FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

The Lean Startup Methodology: A Catalyst for Semiconductor Innovation

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Abstract

This thesis investigates the integration of Lean Startup principles into the semiconductor lithography industry's research and development (R&D) procedures. This field has historically relied on highly structured models that emphasize predictability, traceability, and risk mitigation, such as the V-Model and Technology Readiness Levels (TRLs). However, time-to-market pressures, technological uncertainty, and increasing market volatility are forcing businesses to take more flexible and iterative approaches.

This study identifies key issues with current R&D practices through a conceptual and simulation-based analysis, such as the high cost and complexity of physical prototyping, limited early customer involvement, and delayed feedback loops. It assesses the selective use of Lean Startup techniques in early-stage, high-uncertainty development phases, including validated learning, rapid experimentation, and MVP development.

The results give credence to the application of a hybrid development framework that blends the rigor of conventional models with the flexibility of Lean Startup. While preserving compliance and system-level dependability in later phases, this dual-track approach allows for quicker innovation and risk reduction in early development.

The thesis ends with actionable implementation suggestions, such as purchasing simulation tools, implementing dual governance structures, launching cultural transformation programs, and updating performance metrics to reflect customer validation and learning. The study's limitations are noted, and recommendations are made for further research in the areas of executive engagement, quantitative validation, and wider industry application. All things considered, the suggested framework encourages more flexible, client-focused innovation in hardware-intensive industries like semiconductor lithography.

Keywords: Lean Startup, hybrid development model, semiconductor lithography, R&D innovation, technology readiness levels (TRLs), V-Model, iterative development, hardware innovation, organizational agility

Resumo

A Metodologia Lean Startup: Um Catalisador para a Inovação na Indústria dos Semicondutores

Esta dissertação investiga a integração dos princípios do Lean Startup nos processos de investigação e desenvolvimento (I&D) da indústria de litografia de semicondutores. Este setor tem historicamente recorrido a modelos altamente estruturados que privilegiam a previsibilidade, a rastreabilidade e a mitigação de risco, como o V-Model e os Technology Readiness Levels (TRLs). No entanto, a crescente pressão para reduzir o tempo de colocação no mercado, a incerteza tecnológica e a volatilidade dos mercados estão a levar as empresas a adotar abordagens mais flexíveis e iterativas.

O estudo identifica problemas-chave nas práticas atuais de I&D através de uma análise conceptual e baseada em simulações, como o elevado custo e complexidade da prototipagem física, o envolvimento limitado dos clientes nas fases iniciais e os ciclos de feedback tardios. Avalia-se a aplicação seletiva de técnicas Lean Startup nas fases iniciais de desenvolvimento, caracterizadas por elevada incerteza, incluindo aprendizagem validada, experimentação rápida e desenvolvimento de produtos minimamente viáveis (MVPs).

Os resultados sustentam a adoção de um modelo de desenvolvimento híbrido que combina o rigor dos modelos tradicionais com a flexibilidade do Lean Startup. Esta abordagem de via dupla permite acelerar a inovação e reduzir riscos nas fases iniciais, sem comprometer a conformidade normativa e a fiabilidade dos sistemas nas fases mais avançadas.

A dissertação termina com recomendações práticas para a implementação do modelo, tais como o investimento em ferramentas de simulação, a adoção de estruturas de governação dual, a promoção de programas de transformação cultural e a atualização dos indicadores de desempenho, de forma a refletir a validação junto do cliente e a aprendizagem iterativa. As limitações do estudo são reconhecidas, e são propostas direções futuras de investigação, incluindo o envolvimento de decisores de topo, a validação quantitativa e a aplicação alargada do modelo noutros setores tecnológicos. Em suma, o modelo proposto promove uma inovação mais ágil, informada pelo cliente e adaptada à realidade de indústrias com forte componente de hardware, como a litografia de semicondutores.

Palavras-chave: Lean Startup, modelo híbrido de desenvolvimento, litografia de semicondutores, inovação em I&D, níveis de maturidade tecnológica (TRLs), V-Model, desenvolvimento iterativo, inovação em hardware, agilidade organizacional.

UN Sustainable Development Goals

The United Nations Sustainable Development Goals (SDGs) provide a global framework to achieve a better and more sustainable future for all. It includes 17 goals to address the world's most pressing challenges, including poverty, inequality, climate change, environmental degradation, peace, and justice.

The specific Sustainable Development Goals mentioned have the following names:

SDG 8 Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all

SDG 9 Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation

SDG 12 Ensure sustainable consumption and production patterns

SDG 13 Take urgent action to combat climate change and its impacts

Table 1: UN Sustainable Development Goals that this Thesis contributes to

SGD	**Target**	**Contribution**	**Performance Indicators and Metrics**
8	8.2	Applying Lean Startup methodologies enhances innovation and process agility in the semiconductor industry, leading to higher productivity through technological upgrading.	Increase in rate of innovation adoption or product development cycles; reduction in R&D-to-market time.
9	9.5	Encouraging research and industrial innovation in lithographic processes supports sustainable industrialization and fosters high-tech innovation ecosystems.	Growth in R&D investment in semiconductor manufacturing; number of new validated process innovations.
12	12.2	Lean Startup helps minimize resource and material waste in early-stage product development, aligning with sustainable production goals.	Reduction in material waste during prototyping phases; efficiency improvements in production processes.
13	13.2	More efficient lithographic processes contribute to lower energy us and emissions, indirectly aiding climate mitigation strategies.	Decrease in CO emissions per unit produced; energy use per lithographic process cycle.

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This work carries the echoes of your love, your patience, your belief, for I am nothing alone.

Inês Machado Rodrigues

"The one who plants trees, knowing that he will never sit in their shade, has at least started to understand the meaning of life."

Rabindranath Tagore

Contents

List of Figures

List of Tables

List of Acronyms

BJT	Bipolar Junction Transistor
BML	Build Measure Learn Loop
CASE	Computer-Aided Software Engineering
CD	Critical Dimension
DfM	Design for Manufacturability
FET	Critical Field Effect Transistor
ICs	Integrated Circuits
ISO	International Organization for Standardization
IoT	Internet of things
LS	Lean Startup
MVP	Minimum Viable Product
R&D	Research and Development
TRL	Techinal Readiness Level

Chapter 1

Introduction

This first chapter will elaborate on the motivations and objectives driving the development of this thesis, provide an overview of the main steps of the study, and describe the overall structure of the thesis.

1.1 Context

This thesis elaborates on the potential of Lean Startup principles to drive innovation and product development (R&D) in the semiconductor industry, most specifically within Lithographic System Industry.

The Lean Startup methodology is a business framework developed by entrepreneur Eric Ries that offers an innovation management framework helping startups develop products and services more efficiently and successfully in conditions of extreme uncertainty and often very little capital. At its core, Lean Startup is about reducing waste, optimizing resources, accelerating learning, and increasing the chances of building something customers want and need, mitigating risk, and therefore accelerating time to market [26, 34].

By adopting practices such as validated learning, rapid prototyping, and iterative development, semiconductor companies can improve efficiency, reduce time-to-market, and implement a culture of continuous innovation.

Traditional business frameworks making use of project/product management models (waterfall, V-model, etc...), rely heavily on planning and predicting outcomes. Lean Startup encourages rapid experimentation, continuous feedback, and fast product development [2].

To enable short development cycles and rapid experimentation, these methodology is based on the following concepts:

- Build-Measure-Learn Loop: foundation of the Lean Startup Methodology, build a basic version of the product and test as fast as possible with real uses to collect feedback for further development.

- Validated Learning: Startups use real-world customer data to test hypothesis about their product or business framework and base the learning as maximum as possible in evidence and not assumptions.
- Pivot or Persevere: Based on the learning, teams must decide whether to pivot (make a great change in business direction) or persevere (continue improving the current defined path).
- Innovation Accounting: this methodology follows tools that are mean to track progress instead of traditional indicators such as revenue or profit.

The Lean Startup methodology helps companies reduce risk and waste in the product development process. By focusing on rapid experimentation and early customer feedback, businesses can avoid spending time and resources building features or products that do not meet real needs. This approach also promotes strong customer focus, ensuring that the product evolves based on actual user input rather than internal assumptions. In addition, Lean Startup encourages agility: teams are more prepared to adapt to change, pivot when necessary, and iterate quickly based on what they learn.

1.2 Motivation and Objectives

The semiconductor industry plays a pivotal role in creating ubiquitous technology ecosystem, that powers our society (consumers electronic, healthcare devices, AI, energy transition, automation industry, etc) [3, 42].

However, this industry faces growing pressure to innovate rapidly while meeting the demands of an increasingly dynamic market. Factors such as supply shortages, geopolitical tensions, and the need for sustainable development are further intensifying these challenges [22, 42].

Traditional project/product development models characterized by substantial investments and prolonged R&D cycles are struggling to keep pace with the industry high capital demands, extended timelines, and rapidly evolving technologies [40, 43].

