300	-0.4553	0.4000	-1.5870	-0.0304	0.8106
2	40	15.247	2.152	4	3.4	43.33	15.2568	12.8800	-0.0024	0.0006	-0.1958	-0.0105	0.2249
38	41	8.421	4.152	4	1.5	43.33	8.9205	491.0800	-0.0949	0.0234	-4.5521	-0.1373	2.8503
39	42	8.421	2.152	4	5.3	43.33	8.4659	46.7700	-0.0132	0.0047	-0.5882	-0.0233	0.5739
24	43	8.421	4.152	5	3.4	43.33	8.9244	515.3400	-0.0887	0.0207	-4.9159	-0.0950	2.9638
11	44	8.421	2.152	4	3.4	47.33	8.5032	89.3000	-0.0207	0.0063	0.9342	-0.0414	0.8340
9	45	8.421	2.152	4	3.4	39.33	8.4536	35.7500	-0.0114	0.0045	-0.5108	-0.0202	0.4987
14	46	15.247	3.152	3	3.4	43.33	15.2639	22.2700	-0.0047	0.0012	-0.2745	-0.0227	0.3580

RQ5 to RQ7 Box-Behnken Design for an American 450mm Fab

Random Order	Run #	(S) PV CF [$ Billions]	(X) Invest [$ Billions]	(T) Lifetime [Years]	(σ) Volatility [%]	(r) Interest [%]	(C) Call [$ Billions]	(P) Put [$ Billions]	Delta Δ	Vega ν	Theta θ	Gamma Γ	Rho ρ
33	1	1.6240	14.62	4	52.0	1.5	0.0323	12.1769	0.0624	0.3987	-0.0270	0.0727	0.2758
4	2	59.5950	18.34	4	52.0	3.4	45.0263	1.4392	0.9628	9.6850	-1.0495	0.0013	49.4031
10	3	30.6095	18.34	4	52.0	1.5	17.4108	4.0733	0.8577	13.7747	-1.0280	0.0071	35.3766
21	4	30.6095	10.90	3	52.0	3.4	21.4897	0.7232	0.9564	4.9019	-0.6895	0.0034	23.3528
24	5	30.6095	18.34	5	52.0	3.4	19.1246	3.9879	0.8786	13.8025	-0.9819	0.0057	38.8473
37	6	30.6095	10.90	4	43.1	3.4	21.6525	0.5570	0.9630	4.9506	-0.5327	0.0031	31.2979
17	7	30.6095	14.62	4	43.1	1.5	18.4383	1.5974	0.9127	9.7151	-0.6659	0.0060	38.0008
30	8	30.6095	14.62	5	52.0	1.5	20.1254	3.0795	0.9000	12.0148	-0.7361	0.0049	37.1107
35	9	1.6240	14.62	4	52.0	5.3	0.0443	10.2474	0.0824	0.4937	-0.0368	0.0900	0.3580
42	10	30.6095	14.62	4	52.0	3.4	19.9669	2.1184	0.9133	9.6697	-0.9001	0.0050	31.9533
32	11	30.6095	14.62	5	52.0	5.3	21.4827	2.0898	0.9257	9.6158	-0.8633	0.0039	34.2686
3	12	1.6240	18.34	4	52.0	3.4	0.0232	14.4072	0.0465	0.3159	-0.0223	0.0576	0.2089
13	13	1.6240	14.62	3	52.0	3.4	0.0130	11.5913	0.0303	0.1930	-0.0180	0.0469	0.1087
14	14	59.5950	14.62	3	52.0	3.4	46.8496	0.4569	0.9832	4.3180	-0.7734	0.0008	35.2243
23	15	30.6095	10.90	5	52.0	3.4	22.7802	1.3666	0.9469	7.4039	-0.5959	0.0030	31.0211
2	16	59.5950	10.90	4	52.0	3.4	50.4300	0.3490	0.9888	3.5005	-0.5165	0.0005	33.9952
43	17	30.6095	14.62	4	52.0	3.4	19.9669	2.1184	0.9133	9.6697	-0.9001	0.0050	31.9533
16	18	59.5950	14.62	5	52.0	3.4	48.3950	1.1344	0.9736	8.1593	-0.7515	0.0009	48.1246
18	19	30.6095	14.62	4	60.9	1.5	20.3163	3.4754	0.8971	10.9737	-0.9425	0.0048	28.5679
36	20	59.5950	14.62	4	52.0	5.3	48.4140	0.6461	0.9810	5.5235	-0.8916	0.0007	40.1960
22	21	30.6095	18.34	3	52.0	3.4	16.8708	2.8228	0.8712	11.1409	-1.2987	0.0076	29.3929
28	22	59.5950	14.62	4	60.9	3.4	48.2842	1.4501	0.9696	8.2088	-0.9478	0.0009	37.9866
39	23	30.6095	10.90	4	60.9	3.4	22.7619	1.6664	0.9416	7.1391	-0.7495	0.0031	24.2409
5	24	30.6095	14.62	3	43.1	3.4	18.3404	0.9332	0.9332	6.8696	-0.8410	0.0057	30.6691
11	25	30.6095	10.90	4	52.0	5.3	22.6733	0.8815	0.9570	5.5958	-0.7146	0.0029	26.4777
40	26	30.6095	18.34	4	60.9	3.4	19.2114	4.6098	0.8731	12.7349	-1.2249	0.0056	30.0561
41	27	30.6095	14.62	4	52.0	3.4	19.9669	2.1184	0.9133	9.6697	-0.9001	0.0050	31.9533
44	28	30.6095	14.62	4	52.0	3.4	19.9669	2.1184	0.9133	9.6697	-0.9001	0.0050	31.9533
1	29	1.6240	10.90	4	52.0	3.4	0.0676	7.9576	0.1190	0.6460	-0.0463	0.1178	0.5029
31	30	30.6095	14.62	3	52.0	5.3	19.5219	1.3832	0.9261	7.4214	-1.1109	0.0051	26.4760
46	31	30.6095	14.62	4	52.0	3.4	19.9669	2.1184	0.9133	9.6697	-0.9001	0.0050	31.9533
19	32	30.6095	14.62	4	43.1	5.3	19.8350	1.0526	0.9375	7.5286	-0.8753	0.0047	35.4461
15	33	1.6240	14.62	5	52.0	3.4	0.0753	10.7856	0.1226	0.7373	-0.0425	0.1075	0.6188
45	34	30.6095	14.62	4	52.0	3.4	19.9669	2.1184	0.9133	9.6697	-0.9001	0.0050	31.9533
29	35	30.6095	14.62	3	52.0	1.5	18.4903	1.8575	0.9067	8.8422	-0.9053	0.0060	27.7901
6	36	30.6095	14.62	5	43.1	3.4	19.8913	1.6161	0.9229	9.8927	-0.7106	0.0049	41.7942
12	37	30.6095	18.34	4	52.0	5.3	18.7269	2.9538	0.8881	11.6551	-1.2058	0.0060	33.8269
34	38	59.5950	14.62	4	52.0	1.5	46.8001	0.9737	0.9731	7.4008	-0.6490	0.0010	44.7728
27	39	1.6240	14.62	4	60.9	3.4	0.0899	11.2269	0.1393	0.7204	-0.0595	0.1121	0.5452
9	40	30.6095	10.90	4	52.0	1.5	21.6222	1.2779	0.9419	7.1153	-0.5706	0.0037	28.8300
38	41	30.6095	18.34	4	43.1	3.4	16.9659	2.3643	0.8816	12.1311	-0.9942	0.0075	40.0772
26	42	59.5950	14.62	4	43.1	3.4	47.1600	0.3259	0.9868	4.0552	-0.6144	0.0007	46.5824
20	43	30.6095	14.62	4	60.9	5.3	21.3703	2.5879	0.9177	9.2985	-1.0640	0.0041	26.8792
25	44	1.6240	14.62	4	43.1	3.4	0.0101	11.1471	0.0250	0.1896	-0.0112	0.0417	0.1216
7	45	30.6095	14.62	3	60.9	3.4	19.7685	2.3612	0.9074	8.7966	-1.1650	0.0051	24.0155
8	46	30.6095	14.62	5	60.9	3.4	21.7910	3.5159	0.9112	11.0020	-0.8775	0.0039	30.5056