The Lean Startup Methodology offers a compelling methodology to address the described challenges. Research suggests that the methodology studied might not only be suitable for young companies or start-ups; in fact, larger companies used and experimented with the methodology in their product development cycles (to be explored in Chapter 2). Despite existing successful cases and plenty of literature on Lean Startup, few studies have examined its application in industries with high technological complexity and capital intensity, such as the semiconductor industry [35].

This thesis is motivated by the potential for Lean Startup to bring greater agility and customer responsiveness to semiconductor product essential development—capabilities for navigating fast-changing markets without sacrificing quality or scalability [34]. By investigating its adoption in this context, the research aims to contribute both to academic discourse and to practical insights for industry stakeholders.

The primary objectives of this thesis are:

- To critically evaluate the applicability and challenges of implementing Lean Startup principles within the semiconductor industry.
- To provide actionable insights on how semiconductor companies can integrate Lean Startup practices into their product development strategies to enhance innovation and efficiency. Through this analysis, the research seeks to bridge the gap between Lean Startup theory and semiconductor industry practice, and contribute to both academia and industry practitioners.

1.3 Research Questions

As mentioned in 1.2, giving the topic of the current study the general research problem is described below.

General Research Problem: How can the Lean Startup methodology catalyze innovation in the lithographic semiconductor industry?

This question can be further divided into the following sub-questions that can also be considered secondary questions to further narrow the scope of this research.

Foundational Questions:

- What are the key principles of Lean Startup, and how do they compare with traditional R&D models used in the semiconductor industry?
- What challenges and constraints are unique to lithographic system development that impact the applicability of Lean Startup?

Applicability Questions:

- How could Lean Startup concepts such as MVPs, validated learning, and fast feedback be adapted for use in complex hardware development environments?

Implementation Questions:

- How can semiconductor ventures adapt organizational structures to support the Lean Startup experimentation?

1.4 Dissertation Structure

Together with this Introduction, this dissertation consists of eight chapters, each building upon the previous to address the research objectives.

- Chapter 1 introduced the topic, outlines the research problem, and presented the key questions guiding the study.

- Chapter 2 provides a review of relevant literature, covering Lean Startup theory and semiconductor theory.
- Chapter 3 offers an overview of the semiconductor industry, with a specific focus on lithography R&D and its unique challenges.
- Chapter 4 presents the research methodology, including the simulation-based conceptual approach used to explore hybrid development models.
- Chapter 5 presents the simulation findings and examines the implications of Lean Startup techniques within a staged development framework.
- Chapter 6 analyzes the results in relation to existing literature and proposes a structured hybrid development model.
- Chapter 7 summarizes the main conclusions and provides actionable recommendations for practitioners in the semiconductor industry.
- Finally, Chapter 8 lists its limitations and suggests ways for future research to confirm and build on the proposed framework.

Chapter 2

Literature Review

This chapter examines the existing literature related to the Lean Startup (LS) methodology and its potential to speed up innovation, focusing on its use in the complex and costly semiconductor lithographic industry.

The chapter is divided into two main sections:

- Section 2.1.1 looks at the theory and practical uses of the Lean Startup methodology. It discusses its main principles, benefits, and known drawbacks, as well as the challenges faced when used in large organizations or heavily regulated industries. In this section it will be discussed the critiques of the LS approach, particularly regarding premature scaling, over-reliance on customer feedback, and the risk that innovation might become incremental instead of groundbreaking. This section also identifies gaps in the current literature, such as the lack of long-term studies and limited evidence showing the methodology's effectiveness in capital-intensive sectors like semiconductors.
- Section 2.1.2 offers a technical overview of semiconductor development, emphasizing the basic principles that shape this field. This section introduces essential concepts like transistors, integrated circuits, Moore's Law, the Rayleigh criterion, node scaling, and overlay. These concepts are vital for understanding the technological landscape of the semiconductor industry and the factors that affect how innovation happens within it (that are necessary for Chapter 3.

By looking at both the Lean Startup framework and the technical realities of semiconductor development, this chapter sets the stage for assessing how the LS methodology might be effectively adjusted or challenged when applied to innovation in semiconductor lithography.

It points out both the possibilities and limits of Lean Startup principles when addressing high-risk, long-cycle, and precision-dependent technological innovation.

2.1 Lean Startup Methodology

The Lean Startup methodology, a framework intended to increase the effectiveness and success of startup development, is examined in this section. It provides a contemporary method for establishing startups in highly uncertain environments by emphasizing validated learning and iterative product development.

2.1.1 Introduction to Lean Startup

Eric Ries introduced the new approach in his 2011 book The Lean Startup: How Today's Entrepreneurs Use Continuous Innovation to Create Radically Successful Businesses. This business approach has become a crucial element in today's discussions of innovation and entrepreneurship. The methodology, grounded in the principles of lean manufacturing [46] and agile software development [15], emphasizes a systematic, data-driven and scientific framework for launching and managing successful startups or developing new products with the goal of achieving market success. Its priority on waste reduction and providing a means to function in situations of severe uncertainty contributed to its popularity.

Instead of relying on traditional business planning and large upfront investments, this approach promotes an empirical, quick test-and-learn process that validates all assumed business hypothesis. The pivotal objective is to build a "skeleton" product fast, measure the customer feedback and learn from the results to make informed decisions on the next steps. This objective is called Build-Measure-Learn [34]. This cycle is believed to promote a more efficient and tailored approach to innovate, allowing the entrepreneurs to pivot or persevere based on facts.

The Startup Lean methodology addresses the majority of the risks that make a startup fail, such as lack of market need (by creating a product without confirming a real market demand and poor customer interest), insufficient capital (running out of funds too soon before achieving profitability or product-market fit), inexperienced founders (lack of domain experience and experimentation leading to poor decision-making and delayed execution), overcomplicated products (introducing too much complexity by trying to create a perfect product rather than a needed one, leading to excessive costs), failure to pivot (being conservative in their strategy model, failing to adapt and adjust their business based on customer feedback), regulatory and legal challenges (often ignoring complex regulations and legal requirements and tackling them when it is too late and expensive) and timing issues (either entering the market too early or too late, missing opportunities).

2.1.2 Foundations of the Methodology

Lean Startup is grounded in the principles of lean thinking, especially the idea of minimizing waste while maximizing customer value. This idea, originally developed in the context of manufacturing [46], has been adapted by Ries to address inefficiencies in the product development process, especially in tech-driven or innovation-heavy environments. The methodology also draws from customer development theory [1], which argues that startups should actively validate assumptions about customers, rather than relying on untested business plans.

Ries' work further incorporates elements of scientific experimentation, treating entrepreneurship as a series of hypotheses to be tested rather than a rigid plan to be executed [6]. In this sense, Lean Startup departs from traditional business frameworks by promoting a learning-oriented approach to market creation and product design, where failure is seen not as a setback but as a source of insight [10].

2.1.3 Core Concepts

At the heart of the Lean Startup approach are several key concepts.

1. Build-Measure-Learn Loop

This iterative cycle is the central mechanism by which Lean Startup operates. The process begins with turning ideas into a Minimum Viable Product (MVP)—a version of the product with just enough features to gather validated learning about customers [34]. The MVP is not designed to be perfect but to test fundamental hypotheses as quickly and cheaply as possible. Once the MVP is built, entrepreneurs measure how it performs with customers and learn from the results. This loop enables continuous refinement of the product and business framework (Figure 2.1).

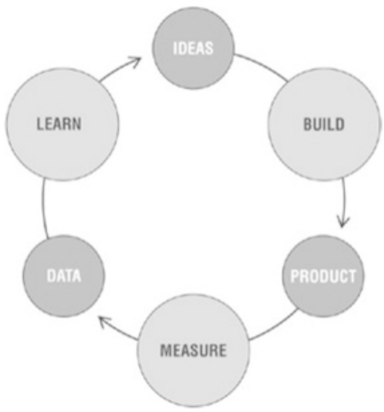

Figure 2.1: Build-Measure-Learn diagram [34]

The first step in the BML loop is to create the MVP (Build), as explained above, a product or prototype, that includes only the essential features necessary to solve the core problem of the target customer. In this step, it is also a goal to release the MVP as quickly and inexpensively as possible.

After the MVP is launched, the next step, Measure, is where the startup collect customer reactions and behaviors, using quantitative and qualitative data. Possible key metrics are customer usage, adoption rates, retention rates, and global feedback, which provide meaningful insights at an early development stage into whether the product is meeting the customer needs. The goal is to evaluate the hypothesis made in the first step: whether the product solves the customer's problem in a desirable way and if there is a viable market for this product.

The last step of the loop, called Learn, is to analyze and apply all learning from the customer feedback, making all necessary adjustments in the product and business framework.

Startups process the results and conclude if their hypothesis is correct. In the case of the feedback supporting the business hypothesis, the startup may proceed to its next iteration, improving features or requirements, adding necessary complexity and scaling. If the feedback suggests the hypothesis is wrong, the startup may change direction and test a different approach (also called pivot). Any change applied this early in the development process is much easier and cheaper than in later stages, keeping the startup financially safer.

2. Validated Learning

Validated Learning is the process of validating your assumptions about the product (for instance, feasibility and value), customer needs and market insights. It is very often the case that a strategic plan (including product roadmaps and market forecasts) is rigidly rooted on those assumptions being accepted as true. It is of the outermost importance to test those assumptions as early as possible instead of building the company future on top of it [34].

Validated learning allows startups to gain clarity on whether their product or business model will work in the market and if not, why. It helps them reduce risk by identifying problems early and throughout the process and if adjustments to the product or plan are necessary (pivoting). Startups survive by having valuable continuous innovation on the right direction. This same concept is applicable for big companies in the semiconductor industry that depend on fast cut-edge continuous innovation.

3. Pivot or Persevere

Each cycle of the BML loop results in a fundamental decision point: whether to pivot or persevere. Using the loop model and based on validated learning and empirical data, the startup must choose whether to continue its current trajectory (persevere) or make a fundamental change in the product, strategy, service or business model (pivot). Very similar to the concept of iterative augmentation in agile [1, 34].

It makes sense to keep adding features, scaling operations, and gradually upgrading the product (therefore making it more complex) if empirical data explicitly demonstrates that the current approach or product is successfully satisfying customer or market needs and complementing the startup's value proposition.

On the other hand, the startup needs to pivot and change course if the result of the validated learning show that the product is not gaining the traction it needs or it is not suitable and needed by the customer or market. A pivot is a planned course adjustment intended to test a new theory on the product, business model, or expansion plan rather than a failure.

A pivot often involves altering one of the nine elements of the Business Model Canvas [31], such as changing the customer segment, value proposition, revenue model, or distribution channel. The idea is to retain what has been learned while shifting toward a more viable direction.

Types of pivots defined by Ries[34]:

- Zoom-in pivot: A single feature becomes the whole product.

- Zoom-out pivot: The current product becomes a single feature of a larger product.
- Customer segment pivot: Targeting a different group of customers.
- Platform pivot: Switching between application and platform layers.
- Business architecture pivot: Changing from "high margin/low volume" to "low margin/high volume" or vice versa.

Pivoting becomes a form of strategic flexibility that allows startups to adapt quickly to market signals. In their Harvard Business School note on hypothesis-driven entrepreneurship, Eisenmann [6] explains that companies are likely to undergo several pivots before achieving a durable product-market fit.

4. Innovation Accounting

Ries introduces the idea of innovation accounting, as a framework for measuring progress when inadequate traditional financial metrics are not yet meaningful for a startup in evaluating early-stage innovation.

Opposing conventional accounting, which relies on revenue and profitability, innovation accounting focuses on actionable learning milestone, funnel conversion rates, progress metrics that reflect customer engagement and product development effectiveness (reflecting the BML model and validated learning).

According to Eisenmann ([6]), innovation accounting supports hypothesis-driven entrepreneurship by providing a structured framework for testing assumptions and also enabling faster pivots, when necessary.

2.1.4 Evidence and Organizational Adoption

Many studies explored and confirmed the application of Lean Startup principals in startups and entrepreneurial ventures. Ghezzi [12] found that startups implementing Lean practices were more agile, customer-focused and more likely to pivot in comparison with those following more traditional development methods.

There is evidence showing that the Lean Startup methodology can significantly reduce time-to-market. For example, People10 Technologies reported that using Lean Startup principles, such as MVP (Minimum Viable Product) development and iterative customer feedback, led to a 35% to 40% reduction in go-to-market time and cost for digital products ([24]). Likewise, Lomit Patel ([18]) states that companies using Lean Startup frameworks can achieve up to 30% faster time-to-market, thanks to shorter development cycles and real-time market validation. These findings suggest that Lean Startup practices not only improve innovation results but also create measurable efficiencies in product development timelines.

A known example is Dropbox. This company validated their core product through an simple MVP video before building out the platform. This allowed them to collect feedback and test the market before committing resources to its development. It also secured early user feedback and investor confidence [34]. In a similar way, Airbnb's initial MVP (renting out mattresses in their apartment) supported the validation of their concept and led to the creation of a completely new and disruptive business approach [2]. The founder of Zappos (Tony Hsieh) tested the market interest and customer behavior by posting photos of shoes online before having any inventory, thereby reducing the risk and validating demand[20].

Although originally conceived for startups, there can be found evidence of its application also in large corporations, particularly in R&D and innovation.

One article by Herburger, Jesemann, Beichter et al. explores the adaptation of the Lean Startup approach by investigating whether agile, customer-centered innovation methods can improve the responsiveness and success rate of a physical product development. Using a four stage research process (including expert interviews and real-world pilots in medium size industrial firms) the article reveals that the principals such as rapid prototyping, iterative learning and early customer validation are both applicable and beneficial in the manufacturing context. These firms reported improved innovation performance, including identification of bad ideas early in the process and greater team agility. The study also emphasizes key-challenges. The authors concluded that while migration might not be straightforward, the LS approach can be successfully implemented in large manufacturing companies and benefit their product development agility and customer satisfaction [21].

Another example, General Electric (GE), created and implemented the "FastWorks" program in 2014 to apply Lean Startup techniques for accelerating product development, embedding a culture of rapid experimentation and to minimize the risks associated with large-scale investments[8]. GE trained thousands of employees and significantly shortened product development timelines (an Advances Gas Path project was brought to market two years earlier than GE's previous development cyles). Another identified benefit was cost savings, the same project mentioned above, came in 40% cheaper than previous traditional methods. A more meaningful benefit for the context of this thesis, was the improved innovation culture in GE. The implementation of FastWorks led to a cultural shift within the company, employees became more used to the iterative, feedback-driven feedback environment that in the end generated more ideas and advancement to long existing technical problems [9, 33].

Other major firms, including Intuit, Qualcomm, Toyota and Ericsson, have integrated LS practices to stimulate entrepreneurial thinking and promote innovation within corporate structures [5, 35].

The influence of Lean Startup extends beyond individual case studies. In [4] The Lean Entrepreneurs, Cooper, Vlaskovits, and Ries explore how large companies can use Lean principles to reduce the risk of innovation by testing assumptions early and iteratively.

The key advantages of the Lean Startup approach include:

- Faster Time-to-Market: By launching MVPs and iterating based on early feedback, companies can validate assumptions and rapidly improve products.

- Reduced Waste: Lean Startup promotes evidence-based decision making, enabling startups to avoid investing heavily in ideas that lack market validation and prevents complex products or complex development processes.

- Scalability: Iterative refinement based on customer feedback leads to solutions better aligned with market needs, facilitating smoother growth and improved customer retention.
- Improved Product-Market Fit: Constant interaction with users ensures that products are continuously adjusted to meet real needs, improving satisfaction and retention.
- Increased Innovation: Lean Startup fosters a culture of learning and experimentation, enabling organizations to quickly adapt to change.

This methodology fosters quick changes and adaptation through iterative development, validated learning, and, most important, customer feedback.

2.1.5 Critical Reviews

Although there is several literature and studies supporting the method, Lean Startup has also attracted critical scrutiny from academics, practitioners, and entrepreneurs who question its applicability in both industry and entrepreneurship.

The most common critic is the overemphasis on Minimum Viable Products (MVPs) which is the fundamental component of the Lean Startup Methodology. Critics argue that too much focus on MVP can result in simplistic products that do not generate meaningful customer feedback neither create customer adoption and keep retention [23]. Lean Startup methodology does not always translate effectively to other sectors. In capital-intensive industries (such as biotechnology, manufacturing, or education) or in extremely regulated and complex industries (such as healthcare, pharma or aerospace), the cycles of experimentation and iteration are inherently longer and more costly. An MVP may not be feasible due to all the legal and compliance requirements that make the identity of such industries [12].

Another opposing argument to the methodology is that the methodology is based on a measurement of validated learning. Quantifying such learnings remains systematically problematic and vague. As noted by Ghezzi [12], validated learning is based on subjective judgments, and too much data collected could be redundant and noisy creating misleading information. The fact that traditional metrics are not being used may obscure the actual progress and results of a venture and cause its failure. There is a high risk of having a product development process that is interactive but unfocused, resulting in waste (the same principle that lean promises to tackle).

The encouragement of rapid iteration and responsiveness to market feedback can also promote premature scaling or too much pivoting. The Startup Genome Project [25] disclosed that a great number of startups fail due to scaling prematurely based on unreliable indicators of market fitness. Too much pivoting without sufficient validation can result in strategic drift, fatigue and loss of focus. The agility comes at the expense of long-term strategy and team morale [23].

Also, having a passionate focus on speed and constant experimentation can contribute to the already high-pressure environment that a startup typically has. The urgency to drive innovation may foster a culture that prioritizes rapid output over sustainable work practices. Research shows that pressure to perform in this environment can lead to burnout that negatively impacts (understaffed) startup [23].