RQ5 to RQ7 Box-Behnken Design for a European 450mm Fab

Random Order	Run #	(S) PV CF [€ Billions]	(X) Invest [€ Billions]	(T) Lifetime [Years]	(σ) Volatility [%]	(r) Interest [%]	(C) Call [€ Billions]	(P) Put [€ Billions]	Delta Δ	Vega ν	Theta θ	Gamma Γ	Rho ρ
23	1	26.335	10.91	5	43.33	3.4	18.1234	0.9877	0.9417	6.8553	-0.5242	0.0046	33.4114
9	2	26.335	10.91	4	43.33	1.5	17.0109	0.9455	0.9357	6.6238	-0.4733	0.0055	30.5416
26	3	51.080	13.51	4	39.47	3.4	39.5132	0.2253	0.9878	3.2297	-0.5315	0.0008	43.7807
17	4	26.335	13.51	4	39.47	1.5	14.9548	1.3290	0.9060	8.8351	-0.5697	0.0081	35.6726
10	5	26.335	16.11	4	43.33	1.5	13.7830	2.6148	0.8577	11.8579	-0.7744	0.0099	35.2312
19	6	26.335	13.51	4	39.47	5.3	16.2597	0.8488	0.9344	6.7308	-0.7747	0.0061	33.4049
25	7	1.590	13.51	4	39.47	3.4	0.0057	10.2078	0.0160	0.1275	-0.0070	0.0319	0.0792
42	8	26.335	13.51	4	43.33	3.4	15.9243	1.3764	0.9132	8.3277	-0.7274	0.0069	32.5166
33	9	1.590	13.51	4	43.33	1.5	0.0098	11.1431	0.0246	0.1835	-0.0104	0.0419	0.1173
7	10	26.335	13.51	3	47.19	3.4	15.4339	1.2938	0.9115	7.3139	-0.8668	0.0074	25.7286
28	11	51.080	13.51	4	47.19	3.4	39.8416	0.5538	0.9786	5.2434	-0.6542	0.0011	40.5757
34	12	51.080	13.51	4	43.33	1.5	38.8315	0.4748	0.9792	5.1164	-0.4449	0.0011	44.7413
36	13	51.080	13.51	4	43.33	5.3	40.4376	0.2867	0.9865	3.5245	-0.7185	0.0008	39.8193
27	14	1.590	13.51	4	47.19	3.4	0.0227	10.2248	0.0494	0.3246	-0.0210	0.0680	0.2231
16	15	51.080	13.51	5	43.33	3.4	40.2453	0.5632	0.9790	5.7748	-0.5820	0.0010	48.7981
8	16	26.335	13.51	5	47.19	3.4	16.9903	2.0482	0.9068	9.8136	-0.6975	0.0060	34.4771
37	17	26.335	10.91	4	39.47	3.4	17.3697	0.5524	0.9539	5.0944	-0.5150	0.0047	31.0203
31	18	26.335	13.51	3	43.33	5.3	15.6704	0.8544	0.9301	6.1171	-0.9097	0.0068	26.4874
18	19	26.335	13.51	4	47.19	1.5	15.6654	2.0486	0.8930	9.7076	-0.6905	0.0074	31.4296
32	20	26.335	13.51	5	43.33	5.3	17.3055	1.3305	0.9261	8.2473	-0.7330	0.0055	35.4343
13	21	1.590	13.51	3	43.33	3.4	0.0031	10.6131	0.0096	0.0711	-0.0056	0.0216	0.0366
5	22	26.335	13.51	3	39.47	3.4	14.9088	0.7687	0.9289	6.1995	-0.7328	0.0075	28.6752
15	23	1.590	13.51	5	43.33	3.4	0.0292	9.8371	0.0608	0.4277	-0.0208	0.0781	0.3369
43	24	26.335	13.51	4	43.33	3.4	15.9243	1.3764	0.9132	8.3277	-0.7274	0.0069	32.5166
40	25	26.335	16.11	4	47.19	3.4	14.8667	2.5882	0.8722	11.0122	-0.9252	0.0084	32.4297
3	26	1.590	16.11	4	43.33	3.4	0.0072	12.4787	0.0187	0.1453	-0.0086	0.0331	0.0898
46	27	26.335	13.51	4	43.33	3.4	15.9243	1.3764	0.9132	8.3277	-0.7274	0.0069	32.5166