Lean Startup principles assume that customer feedback is both available and reliable. However, customers may not always be able to articulate their needs or predict their future behaviors. Ted Ladd [23] highlights that relying too much on customer input can result in incremental innovation instead of radical innovation. As an example, feedback from early product adopters can reflect niche use cases and fail to capture larger markets, leading the startup to not be able to scale their solutions. Henry Ford has famously mentioned that if he asked people what they wanted, they would have said faster horses. This illustrates how focusing solely on the customer's stated desires can lead to missing bigger innovation opportunities.

Early market testing and releasing MVPs is a very risky action for an early (and perhaps not profitable) startup to take. This can expose innovative ideas to (stronger) competitors, increasing the risk of imitation. This exposure has the risk of undermining the competitive advantage and the market penetration.

Euchner emphasizes that LS is effective for startups but often triggers resistance in established firms due to their emphasis on control, structure and core business stability. His work identifies six key fears born from LS methodology (summary can be found in table 2.1) but also identifies ways to mitigate them [7].

Jim Euchner tested and adapted the Lean Startup approach in large corporations, referencing lessons and case studies from companies where Euchner himself worked directly or conducted researches (e.g. Akron-based Goodyear Tire & Rubber Company, healthcare, financial services, energy and consumer goods).

In summary, while the Lean Startup offers a valuable framework for innovation and agile customer-centric development, it is not without its criticisms and lack of use cases proving those critics wrong.

2.1.6 Summary and Review Gaps

Despite Lean Startup widespread adoption across industries and popularity among entrepreneurs, there are significant gaps on theoretical and practical understandings of the practices.

The current body of LS (Lean Startup) research focuses mainly on short-term metrics as time-to-market, product-market-fit and early stage performance indicators [14]. However, there is not a thorough investigation on longitudinal analysis such as scalability, sustainability and strategic evolution on startups employing LS. Ghezzi [11] highlights the lack of studies referring to the long-term implications of iterative pivoting and how it can affect venture growth, long-term and strategy coherence, and organization stability. Hereby a gap that asks for more rigorous research tracking ventures over longer periods to evaluate the effectiveness of this methodology.

Another unresolved clarity is the applicability of LS principles in sectors outside digital, software or service sectors. As mentioned in 2.1.5, in highly regulated, capital-intensive industries (including semiconductors) the development of MVP is often restricted by safety standards, long development cycles or high upfront investment costs. Although available research can be found

Table 2.1: Conflicts Between LS and Big Companies

Lean Startup Principle	**Organizational Concern**	**Mitigating Structure ("Yes...And" Approach)**
Iterative experimentation and pivoting	Perceived unpredictability and chaos; deviation from strategic plans	Implement a structured stage-gate process to evaluate progress and risk at predefined checkpoints
Minimum Viable Products (MVPs)	Risk of compromising daily operations	Use a phasing approach — initiate small-scale pilots and progressively integrate with core operations (increasing people over time)
Unconstrained exploration of ideas and testing	Misalignment with corporate strategy; perceived irrelevance	Constrain exploration to opportunity spaces that leverage organizational capabilities and strategic intent
Business model innovation	Potential destruction or destabilization of existing businesses	Apply the Business Model Pyramid framework to assess innovation impact on the core business and value chains
Aggressive scaling of validated ideas	Internal competition for resources; political conflicts that may lead to team disengagement	Create separate-but-connected innovation teams to isolate early-stage projects while maintaining strategic link
Use of innovation accounting and learning metrics	Misinterpretation of early failures; inconsistency with performance metrics	Develop leadership teams skilled in both exploratory and exploitative management to contextualize innovation progress

on the matter [5, 12], most studies lack generalized empirical evidence to support its efficacy. Therefore, the applicability of LS in the aforementioned context remains debatable (as well as its benefits).

In short, the LS methodology offers a variety of compelling concepts for agile innovation and market product adoption but substantial scientific gaps remain. There is a lack of longitudinal evidence, conceptual vagueness, limited cross-sector applicability, and weak theoretical development.

2.2 Understanding Semiconductor Development

Semiconductor development is a highly specialized field that requires an understanding of materials science, physics, electrical engineering, optics, and nanotechnology.

The development of modern semiconductors and microchips is supported by a variety of theoretical concepts that guide its scaling, design, and fabrication processes. The next subsections will explore several critical principles that have shaped semiconductor technology, including Moore's Law, the Rayleigh criterion, node scaling, node transition, and overlay.

These concepts are fundamental to understanding how semiconductor devices evolve and what challenges lie ahead in further scaling the technology, also relevant for the semiconductor industry.

2.2.1 Semiconductors

At the simplest level, semiconductors are materials with electrical properties that fall between those of conductors, like metals, and insulators, like rubber and ceramics. Common semiconductor materials include silicon (Si), germanium (Ge)and gallium arsenide (GaAs).

The greatest ability of semiconductors is to conduct and control the flow of electrical current under certain conditions, which are controlled by adding impurities in a process known as doping [42]. This ability is critical in electronic components and as such, they are used in virtually all modern electronic devices, including computers, mobile phones, consumer electronics, medical devices and automobiles.

2.2.2 About Transistors, Integrated Circuits and Chips

Another fundamental definition to understand semiconductor development are the transistors; these are considered the "basic unit" of modern electronics, as a cell is the basic unit of life.

First developed in 1947 at Bell Laboratories by John Bardeen, Walter Brattain, and William Shockley, the transistor replaced large and bulky vacuum tubes and revolutionized the field of electronics [36].

Early transistors were fabricated from germanium and later silicon, and typically included three terminals—emitter, base, and collector in bipolar junction transistors (BJTs), or source, gate, and drain in field-effect transistors (FETs) as shown in Figure 2.2 [41].

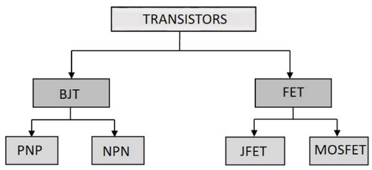

Figure 2.2: Transistor Types

Transistors control current flow with precision, switch signals on and off (ideal for digital logic and commands), and can amplify signals (essential for analog circuits).

They are now made from semiconductor material, typically silicon ([41]). In Figure 2.3 is represented as example, a BJT, bipolar junction transistor.

The development of transistors allowed the miniaturization of circuits, and their development over the years has driven the exponential increase in computing power plus the reduction in size/cost of semiconductor devices (further explained in Sub-Section 2.2.3).

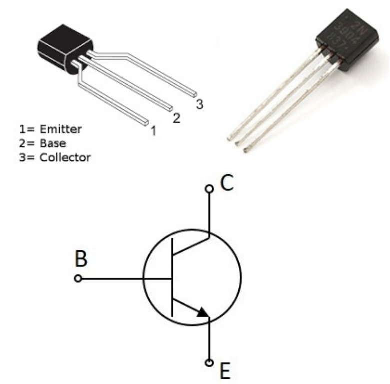

Figure 2.3: BJT Example and diagram

Integrated circuits (IC) are a microelectronic device that contains thousand to billions of transistors and other components (such as resistors and capacitors) fabricated onto a single semiconductor substrate. They perform complex functions such as amplification, data processing, energy conversion, signal modulation and memory storage.

ICs emerged in the late 1950s as a solution to overcome the limitations of assembling complex circuits from many discrete transistors and components. They were independently developed by Jack Kilby at Texas Instruments (1958) and Robert Noyce at Fairchild Semiconductor (1959).

In Table 2.2 it is shown a comprehensive comparison and the relationship between transistors and ICs.

On its turn, the term chip refers to the semiconductor die, the physical piece of silicon that contains one or more ICs are fabricated on a wafer (a thin circular slice of crystalline semiconductor material, mostly silicon) and the wafer is diced into many individual chips that contain thousands of transistors as explained above. Chips serve as the functional units within modern electronic systems [17].

The progression from discrete transistors to integrated circuits and then to chips and wafers reflects a broader trend of increasing integration, complexity, and manufacturing efficiency. The invention of the transistor laid the foundation for modern electronics. The development of ICs made it possible to integrate large numbers of transistors into a compact space.

This layered hierarchy — transistor $\rightarrow$ IC $\rightarrow$ chip $\rightarrow$ wafer (see Figure 2.4) - forms the backbone of the semiconductor industry and underlies all contemporary digital and analog technologies, from smartphones and cloud computing to medical devices and industrial automation.

Table 2.2: Transistor and Integrated Circuits comparison

Feature	**Transistor**	**Integrated Circuit**
Function	Switch amplifier	Performs complex electronic functions
Scale	Single component	Collection of thousands to billions of components
Complexity	Simple	Very complex
Usage	Building block of circuits	Complete electronic circuits on a chip
Fabrication	One device per chip (in discrete form)	Many devices on a single chip

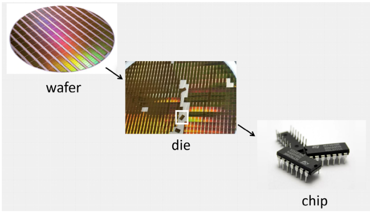

Figure 2.4: Wafer, die, chip relationship

2.2.3 Moore's Law

Moore's Law, is an observation articulated by Gordon Moore in 1965, and prescribes that the number of transistors on integrated circuits (ICs) would double approximately every two years, leading to an exponential increase in computational power and a decrease in cost (halved) per transistor [29]. This observation was not only predictive but became a guiding principle for the semiconductor industry, driving innovation, shaping technological development, and influencing economic models in the digital age.

In the decades following Moore's initial observation, the semiconductor industry witnessed rapid advancements in miniaturization and performance. The scaling of transistors enabled the development of faster, more efficient processors, contributing to the proliferation of personal computing, mobile technology, and the expansion of the internet. This consistent doubling of transistor density led to dramatic reductions in costs, making powerful computing capabilities accessible to a broader range of industries and consumers.

However, as transistor sizes approach the physical limits of miniaturization (on the order of nanometers), the ability to maintain Moore's Law has become increasingly challenged [37]. Quantum effects, such as electron tunneling, and thermal management issues, pose significant obstacles to further scaling, suggesting that traditional methods of transistor scaling may no longer suffice to sustain the rapid growth in computational power seen in the past. Despite these challenges, many industry experts and researchers continue to explore novel materials, architectures, and alternative computing paradigms to extend the principles of Moore's Law, including quantum computing [42].

Despite the potential slowing of Moore's law in its traditional form, the impacts of its initial decades of growth are undeniable. The exponential increase in computational power has revolutionized nearly every facet of modern society, from artificial intelligence to healthcare, transportation, and communication. However, the question remains whether the industry will find new ways to keep up with the demands of an ever-expanding digital ecosystem as the fundamental principles of transistor scaling reach their limits.

2.2.4 Rayleigh criterion

The Rayleigh criterion is a significant concept in optics that establishes the limit of resolution of image-forming systems, including optical microscopes and lithography tools. In semiconductor manufacturing, it plays a critical role in establishing the smallest feature size that can be patterned on a silicon wafer during photolithography [32].

Photolithography, also known as semiconductor lithography, is a significant process in microfabrication that involves the transfer of geometric patterns onto a substrate (a wafer), using light sensitive photoresist and masks.

The process begins with the application of a light-sensitive material, or photoresist, onto the surface of the wafer. The coated wafer is then exposed to ultraviolet light through a photomask containing the desired pattern. On exposure, the photoresist undergoes chemical changes enabling selective removal during development and thereby creating a patterned resist layer. The pattern serves as a template for subsequent process steps such as etching or material deposition, which collectively define the intricate features of integrated circuits [27, 39].

The resolution limit imposed by the Rayleigh criterion has direct implications for the scalability and functionality of semiconductor devices, highlighting its central position in the advancement of lithographic technologies.

The Rayleigh formula (Equation 2.1) is given by:

$$CD = k_1 \frac{\lambda}{NA} \tag{2.1}$$

Where:

- CD is called critical dimension or resolution.
- λ is the wavelength of the light used in the photolithography system.
- NA is the numerical aperture of the lens.
- k_1 is a process-dependent constant that typically is close to 0.5.

Equation 2.1 shows that reducing the feature size of transistors (and thus increasing the density of transistors) requires either using shorter wavelengths of light or improving the numerical aperture (NA) of the lens system used in photolithography.

2.2.5 Node Scaling and Transition

Node scaling refers to the process of reducing the size of individual transistors and their associated components, such as gates and interconnects, in semiconductor devices. The term "node" typically refers to the process technology used to manufacture ICs, expressed in nanometers (nm). For example, a "7nm node" refers to the technology used to manufacture transistors with dimensions in the range of 7 nanometers.

Historically, Moore's Law was closely tied to node scaling: each new generation of chips would use a smaller node size, leading to more transistors packed into a given chip area. However, node scaling is no longer simply about reducing the gate length, as physical and electrical effects begin to limit further size reduction. As transistors approach the sub-10nm range, issues such as quantum tunneling, leakage currents, and heat dissipation become increasingly difficult to manage. These challenges have led to the exploration of alternative materials (such as graphene and carbon nanotubes) and new architectures (such as finFETs and gate-all-around (GAA) transistors) to overcome the limitations of traditional scaling [37, 42].

As semiconductor nodes shrink, the Rayleigh criterion presents a significant challenge to optical lithography, as it sets fundamental limits on the resolution achievable in a given process [42].

2.2.6 Overlay

Overlay is a fundamental concept for semiconductor manufacturing. It refers to the accuracy between the different layers of a semiconductor wafer during the photolithography process. Each semiconductor device is produced in many steps, where layers of materials and patterns are deposited and etched in sequence. For the final product to operate correctly, those patters have to be aligned in a very precise way; in case these layers are not aligned, it can lead to electrical failures such short circuits, broken connections which impact the product and can even make it wasteful (impacting yield and profitability).

The overlay budget is typically expressed in nanometers, and maintaining tight control over overlay accuracy is essential for producing high-yield devices at smaller nodes [42].

Modern lithography systems apply advanced techniques to minimize overlay error with node scaling, the accuracy needed for overlay becomes increasingly strict. The introduction of techniques such as double patterning and immersion (under water) lithography has further increased the complexity of overlay control, requiring higher measurement accuracy and robust process monitoring.

In summary, overlay control is a critical aspect of semiconductor manufacturing, directly influencing device performance and production efficiency. As the industry advances toward ever-smaller technology nodes, continued innovation in overlay metrology and process control remains essential to meet the demands of next-generation semiconductor devices.

2.2.7 Semiconductor Development Summary

This section provided a foundational overview of semiconductor development, exploring both the materials and principles that underpin modern microelectronics. Semiconductors, primarily silicon-based, are essential for controlling electrical current in electronic devices. Their unique properties, particularly when modified through doping, enable the creation of transistors—the building block of all modern digital and analog circuits.

The progression from individual transistors to integrated circuits (ICs) and finally to semiconductor chips and wafers reflects the increasing complexity, miniaturization, and integration of technology. This evolution has been driven in large part by Moore's Law, which predicted and guided the exponential growth of transistor density, reducing cost and improving performance. However, the continuation of this trend now faces serious challenges due to physical and quantum limitations at extremely small scales.

The Rayleigh criterion was introduced as a key limitation in photolithography, determining the minimum feature sizes that can be patterned onto wafers. This directly affects the industry's ability to scale down device dimensions. In tandem, node scaling and node transition processes illustrate how manufacturing advances aim to reduce transistor size and improve chip performance, even as scaling becomes more complex and less predictable.

Finally, Chapter 2 addressed overlay, the precision alignment of multiple lithographic layers, which becomes increasingly critical as the feature sizes shrink. An accurate overlay is vital for functional devices and high manufacturing yield.

Together, these concepts form the technical and conceptual backbone of semiconductor development. Understanding them is essential to grasp how electronic devices continue to evolve and what technological barriers must be overcome in the future of computing and electronics.

Chapter 3

The Semiconductor Industry

The semiconductor industry plays a pivotal role in the global economic and political stage. The industry creates the technological foundation for major strategic challenges of today: energy transition and Artificial Intelligence.

3.1 Introduction

The amount of data being generated and stored every day is estimated to be around 400 million Terabytes ([19]), which required high data density to sustain existing and new datacenter (more density means more data stored in the same physical volume of a chip - see Figure 3.1). Machine Learning and Blockchain (used, for instance, in the context of cryptoassets) depend on high processing/computational power. Both data storage and computational power are paramount for technological progress and rely on innovation on the semiconductor industry.

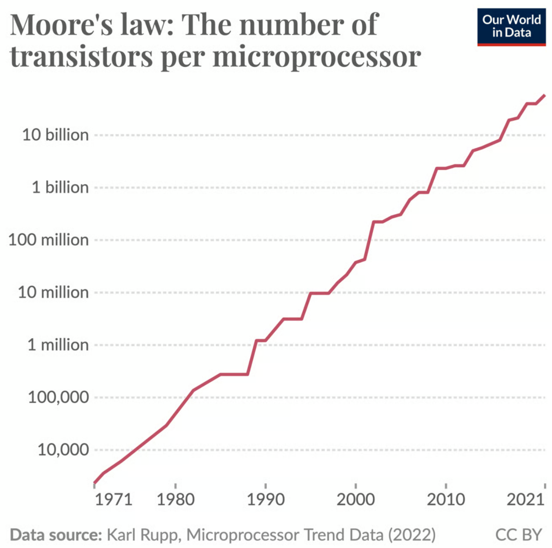

Figure 3.1: Moore's Law: number of transistors per microprocessor [30]

The total value of the semiconductor market is now estimated to be around 625 billion dollars in 2024 and expected to be 1.3 trillion dollars by 2034 ([13]). These figures highlight the economic and financial impact of the semiconductor industry.

This chapter looks at the semiconductor industry's important role in today's economy, especially in supporting AI and data-driven infrastructures. Section 3.2 covers the historical development of semiconductor technology. Section 3.3 provides an overview of the industry's global value chain and major challenges, particularly in lithography, where innovation cycles can last up to a decade. Section 3.4 reviews standard product development methods and introduces the hybrid model now used in lithographic equipment. Lastly, Section 3.5 presents a short resume of the chapter.