6	28	26.335	13.51	5	39.47	3.4	16.2622	1.3201	0.9178	8.9376	-0.6218	0.0065	39.5627
14	29	51.080	13.51	3	43.33	3.4	39.0721	0.1921	0.9888	2.6042	-0.5769	0.0008	34.3062
1	30	1.590	10.91	4	43.33	3.4	0.0223	7.9550	0.0513	0.3349	-0.0202	0.0764	0.2373
12	31	26.335	16.11	4	43.33	5.3	15.0954	1.7879	0.8935	9.6790	-0.9715	0.0080	33.7556
29	32	26.335	13.51	3	43.33	1.5	14.6385	1.2140	0.9074	7.5675	-0.6854	0.0084	27.7863
11	33	26.335	10.91	4	43.33	5.3	18.1259	0.6117	0.9550	4.9965	-0.6431	0.0042	28.1114
35	34	1.590	13.51	4	43.33	5.3	0.0153	9.3544	0.0366	0.2551	-0.0161	0.0582	0.1720
20	35	26.335	13.51	4	47.19	5.3	16.8262	1.4153	0.9198	7.8442	-0.8550	0.0060	29.6088
2	36	51.080	10.91	4	43.33	3.4	41.7350	0.1777	0.9911	2.4483	-0.4350	0.0005	35.5706
41	37	26.335	13.51	4	43.33	3.4	15.9243	1.3764	0.9132	8.3277	-0.7274	0.0069	32.5166
38	38	26.335	16.11	4	39.47	3.4	14.0383	1.7598	0.8829	10.3552	-0.8243	0.0095	36.8730
24	39	26.335	16.11	5	43.33	3.4	15.2740	2.5254	0.8785	11.8880	-0.7825	0.0079	39.3237
39	40	26.335	10.91	4	47.19	3.4	17.8138	0.9966	0.9394	6.3231	-0.6086	0.0048	27.7215
30	41	26.335	13.51	5	43.33	1.5	15.9029	2.0968	0.8945	10.7449	-0.5805	0.0071	38.2941
44	42	26.335	13.51	4	43.33	3.4	15.9243	1.3764	0.9132	8.3277	-0.7274	0.0069	32.5166
45	43	26.335	13.51	4	43.33	3.4	15.9243	1.3764	0.9132	8.3277	-0.7274	0.0069	32.5166
21	44	26.335	10.91	3	43.33	3.4	17.0008	0.5128	0.9541	4.3967	-0.5939	0.0049	24.3877
22	45	26.335	16.11	3	43.33	3.4	13.5139	1.7217	0.8782	9.2201	-0.9929	0.0102	28.8573
4	46	51.080	16.11	4	43.33	3.4	37.6715	0.6530	0.9727	6.4295	-0.7567	0.0014	48.0531

Appendix F: Multiple Regression Models

American foundry models for RQ1 to RQ7

RQ1 American fab expand capacity option value = 0.7016 + (9.2425E-01)*S + (-1.0285)*X_E + (-4.9418E-02)*T_3 + (-1.4418E-02)*r + (-3.4366E-03)*σ + (1.7573E-01)*S*X_E + (1.7677E-03)*S*T_3 + (1.8148E-03)*S*r + (4.0105E-05)*S*σ + (6.0375E-02)*X_E*T_3 + (2.4573E-02)*X_E*r + (5.9574E-03)*X_E*σ + (5.0000E-03)*T_3*r + (8.5955E-04)*T_3*σ + (-5.6032E-04)*r*σ + (2.2545E-03)*S^2 + (-5.0747E-04)*X_E^2 + (-5.8354E-03)*T_3^2 + (-5.4767E-04)*r^2 + (1.4466E-06)*σ^2

RQ2 American fab contract capacity option value = 0.4998 + (0.9789)*S + (-0.2234)*Xs + (-5.7046E-02)*T_3 + (2.6765E-02)*r + (-8.6561E-03)*σ + (-3.1611E-02)*S*Xs + (-1.1345E-03)*S*T_3 + (1.0265E-03)*S*r + (-3.0914E-04)*S*σ + (3.9959E-02)*Xs*T_3 + (-1.1965E-02)*Xs*r + (7.5595E-03)*Xs*σ + (-3.1842E-03)*T_3*r + (1.6545E-03)*T_3*σ + (-3.5925E-04)*r*σ + (2.1254E-03)*S^2 + (1.1468E-01)*Xs^2 + (-4.5021E-03)*T_3^2 + (5.2516E-05)*r^2 + (1.1757E-05)*σ^2

RQ3 American fab defer option value = 1.7187 + (7.8053E-01)*S + (-9.0104E-01)*X_3 + (-4.8461E-02)*T_{2A} + (1.3135E-01)*r + (-3.5563E-02)*σ + (-2.4568E-02)*S*X_3 + (-5.3752E-04)*S*T_{2A} + (7.7167E-03)*S*r + (6.0992E-04)*S*σ + (2.9750E-03)*X_3*T_{2A} + (1.5079E-02)*X_3*r + (9.4101E-03)*X_3*σ + (5.2632E-05)*T_{2A}*r + (6.2640E-04)*T_{2A}*σ + (-2.8918E-03)*r*σ + (6.5335E-03)*S^2 + (2.1395E-02)*X_3^2 + (4.0600E-03)*T_{2A}^2 + (-2.0517E-03)*r^2 + (2.1212E-04)*σ^2

RQ4 American fab abandon option value = 3.3961 + (8.9673E-01)*S + (-2.7723E-01)*S_V + (-3.8813E-01)*T_3 + (5.9342E-02)*r + (-6.7464E-02)*σ + (-3.3594E-02)*S* S_V + (1.5297E-04)*S*T_3 + (1.4682E-03)*S*r + (-1.4084E-04)*S*σ + (5.5450E-02)* S_V*T_3 + (-1.2711E-02)* S_V*r + (9.4944E-03)* S_V*σ + (-7.7105E-03)*T_3*r + (5.1882E-03)*T_3*σ + (-8.7079E-04)*r*σ + (5.2629E-03)*S^2 +(4.3419E-02)*Sv^2 + (4.4438E-03)*T_3^2 + (2.8722E-03)*r^2 + (3.2701E-04)*σ^2

RQ4 American fab abandon put value = 2398.5224 + (-96.5257)*S + (-67.1161)* S_V + (-298.4384)*T_3 + (82.5660)*r + (-51.1368)*σ + (-34.7782)*S* S_V + (-3.6968E-02)*S*T_3 + (0.9660)*S*r + (-0.1137)*S*σ + (43.99)* S_V*T_3 + (-12.3882)* S_V*r + (8.2444)* S_V*σ + (-9.1395)*T_3*r + (4.4354)*T_3*σ + (-0.9295)*r*σ + (5.2035)*S^2 + (30.394)* S_V^2 + (3.2981)*T_3^2 + (1.6294)*r^2 + (0.2330)*σ^2

RQ5 American fab delta = 0.2156 + (5.2397E-02)*S + (-2.3012E-02)*X + (-1.9445E-02)*T + (-3.2556E-03)*σ +(1.1342E-03)*r + (1.0781E-04)*S*X + (-8.7889E-04)*S*T + (-1.2744E-04)*S*σ + (-5.4928E-05)*S*r + (1.1358E-03)*X*T +(9.7409E-05)*X*σ + (5.4117E-04)*X*r + (3.9607E-04)*T*σ + (8.2895E-04)*T*r + (-6.2093E-05)*σ*r + (-4.5962E-04)*S^2 + (-3.6282E-05)*X^2 + (1.3146E-03)*T^2 + (4.1530E-05)*σ^2 + (-3.0298E-04)*r^2

RQ5 to RQ7 American fab call value = 12.6324 + (0.5934)*S + (-1.1164)*X + (-1.1453)*T + (-0.1666)*σ + (3.7317E-02)*r + (-1.2426E-02)*S*X + (1.2792E-02)*S*T + (1.0121E-03)* S*σ + (7.2718E-03)*S*r + (6.4738E-02)*X*T + (8.5787E-03)*X*σ + (9.3732E-03)*X*r + (1.3247E-02)*T*σ + (4.2855E-02)*T*r + (-5.0665E-03)*σ*r + (4.5943E-03)*S^2 + (8.6822E-03)*X^2 + (-3.2152E-02)*T^2 + (5.1706E-04)*σ^2 + (-2.1105E-03)*r^2

RQ6 American fab vega = -34.6084 + (5.9394E-02)*S + (1.1466)* X + (3.6118)*T + (0.6147)*σ + (0.3326)*r + (1.5104E-02)*S*X + (2.8437E-02)*S*T + (3.5109E-03)*S*σ + (-8.9532E-03)*S*r + (1.0726E-02)*X*T + (-1.1966E-02)*X*σ + (-2.1226E-02)*X*r + (-2.2969E-02)*T*σ + (-0.1287)*T*r + (7.5591E-03)*σ*r + (-7.2594E-03)*S^2 + (-7.4709E-03)*X^2 + (-0.2185)*T^2 + (-3.7109E-03)*σ^2 + (-8.4516E-03)*r^2

RQ7 American fab theta = 2.6823 + (-1.3333E-02)*S + (-9.0779E-02)*X + (-0.4116)*T + (-3.2806E-02)*σ + (-0.1098)*r + (-1.2914E-03)*S*X + (4.0020E-04)*S*T + (-2.7629E-04)*S*σ + (-1.0568E-03)*S*r + (1.5000E-02)*X*T + (-1.0496E-04)*X*σ + (-1.1955E-03)*X*r + (4.4129E-03)*T*σ + (1.0316E-02)*T*r + (1.2995E-03)*σ*r + (5.8457E-04)*S^2 + (7.8255E-04)*X^2 + (-8.5417E-04)*T^2 + (7.8746E-05)*σ^2 + (1.4808E-03)*r^2