This background is crucial for understanding how and why traditional processes could improve by integrating Lean Startup principles in the following chapters.

3.2 Historical Context

It is not possible to pinpoint the discovery of semiconductor materials. This was a succession of incremental advancements between the 19^{th} to 20^{th} centuries.

Early observations of semiconductor behavior are credited to Faraday while studying the varying conductivity of silver silver sulfide with temperature.

Simply put, a semiconductor is a material that either conducts or blocks electric current depending on some factors including voltage direction/polarity. This property makes it the central piece to create transistors (explained in Chapter 2) which are the building blocks for both digital electronics - where 0s (block) and 1s (conduct) represent the bits - and analog electronics - where transistors will behave as amplifiers to control an input signal.

As explained in Chapter 2, the first working transistor (initially made with Germanium as semiconductor) was created at Bell labs in 1947. This lead to the invention of the first integrated circuit (IC), also known as microchip, at Texas Instruments in 1958. The ICs significantly reduced size and cost of electronic circuits, paving the way for modern electronics.

In the 1960s Silicon was established as the dominant semiconductor due to it's abundance in nature and lower cost.

In the same decade Gordon Moore (co-founder and former CEO of Intel) observed that the number of transistors in an IC was doubling every two years. This lead to the creation of the so-called 'Moore's Law'. 'Moore's Law' is not a scientific law, but rather a heuristic based on observation. The definition of 'Moore's Law' has been changing over time and currently is widely interpreted as co-relating time with transistor density. 'Moore's Law' is very relevant in the industry. So far it was almost always met showing the growth and in many aspects pushing the technological advancements.

During the 1980s and 1990s we observed a rise in consumers electronics and the personal computer revolution that created a very high demand of new and better ICs (cheaper and with more transistors). The trend continued with the Internet, smartphones, IoT (Internet of Things)

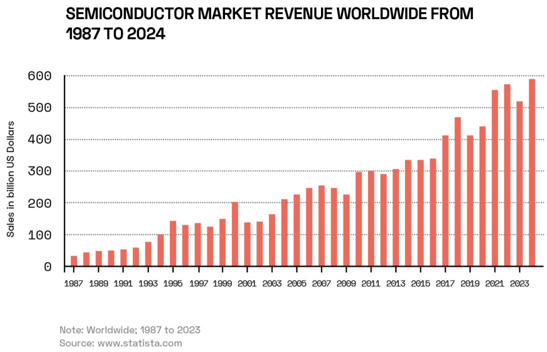

Figure 3.2: Semiconductor Market Revenue Worldwide from 1987 to 2024 [38]

and all other modern devices. The steady increase in demand is reflected in the following graph depicting the semiconductor market value (Figure 3.2).

Between 2000 and 2010, the semiconductor industry experienced significant globalization, supply chain expansion and consolidation, driven by factors like the emergence of China as a major economic player. This period saw increased vertical specialization, with companies focusing on specific parts of the value chain. Manufacturing moved to East Asia due to cost-effectiveness and due to the fact that the Asian companies were more willing to take risks. ([16]).

In the recent years, the industry has been affected by circumstantial events and global politics. The global chip shortage, initially triggered by the pandemic, has seen some easing in production and demand, particularly in areas like consumer electronics. However, challenges remain, with some sectors like automotive still facing sporadic tightness in specific components causing a 200 billion dollar global cost in the industry due unfinished product ([28]).

New concerns have also emerged, including US export restrictions on key materials to China and geopolitical tensions (example China-Taiwan), potentially leading to further disruptions. Building new chip factories (called fabs) takes years and a big investment (tens of billions dollars) making it a long-term challenge to address the supply-demand imbalance and re-locate production to Europe and US ([16]).

3.3 Industry overview and scope

This industry is characterized by high capital intensity, global inter-dependencies (complex and international supply chain), highly skilled labor and sensitivity to economic cycles. As mentioned before, a single fab can cost tens of billions of dollars. Even with government investments (for example, EU Chips act) the cost is still a major blocker. This is one of the challenges for innovation in this industry that include geopolitical risks (amplified by the concentration of production in East Asia, Taiwan in specific), high water and energy consumption, physical limits to scaling, export controls.

The value chain high-level overview (see Figure 3.3) consists of:

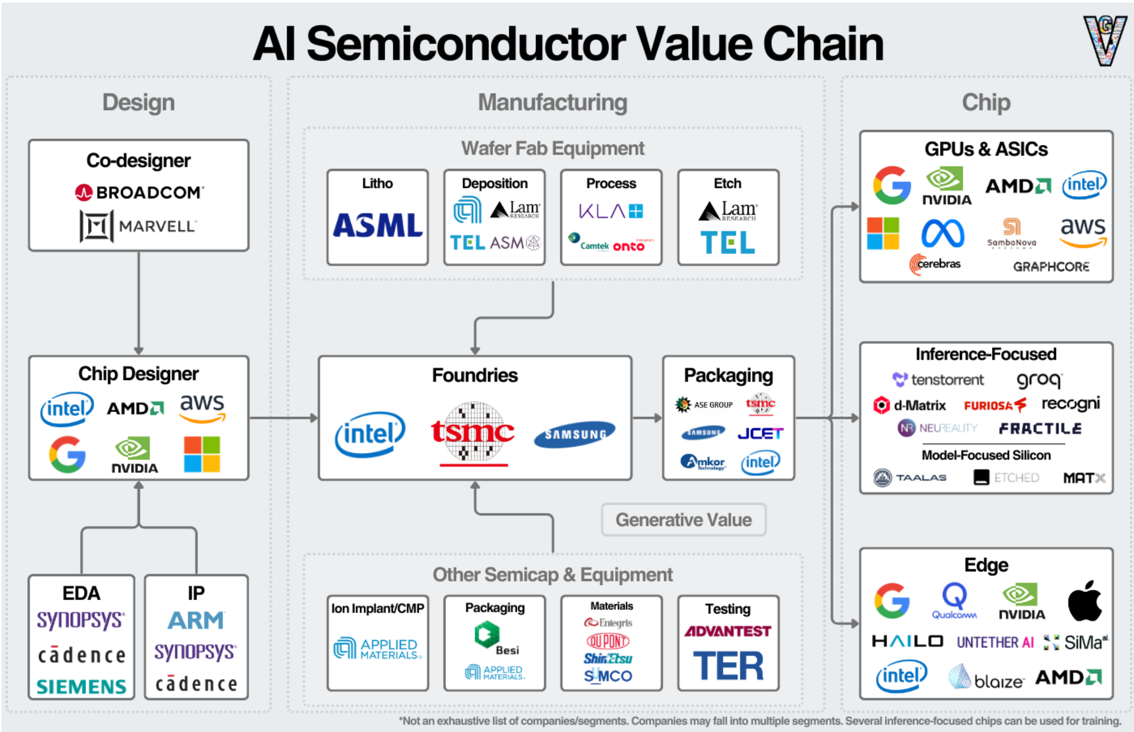

Figure 3.3: Semiconductor Landscape [44]

1. Design: chip architecture, defining its functionality, and validating the design. Very often companies that design chips are 'fabless' and outsource the manufacturing process to 'foundries'.

2. Manufacturing: consisting of creation of the chips in foundries, but also the necessary equipment for the fabs (lithography machines, metrology equipment, etc). Some companies – called Integrated Device Manufacturers - are both designers and manufacturers of chips.

3. Chip selling: usually consisting of the end products for the final customer.

Although the industry can be characterized by a rapid technological change (driven by ruthless competition in the end customer electronic products segment) some sectors have relatively slow innovation cycles. This is the case of lithography: designing and developing new machines to manufacture chips using lithographic techniques can take several years, up to a decade ([16]).

The scope of this thesis is therefore the industry of lithographic machines production given that the innovation cycles are slower and it is nowadays a bottleneck for the complete value chain (as referred to in Chapter 1).

3.4 Product development management models in the industry

In this section, classic product development management models/frameworks (V-model, Waterfall, Concurrent Engineering, TRL – Technology Readiness Level) will be described. The section

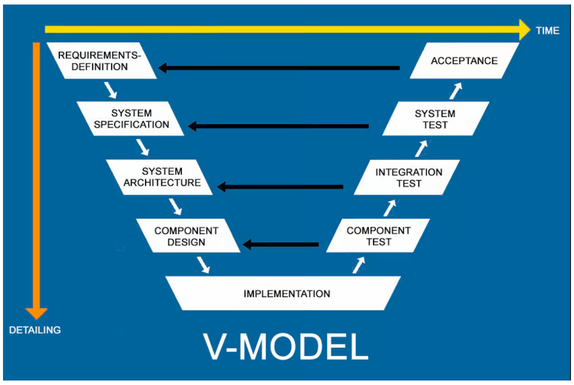

Figure 3.4: V-Model [45]

finishes with the description of the hybrid model used in the lithography industry which is a combination of the others.

3.4.1 V-model

The V-model (Figure 3.4) is a product development and testing methodology that emphasizes parallel verification and validation activities throughout the development lifecycle. In this context, validation can be interpreted as making sure that we are 'building the right product' and verification as 'building the product right'.

This approach is structured in layers that emerge from the functional breakdown (system, subsystem, module, component). The deeper the layer, the larger the detail of the system. Each development phase or layer (left side of the V) has a corresponding testing and integration phase (right side of the V). This implies that during the development phase the tests are also described such that during system/component/module integration the verification can take place.

This model is particularly well-suited for projects with well-defined requirements and a focus on quality and documentation, as it ensures that testing is integrated from the beginning.

3.4.2 Waterfall

The waterfall model consists of a linear approach to product development, with a well-defined, sequential structure that is easy to understand and manage.

Each phase has specific deliverables and and progress is tracked through milestones. It is suitable for small/medium size projects with stable requirements. Nevertheless, it doesn't promote customer involvement which means that feedback comes late and changes are very expensive.

3.4.3 Concurrent Engineering

Concurrent engineering is a product development approach where different aspects of a product's lifecycle (design, manufacturing, and quality) are developed in parallel rather than sequentially.

This simultaneous approach aims to reduce product development time and costs by integrating all stakeholders (functional teams, quality managers, industrialization engineers, architects) early in the process. Therefore this model requires permanent cross-functional team collaboration. By fostering collaboration and communication between teams, concurrent engineering helps identify and address potential issues early on, leading to improved product quality and faster time to market.

3.4.4 Technology Readiness Levels

Technology Readiness Levels (TRLs) are a measurement system used to assess the maturity of a product from concept (TRL 1) to production (TRL 9). TRLs help determine if a technology is ready for further development hence evaluating risk and uncertainty (as the readiness level of a product increases, the risk diminished and uncertainty is reduced). They provide an understanding of a product development stage, facilitating communication and decision-making across different interdependent projects.

3.4.5 Hybrid frameworks

In the lithographic industry, a combination of the above mentioned models is used. Each V-Model phase maps to a certain maturity/readiness level. This readiness levels are linear and used as milestones with certain expected deliverables (Waterfall) to make decisions regarding continuation of development. Each milestone expects parallel but interdependent deliverables coming from different teams (architects, quality managers, industrial engineers, etc) requiring communication and collaboration throughout the complete lifecycle of the product development.

3.5 Summary

This Chapter provided an overview of the semiconductor industry's technological, economic, and strategic importance. It started with a historical perspective, tracing the evolution from early experiments in semiconductor behavior to the invention of the transistor and integrated circuit, and the rise of silicon as the main material. The chapter discussed Moore's Law as both a guiding principle and a sign of the industry's fast technological growth.

Next, the chapter explored the current state of the industry, highlighting its role in supporting critical technologies like artificial intelligence, blockchain, and high-density data storage. The analysis pointed out the industry's high capital demands, global value chain, and weakness to geopolitical issues and supply chain disruptions. It focused on the lithography sector, which is key to semiconductor manufacturing but faces long innovation cycles and major barriers to entry.

The final section introduced key product development management models, including the V-model, Waterfall, Concurrent Engineering, and Technology Readiness Levels (TRLs). It discussed their relevance and limitations in the semiconductor industry. The chapter concluded by describing the mixed frameworks used by lithography equipment manufacturers. These frameworks combine elements from the models mentioned earlier to handle complexity, risk, and interdependencies in long-term innovation projects.

This chapter sets the stage for examining how Lean Startup principles, usually linked to fast-paced software and digital product development, can be used to speed up innovation cycles in the traditionally rigid and capital-heavy semiconductor industry, especially in lithographic technology.

Chapter 4

Methodology

This chapter describes the research methodology used to investigate how Lean Startup framework can enhance innovation in lithographic semiconductor companies.

Given the highly specialized and capital-intensive nature of semiconductor lithography, the research is grounded in both theoretical comparison and practical insight through qualitative data collection. Key factors of interest include design for manufacturability (DfM), cost efficiency, responsiveness to change, and time to market.

The objective of this chapter is twofold:

1. to explain the research design and data collection strategy;
2. to define the analytical framework used to compare Lean Startup principles against traditional models such as the V-Model, Waterfall, and Technology Readiness Level (TRL) approaches (as mentioned in Chapter 3).

The present chapter is structured as follows:

- Section 4.1 provides an overview of the methodologies being compared;
- Section 4.2 details the research design;
- Section 4.3 describes the type of data and how was collected;
- Section 4.4 highlights the analysis methods;
- Section 4.5 emphasizes and justifies the metrics used to compare the different models;
- Section 4.6 describes what strategies were applied to ensure trust in the study;
- Section 4.7 explains how did the participants in the study were ensured ethical protection and Section 4.8 summarizes the chapter.

4.1 Selected Product Development Methodologies

In order to evaluate the potential benefits of applying Lean Startup to accelerate innovation within lithographic semiconductor development, this study compared the framework to the product development models currently in use in the industry, as mentioned in Chapter 3.

The methodologies used most frequently include the V model, waterfall, concurrent engineering, and technology readiness level (TRL) models (as explained in Chapter 3). These methodologies form the reference against which Lean Startup principles are evaluated in this study.

In practice, lithographic semiconductor companies often employ hybrid models that blend elements of the above methodologies, with V-Model being the back bone. For instance, a project may follow a V-Model structure at the system level while incorporating concurrent engineering at the subsystem level and TRL milestones for experimental components. For this study the LS methodology will be compared with the V-Model and an Hybrid Model as a combination of waterfall, concurrent engineering, technology readiness level and V-Model.

4.2 Research Design

This study adopts a conceptual, comparative, and simulation based research approach supported by:

- Comparison of the V-Model, Hybrid, and Lean Startup models using systems engineering literature and documented best practices;
- Subsystem development scenarios are simulated using risk events and representative team compositions to show how the model behaves under actual constraints;
- Evaluation using predetermined innovation metrics to gauge performance in important domains such as documentation, iteration, validation lead time, and adaptability.

This method, in contrast to conventional empirical research, uses deductive reasoning and structured conceptual modeling in place of primary qualitative data collection.

4.3 Data Sources

This study used as data sources:

- literature from academia and business on Lean Startup, systems engineering, and product development in the high-tech and semiconductor industries;
- white papers and technical reports from consortiums and companies that manufacture semiconductor equipment;
- internal risk scenarios and simulations of product development teams that are specific to the contexts of lithographic subsystems.

- The creation of simulation scenarios and the comparative framework are both influenced by these sources.

These sources are used to both the comparative framework and the development of simulation scenarios.

4.4 Data Analysis

Two analytical methods were applied and are described in below sub-sections.

4.4.1 Structured Comparative Analysis

A scoring method was developed to evaluate each methodology (Lean Startup, V-Model, Hybrid) against a consistent set of innovation metrics (see Section 4.5). Scoring relied on insights from interviews and literature. A five-point scale measured each metric (1 = low performance, 5 = high performance). The aim was not to measure performance exactly but to pinpoint relative strengths and weaknesses in an organized way. The analysis provides a comparative lens on trade-offs between flexibility, control, speed, and risk.

Results were visualized using comparison tables and radar charts, presented in Chapter 5.

4.4.2 Simulation-Based Evaluation

To demonstrate how each methodology functions under comparable development conditions, a simulated case study was created. This case compares the Lean Startup and V-Model approaches to the design of a new optical alignment subsystem in terms of:

- Specialization and team structure.
- Cycles of iteration and feedback.
- Managing risks and being responsive.
- Effects of interruptions (such as supplier delays).

4.5 Innovation Metrics

To evaluate and compare different development methodologies — including the V-Model, Hybrid approaches, and Lean Startup — this study uses a structured set of innovation-related metrics.

These metrics were derived from systems engineering literature, innovation frameworks (e.g. Lean Startup), and themes emerging from expert interviews. They provide a consistent framework to assess how well each model supports rapid, effective, and manufacturer innovation in complex environments like lithographic semiconductor development.

In Table 4.1 eleven innovation-related metrics were selected to guide the comparative analysis. These were derived from the literature on product development, systems engineering, and Lean innovation.