European foundry models for RQ1 to RQ7

RQ1 European fab expand option value = 1.1854 + (0.8797)*S + (-0.9127)*X_E + (-0.1393)*T_3 + (-2.5599E-02)*r + (-1.7851E-02)*σ + (0.1752)*S*X_E + (3.0655E-03)*S*T_3 + (2.9261E-03)*S*r + (6.6840E-05)*S*σ + (5.1025E-02)*X_E*T_3 + (2.3202E-02)*X_E*r + (5.5337E-03)*X_E*σ + (5.1579E-03)*T_3*r + (2.0375E-03)*T_3*σ + (-4.5395E-04)*r*σ + (5.6459E-03)*S^2 + (-4.6816E-04)*X_E^2 + (4.7917E-05)*T_3^2 + (-3.8146E-04)*r^2 + (1.1445E-04)*σ^2

RQ2 European fab contract option value = -0.3309 + (0.9792)*S + (-0.1144)*Xs + (-2.6833E-03)*T_3 + (3.3407E-02)*r + (1.6686E-02)*σ + (-5.6363E-02)*S*Xs + (-1.6408E-03)*S*T_3 + (1.5806E-03)*S*r + (-5.3747E-04)*S*σ + (3.1988E-02)*Xs*T_3 + (-1.2606E-02)*Xs*r + (7.7633E-03)*Xs*σ + (-2.8289E-03)*T_3*r + (1.0937E-03)*T_3*σ + (-4.1776E-04)*r*σ + (4.9886E-03)*S^2 + (1.3739E-01)*Xs^2 + (-5.6937E-03)*T_3^2 + (-1.0855E-03)*r^2 + (-2.4336E-04)*σ^2

RQ3 European fab compound call option value = 1.4135 + (6.7301E-01)*S + (-8.0960E-01)*X3 + (-4.6795E-02)*T2A + (1.0422E-01)*r + (-3.4909E-02)*σ + (-4.2082E-02)*S*X3 + (-5.9698E-04)*S*T2A + (1.2371E-02)*S*r + (1.0612E-03)*S*σ + (3.8250E-03)*X3*T2A + (1.0013E-02)*X3*r + (9.3562E-03)*X3*σ + (-3.2895E-04)*T2A*r + (5.8750E-04)*T2A*σ + (-2.6908E-03)*r*σ + (1.5904E-02)*S^2 + (2.8679E-02)*X3^2 + (4.3292E-03)*T2A^2 + (-1.1115E-03)*r^2 + (2.5547E-04)*σ^2

RQ4 European fab abandon option value = 1.5349 + (0.8319)*S + (0.2015)*S_V + (-0.1863)*T_3 + (0.1128)*r + (-4.9075E-02)*σ + (-5.9808E-02)*S* S_V + (1.0072E-03)*S*T_3 + (2.0953E-03)*S*r + (-4.1203E-05)*S*σ + (3.3475E-02)* S_V*T_3 + (-1.6158E-02)* S_V*r + (4.0687E-03)* S_V*σ + (-1.0276E-02)*T_3*r + (4.6437E-03)*T_3*σ + (-1.4178E-03)*r*σ + (1.3730E-02*S^2) + (4.8067E-02)*Sv^2 + (-4.0167E-03)*T_3^2 + (3.5319E-04)*r^2 + (4.1667E-04)*σ^2

RQ4 European fab abandon put value = 2067.4261 + (-154.9633)*S + (-36.6293)* S_V + (-219.5826)*T_3 + (86.6697)*r + (-53.9017)*σ + (-60.4025)*S* S_V + (0.1212)*S*T_3 + (1.7231)*S*r + (-0.2360)*S*σ + (39.5950)* S_V*T_3 + (-15.1237)* S_V*r + (9.5519)*S_V*σ + (-9.0316)*T_3*r + (4.0987)*T_3*σ + (-1.0908)*r*σ + (13.8578)*S^2 + (43.4756)*S_V^2 + (0.7431)*T_3^2 + (1.3988)*r^2 + (0.3118)*σ^2

RQ5 European Fab Delta = $0.2495 + (6.0667E\text{-}02)*S + (-1.9511E\text{-}02)*X + (-3.7189E\text{-}02)*T + (-4.0097E\text{-}03)*\sigma + (-5.0816E\text{-}03)*r + (5.5178E\text{-}05)*S*X + (-6.1629E\text{-}04)*S*T + (-1.1150E\text{-}04)*S*\sigma + (-2.4992E\text{-}05)*S*r + (1.2212E\text{-}03)*X*T + (9.4659E\text{-}05)*X*\sigma + (8.3502E\text{-}04)*X*r + (4.1451E\text{-}04)*T*\sigma + (1.1711E\text{-}03)*T*r + (-5.4540E\text{-}05)*\sigma*r + (-6.6155E\text{-}04)*S\text{^}2 + (-1.8553E\text{-}04)*X\text{^}2 + (1.8458E\text{-}03)*T\text{^}2 + (3.7753E\text{-}05)*\sigma\text{^}2 + (-2.6662E\text{-}04)*r\text{^}2$

RQ5 to RQ7 European Fab Call Value = $12.3501 + (0.5674)*S + (-1.1084)*X + (-1.0867)*T + (-0.1936)*\sigma + (-0.0336)*r + (-0.0157)*S*X + (1.1589E\text{-}02)*S*T + (8.1505E\text{-}04)*S*\sigma * (8.5110E\text{-}03)*S*r + (6.1298E\text{-}02)*X*T + (9.5730E\text{-}03)*X*\sigma + (9.9899E\text{-}03)*X*r + (1.3148E\text{-}02)*T*\sigma + (4.8776E\text{-}02)*T*r + (-4.9121E\text{-}03)*\sigma*r + (6.3751E\text{-}03)*S\text{^}2 + (1.0252E\text{-}02)*X\text{^}2 + (-2.0490E\text{-}02)*T\text{^}2 +(8.5475E\text{-}04)*\sigma\text{^}2 + (-2.0170E\text{-}03)*r\text{^}2$

RQ6 European Fab Vega = $-33.3503 + (8.8688E\text{-}02)*S + (1.1623E+00)*X + (2.6084E+00)*T + (7.2818E\text{-}01)*\sigma + (3.8323E\text{-}01)*r + (1.6207E\text{-}02)*S*X + (2.8430E\text{-}02)*S*T + (4.7547E\text{-}03)*S*\sigma + (-8.8455E\text{-}03)*S*r + (2.0125E\text{-}02)*X*T + (-1.4241E\text{-}02)*X*\sigma + (-2.7915E\text{-}02)*X*r + (-1.5440E\text{-}02)*T*\sigma + (-1.3779E\text{-}01)*T*r + (8.2118E\text{-}03)*\sigma*r + (-9.7820E\text{-}03)*S\text{^}2 + (-5.6268E\text{-}03)*X\text{^}2 + (-1.6145E\text{-}01)*T\text{^}2 + (-5.7286E\text{-}03)*\sigma\text{^}2 + (-1.9725E\text{-}03)*r\text{^}2$

RQ7 European Fab Theta = $2.1093 + (-1.3847E\text{-}02)*S + (-7.8826E\text{-}02)*X + (-3.2785E\text{-}01)*T + (-2.5607E\text{-}02)*\sigma + (-9.5495E\text{-}02)*r + (-1.2951E\text{-}03)*S*X + (1.0204E\text{-}04)*S*T + (-2.8451E\text{-}04)*S*\sigma + (-1.4245E\text{-}03)*S*r + (1.3529E\text{-}02)*X*T + (-1.8185E\text{-}04)*X*\sigma + (-1.3816E\text{-}03)*X*r + (3.7759E\text{-}03)*T*\sigma + (9.4474E\text{-}03)*T*r + (1.3806E\text{-}03)*\sigma*r + (6.9326E\text{-}04)*S\text{^}2 + (6.6476E\text{-}04)*X\text{^}2 + (-2.4792E\text{-}04)*T\text{^}2 + (4.3206E\text{-}05)*\sigma\text{^}2 + (1.2148E\text{-}03)*r\text{^}2$

Appendix G: Modeling Performance Parameters

Model	R^2	Adj. R^2	p Value	F ratio	VIF Range
RQ1 A Fab Expand Capacity	1.0000	.9999	<0.0001	31730.3	1.0 to 1.2
RQ1 E Fab Expand Capacity	.9999	.9999	<0.001	15291.6	1.0 to 1.2
RQ2 A Fab Contract Capacity	.9999	.9998	<0.0001	9096.6	1.0 to 1.2
RQ2 E Fab Contract Capacity	.9996	.9993	<0.0001	3274.1	1.0 to 1.2
RQ3 A Fab Defer Investment	.9999	.9999	<0.0001	13752.7	1.0 to 1.2
RQ3 E Fab Defer Investment	.9999	.9997	<0.0001	8730.0	1.0 to 1.2
RQ4 A Fab Abandon Option Value	.9999	.9997	<0.0001	8391.7	1.0 to 1.2
RQ4 A Fab Abandon Put Value	.9837	.9707	<0.0001	75.44	1.0 to 1.2
RQ4 E Fab Abandon Option Value	.9996	.9992	<0.0001	2953.7	1.0 to 1.2
RQ4 E Fab Abandon Put Value	.9838	.9708	<0.0001	75.88	1.0 to 1.2
RQ4 E Fab Abandon Option Value	.9996	.9992	<0.0001	2953.7	1.0 to 1.2
RQ4 E Fab Abandon Put Value	.9838	.9708	<0.0001	75.88	1.0 to 1.2
RQ4 E Fab Abandon Option Value	.9996	.9992	<0.0001	2953.7	1.0 to 1.2
RQ5 A Fab Delta Revenue	.9989	.9980	<0.0001	1107.8	1.0 to 1.2
RQ5 E Fab Delta Revenue	.9995	.9991	<0.0001	2368.9	1.0 to 1.2
RQ5 A Fab NPV	.9997	.9994	<0.0001	3635.0	1.0 to 1.2
RQ5 E Fab NPV	.9997	.9995	<0.0001	4601.4	1.0 to 1.2
RQ6 A Fab Vega Revenue	.9853	.9736	<0.0001	83.82	1.0 to 1.2
RQ6 E Fab Vega Revenue	.9844	.9720	<0.001	79.02	1.0 to 1.2
RQ7 A Fab Theta Revenue	.9873	.9771	<0.0001	97.18	1.0 to 1.2
RQ7 E Fab Theta Revenue	.9893	.9808	<0.001	116.0	1.0 to 1.2

Appendix H: Participant Consent Form

This study is being conducted by the researcher, Thomas Pastore, a doctoral student in Management at Walden University, Minneapolis, Minnesota, USA. You are invited to take part in his research study entitled "A Quantitative Study to Explore Financial Resources and Technology to Transition to 450mm Semiconductor Wafer Foundries." As a prior participant from SEMICON or SPIE you were randomly selected with knowledge of the 450mm wafer transition to share your perspectives about future pilot and production wafer fabs or foundries. Please read this informed consent form prior to giving voluntary acceptance to participate with this academic survey.

Background Information:
The purpose of this study is to compare financial and technological implications as well as the profitability of an American 450mm semiconductor wafer foundry versus one that will be constructed in Europe.

Procedures:
Your voluntary agreement to participate in an anonymous research study involves implied consent to take a quick survey. For each of the 23 questions, please select an answer from pull-down menus that best matches your perspective. The survey should take about 10-12 minutes to complete. The first half of the questionnaire focuses on strategic questions to develop a typical 450mm pilot wafer fab while the second half focuses on a production 450mm wafer fab that can operate at full capacity. If you have any question or need clarification, please ask.

Voluntary Nature of the Study:
Your voluntary decision to participate in this study and to present your perspective on future 450mm wafer fabs is voluntary. Your decision to participate will not affect your relation with SEMICON or SPIE. Being an anonymous participant in this research study, you have complete freedom to refuse to take part in this survey, the freedom to request further clarification about this survey, topic, and freedom to skip any question you are unsure of.

Risks and Benefits of Being in the Study:
As a participant in this research study, you may feel some minor discomfort about making strategic financial or logistic decisions about future events that may occur in the process of establishing 450mm semiconductor wafer foundries. Your decision-making or perspective requested in this study is similar to the types of issues professionals like scientists, engineers, managers, CFOs, and CEOs encounter on a daily basis. Benefits of this study will provide you with the satisfaction of hypothetical participation in some strategic questions that need to be answered by stakeholders in order to build future 450mm wafer fabs that could undoubtedly provide competitive advantages for both America and Europe in the fast-changing world of semiconductor electronics.

Compensation:
There will be no compensation for your participation in this study.

Confidentiality:
Participants in this survey will remain completely anonymous. No company affiliation information, no confidential business information, and no demographic, medical, or education questions will be asked or collected. All academic questions will focus on your perspective on 450mm wafer fabs in the future. There is nothing in the survey that will identify you as a participant. All responses will be securely stored inside a Microsoft Access database for 5 years as required by Walden University. This data will not be available to any company or individual other than the researcher and his dissertation committee supervisor. Do also know that the researcher is not employed by any semiconductor or supplier company.

Contacts and Questions:
If you have questions for this researcher before or after completion of this survey, please contact Thomas Pastore at (USA) or e-mail your concern to

If you would like to communicate about your rights as a participant, you can call Dr. Leilani Endicott. She is the Walden University representative who can discuss this with you. Her phone number is (for US based participants) or 001- (for participants outside the US). The Walden University's approval number for this study is 09-06-13-0039881 and it expires on September 5, 2014. To address any academic concerns or questions, please contact the researcher's faculty advisor, Dr. Aqueil Ahmad at

<u>You may keep this consent form for your records.</u>

Statement of Consent:
I have read the consent information above and understand the scope, terms, and conditions of the proposed study well enough to make a decision about my voluntary involvement. To protect your privacy, signatures will not be collected. Your consent to participate in this academic survey will be acknowledged when you return the survey; this will automatically indicate your consent to participate.

For participants wishing to receive a final summary of the research study, you may request or send a separate e-mail with your contact information. Rest assured that this information will not be revealed to other participants or anyone else, for that matter. I sincerely appreciate your kind support. Thank you.

Appendix I: NIH Research Certificate

Certificate of Completion

The National Institutes of Health (NIH) Office of Extramural Research certifies that **Thomas Pastore** successfully completed the NIH Web-based training course "Protecting Human Research Participants".

Date of completion: 07/23/2012

Certification Number: 954896

Appendix J: Letter of Cooperation

From :Eva Weller []
Date :09/19/2013 08:39 AM
To :Thomas Pastore []
Subject :Re: SEMICON Europa 2013, Request Permission to Research

Dear Thomas,
the promo code gives you free access to the show. You would have to register for the 450mm session. But we have special prices for students, which is 50 Euro. A valid student ID card is required.
best regards
Eva

2013/9/19 Thomas Pastore < >

Dear Eva Weller,

Thank you very much for your kind support. I am thrilled by your permission and am looking forward to my trip to SEMICON Europa. I have sent your letter to the Walden University officials in charge of IRB research ethics.

Regarding the registration code P1211159L, would this allow me to get in free or would I be required to pay admission? I am a SEMI student member. Also I am a member of IEEE and SPIE. Regarding the 450mm forum, is there a fee for this?

Thanks you very much for your generous support of my research and permission to attend SEMICON Europa. It is very much appreciated.

Sincerely,

Thomas Pastore, a Walden University student

Original E-mail
From :Eva Weller []
Date :09/18/2013 04:53 AM
To :Thomas Pastore []
Subject :Re: SEMICON Europa 2013, Request Permission to Research

Dear Thomas,

of course you are very welcome to come to SEMICON Europa 2013 and do your survey.
Please register with this code for the exhibition: P1211159L
Please let me know, if we can support you with your survey.

Best regards
Eva

Kind regards

Eva Weller

SEMI Europe / PV Group
Helmholtzstr. 2-9
Haus D / 3. OG
10587 Berlin

Phone:

Email:

2013/9/18 Thomas Pastore < >

Dear Ms. Eva Weller,

I am in great need of your help. I am a SEMI student member and a university student at Walden University in Minnesota, USA. I would like to come to SEMICON Europa in order to perform research to fulfill part of a requirement for graduation. My plan will be to present a 10 minute survey with participants regarding their future perspectives about 450mm semiconductor wafer fabs.

This survey would be accomplished by presenting 23 questions to voluntary participants that will remain anonymous. My university requires permission to conduct my PhD research study in accordance with ethical protocols in accordance with IRB procedures for our university officials.

Sincerely,
Thomas Pastore, a Walden University student

Curriculum Vitae

Thomas Pastore

Academic Experience:

Executive Masters of Business Administration
Northwestern University – Chulalongkorn University, 2000

Bachelor of Science, Electrical Engineering
Arizona State University, 1990

Electronics Technology
DeVry University, 1978

Professional Experience:

Boeing Research and Technology: Huntington Beach, California (Present – 2000)
Engineer – Scientist: Subject matter expert responsible for performing semiconductor failure investigations on many commercial aircraft, military aircraft, spacecraft, rockets, ships, and submarines.

Siemens Microelectronics: San Jose, California (1998 – 1999)
Sr. Customer Quality Engineer: North American semiconductor quality point of contact for key sales account, Lucent Technologies with the responsibility to improve customer satisfaction for all Siemens semiconductor products at Lucent Technologies by addressing issues with business unit managers in Europe to obtain solutions.

Alphatec Submicron Technology: Bangkok, Thailand (1996 – 1997)
Manager and Sr. Failure Analysis Engineer at that 200mm semiconductor wafer foundry with responsibility to set up a failure analysis laboratory, led the department, evaluate, and purchase analytical lab instruments with an $11 million equipment capital budget.

LG: Bang Pakong, Thailand (1993 – 1995)
Quality Manager: Directed the factory’s TQM plan, responsible for monitoring seven production lines twice daily, reporting factory status to America, maintaining schedule, and managing a final electrical test department for all products bound for America.

Xerox: El Segundo, California (1990 – 1992)
Failure Analysis Engineer: Performed root-cause semiconductor failure analysis on ICs and supported Xerox's 125mm (5") wafer foundry with yield improvements.

Hewlett Packard: Cupertino, California (1978 – 1985)
Failure Analysis Engineer: Set-up a failure analysis department and was responsible for performing semiconductor failure analysis on all production component failures from the manufacturing lines for personal computer and terminal products.

Accomplishments:

Boeing B-1B Award for the discovery of a buried process defect in a high power device
Boeing Proprietary Program Awards for leading semiconductor IC failure investigations
Boeing Anik-F2 Satellite Recognition Award
LG Management Appreciation Award
Eagle Boy Scout Medal

Highlights of Qualifications:

- IEEE Electron Devices Society member
- SEMI student member, SPIE student member
- Corporate finance, valuation, marketing plans, and business plans
- Design of Experiments: Response surface methods, Taguchi methods
- Time Series Analysis: SPSS/ PASW Stat Pack 18, Minitab 16
- Statistical Analysis: Stat Ease Design Expert 8, MegaStat 2007, JMP 10
- Data Analysis: PTC Mathcad 15, Wolfram Mathematica 8, Maple 16
- Database Development: Microsoft Access 1998 to 2010, Macro development

This is a letter of recommendation for Thomas Pastore

I have known Mr. Thomas Pastore since 2007 as a result of a motor drive problem. At the time, we viewed Mr. Pastore's failure analysis laboratory work as exemplary. I have come to know Thomas as a bright technologist, and highly competent engineer, and a team player. Aside from his professional qualifications, which are beyond doubt, Thomas is an erudite person, with high moral values and a very pleasant personality. I have thoroughly enjoyed working with him.

A good deal of our work at Boeing is dependent on how quickly we define the root cause and select an effective corrective action(s). Thomas has outstanding analytical and exceptional laboratory skills that are directly acknowledged by any one who has worked with him on problem solving efforts. Boeing's success is dependent on individuals like Thomas who has top notch technical skills and experience and can bring this value to bear on semiconductor failure analysis. Thomas's skills are sorely needed by anyone faced with a semiconductor problem. Working with Thomas has always been enjoyable.

In my communications with Thomas, he has always been friendly and helpful, with a tone of teamwork always at the forefront. Thomas has always been helpful in providing technical assistance and sharing the functionality of his work.

Please consider the above as only a brief summary of the capabilities and qualities of Thomas Pastore but is meant to reinforce the importance to have his skills at Boeing for now and into the future.

By way of background, I am an Electrical Engineer with more than 47 years of experience and am a member of the Boeing Technical Fellowship.

Sincerely

Randy Brandt

Associate Technical Fellow

Tom has been just great in his help and understanding of Design of Experiments (DOE) and his support for our area. He is not only very good in what he does, but his ability to think out of the box and willing to work with other is an example that many other can learn from.

I am presently running many important multimillion dollar CRAD and IRAD programs in high temperature ceramics for thermal protection systems along with ceramic matrix composites which are considered key to the future of many new and developing platforms. Our work is continually growing and could grow significantly, but the government will not award any large awards unless the technology supporting that program has a Technology Readiness Level (TRL) and Manufacturing Readiness Levels Level (MRL) >6. Therefore besides developing and delivery products our focus this year and next is to raising our TLR and MRL levels with the use of Design of Experiments. This statistical process while being confounded helps us understand the key factors raising our TRL and MRL and reducing cost. Tom’s help in giving us insight into analyzing the data has been critical to our continued success and his in depth knowledge along with ability to apply it in different context has been very useful.

While Tom help and support in the DOE evaluation has been very much appreciated I know this is not in his main area of focus, but these tools are universal and knowing how to apply them in different situation shows how Tom can quickly adapt to whatever problem he needs to solve. I would have never met Tom if his lab was not in building 21 and his willingness in trying to help me solve some real time X-ray problems on a new technology I am presently patenting. One of the things I really like about having the labs centrally located is the personal interaction that comes from it, this is often overlooked. In M&P there are many different technical disciplines along with each having unique lab capabilities. While these capabilities are used day to day to support each activity independently, I find as program manager trying to quickly solve customer problems having quick access to high end experts and capabilities readily give us an advantage and ability to grow. Again I wanted to thank you and your team to allow us to tap into Tom as a company resource.

Warm regards,

Robert A. DiChiara
Boeing Technical Fellow Program Mgr.
Extreme Environment Materials
Boeing Research & Technology

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