Table 4.1: Innovation Metrics and Their Relevance

Metric	**Description**	**Relevance to the Study**
Time to Market	Time required to go from concept to marketable product.	Shorter time to market can increase competitiveness, reduce development cost and free resources for new product generation
Iteration Cost	Cost associated with each cycle of learning, testing, or redesign	High iteration costs inhibit experimentation and slow innovation
Design for Manufacturability (DfM)	Degree to which manufacturability is considered early in the design process	Late DfM involvement often leads to rework, delays, and increased cost
Feedback Frequency	How frequently insights from users or customers are integrated into development	Early and frequent feedback reduces market misalignment and improves functionality
Validation Lead Time	Time between design implementation and functional/system validation	Long validation cycles delay learning and increase the risk of late-stage failure
Change Responsiveness	Ability to adjust development direction when new insights or needs arise	Agile responsiveness is critical when working in uncertain or evolving markets
Cost Efficiency	Overall efficiency in converting development investment into valuable output	Cost-effective development is vital given the capital-intensive nature of lithographic systems
Documentation Traceability	Rigor of documentation and ability to trace design decisions and requirements	Essential in regulated and complex environments to ensure compliance and minimize defects
Risk Management	Ability to identify, mitigate, and respond to technical and project risks	Effective risk management prevents delays and ensures system integrity under high uncertainty
Resource Allocation	Efficiency in distributing personnel, time, and budget across teams or stages	Poor allocation can create bottlenecks and hinder cross-functional collaboration
Organizational Culture	Degree to which the company culture supports experimentation and learning	Culture shapes how new methods like Lean Startup are adopted and whether teams are empowered

These metrics provide a multidimensional view on innovation performance and serve as the basis for the comparative analysis presented in Chapter 5. The thesis looked to have an holistic evaluation of how these methodologies perform in real-world industrial settings (lithographic semiconductor industry) by including both technical-process factors (such as DfM and Validation Lead Time) and organizational enabling factors (like culture and resource allocation).

4.6 Validation and Reliability

To ensure the research was as trustworthy as possible, the following strategies were employed:

- Academic colleagues with experience in systems engineering and product development evaluated the simulation and scoring procedure.
- Sensitivity analyses were performed to see if scoring conclusions remained if and when reasonable assumptions were changed.

The methodology recognizes its conceptual nature and supports strategic discussion and model selection rather than statistically generalizing findings.

4.7 Ethical Considerations

As no personal or organizational data were collected directly through interviews, ethical concerns were minimal. Nonetheless, all sources are properly cited, and all references to real-world scenarios or practices are anonimous or presented in generalized form to avoid disclosure of sensitive information.

4.8 Summary

This chapter presented the methodological framework for examining how Lean Startup can improve innovation in lithographic semiconductor systems. By comparing Lean Startup with the V-Model and a Hybrid methodology that uses structured innovation metrics, the study takes a comparative and simulation-based approach. The findings of this analysis are presented in Chapter 5, along with radar visualizations, scenario-based simulations, and comparative scoring that show real-world variations in model behavior.

Chapter 5

Results

This chapter presents the empirical findings of the thesis, which explores the potential of Lean Startup Framework to enhance innovation in the context of R&D and product development in the semiconductor lithography industry.

The results presented in this chapter form the basis for the discussion in Chapter 6, where implications for practice and integration strategies are described.

The findings are organized as described below:

1. A comparative evaluation of three development models - V Model, Hybrid Model (a combination of V-Model, Waterfall and Technology Readiness Levels), and Lean Startup (all access across innovation performance metrics identified in Chapter 4.
2. A simulation-based scenario that contrasts the application of the V-Model and Lean Startup within the semiconductor lithography context. This includes a detailed comparison of team composition, development approach, and risk response behavior, specifically tailored to a subsystem relevant to lithographic machines.

This chapter begins with a structured analysis (Section 5.1) of the three models, focusing on how each performs when evaluated through the innovation dimensions explained in Chapter 4. These results are grouped into five aggregated in five categories and visualized in a radar chart (Section 5.2).

In Section 5.3, a realistic simulation is introduced, modeling the development of an optical alignment substystem under both V-Model and LS methodologies.

The chapter ends with key takeaways (5.5) and a final summary (5.6).

5.1 Comparative Analysis

To complement the qualitative findings, structured scoring was used to compare three development approaches:

- A. V-Model

- B. Hybrid Model (V-Model + Concurrent Engineering + TRLs)
- C. Lean Startup (Applied selectively, in early development stages)

Each was scored on a five point scale (1 = low performance, 5 = high performance) across the eleven innovation metrics described in Chapter 4. Scores are based on interview insights and literature review and can be seen in Table 5.1.

Table 5.1: Comparative Evaluation of Product Development Frameworks in the Lithographic Systems Industry

Metric	**V-Model**	**Hybrid**	**Lean Startup**
Time to Market	2	3	5
Iteration Cost	1	2	4
Design for Manufacturability (DfM) Integration	5	5	3
Feedback Frequency	1	3	5
Validation Lead Time	1	3	4
Change Responsiveness	1	2	5
Cost Efficiency	2	3	4
Documentation Traceability	5	5	2
Risk Management	4	5	3
Resource Allocation	3	4	4
Organizational Culture Fit	2	3	5

In the sub-sections below a comprehensive explanation on the scoring of Table 5.1 is presented.

5.1.1 Time to Market

The V-Model performs poorly in lowering time to market because of its intrinsically sequential and phase-gated structure. The product launch is frequently delayed because iterations are expensive and validation is postponed until later. By including TRL-based checkpoints, the Hybrid Model makes minor improvements that enable partial parallelization (with concurrent engineering) and early system verification. The Lean Startup approach, on the other hand, performs better in this area by embracing early customer feedback loops and rapid prototyping, which permits the early release of software modules or minimum viable subsystems and speeds up market entry.

5.1.2 Iteration Cost

Iteration is expensive in the V-Model, especially in hardware-centric fields like lithography where dependent subsystems may be affected by upstream design changes. By using incremental TRL gates, which offer organized chances for course correction, the Hybrid Model decreases some of these difficulties. In contrast, Lean Startup places a strong emphasis on early failure and small-batch experimentation, which drastically lowers the cost of iterations. Rework costs are further reduced by using software-in-the-loop techniques, digital twins (), and simulation, particularly in computational lithography or metrology subsystems.

5.1.3 Design for Manufacturability (DfM) Integration

Both the V-Model and Hybrid Model show strong performance in integrating DfM principles. These approaches include manufacturability checks during the system architecture and design phases. This is important in lithographic equipment because mechanical tolerances, optical alignment, and process integration are closely limited. On the other hand, Lean Startup tends to focus on early-stage functionality more than manufacturability. This emphasis can be harmful in situations where the product needs to meet strict fabrication and reliability standards. On the other hand, shorter iterative product development cycles, could encourage design simplification and use of industry parts (for proof of concepts) and therefore increase manufacturability later on.

5.1.4 Feedback Frequency

The V-Model has low feedback frequency because it follows linear development stages. This approach limits input from stakeholders until the validation or testing phases. The Hybrid Model improves on this by providing feedback opportunities at each TRL milestone. However, it still does not have the ongoing interaction found in iterative models. Lean Startup is better than both. It includes methods like customer discovery interviews, usage telemetry, and experimental design to ensure frequent feedback throughout the development process.

5.1.5 Validation Lead Time

The V-Model usually waits until the final testing phase for validation, leading to long wait times. Hybrid methods lessen this delay by including validation checkpoints within TRL frameworks, often through simulation or prototype testing at earlier stages. Lean Startup shortens validation time even more by using MVPs and early test environments to check assumptions before committing to the full system investment.

5.1.6 Change Responsiveness

V-Model methodologies show limited ability to respond to changes because of their strict, documentation-heavy structure and late validation stages. Hybrid models offer more flexibility. They promote incremental development across readiness levels, which helps teams react to failure signals sooner. Lean Startup has the best responsiveness; it is built to support pivots and changes driven by hypotheses based on real-world learning.

5.1.7 Cost Efficiency

While the V-Model can result in high sunk costs from discovering defects or integration issues late in the process, Hybrid models provide moderate cost efficiency by using risk-based stage gates and phased funding. Lean Startup aims to minimize costs by reducing waste. It focuses on avoiding over-engineering and over-designing and instead invests only in features or subsystems that have been validated through real evidence. LS encourages the creation of MVPs that by nature have to be cost caucious.

5.1.8 Documentation and Traceability

Both the V-Model and Hybrid approaches work well in settings that need strict documentation and traceability, like the semiconductor capital equipment industry. These methods keep detailed design records, requirements traceability matrices, and verification protocols, which are important for regulatory compliance and supplier coordination.

On the other hand, Lean Startup focuses less on documentation and more on speed and experimentation. This focus may make it less effective in environments that require high traceability and design control.

5.1.9 Risk Management

Risk management is a key part of the V-Model and Hybrid methodologies. The V-Model focuses on identifying risks and planning how to mitigate them early on. Hybrid models build on this by including risk-based TRL assessments. These assessments help development teams address and reduce risks in subsystems separately. In contrast, Lean Startup accepts a greater level of uncertainty. It handles risk through repeated testing and validation instead of structured analysis. This approach might not be suitable for critical systems that have low tolerance for faults.

5.1.10 Resource Allocation

The V-Model demands a lot of resources at the beginning, which can be wasteful if early assumptions turn out to be wrong. Hybrid models allow for a more flexible resource strategy, matching resources with TRL progress and risk level. Lean Startup is great at gradually using resources. It makes sure that funding increases only after key ideas are proven, which lowers the risk of investing too much in technologies that are not yet tested. Also, startups resort to multidisciplinary teams and low specialization which if implemented in the semiconductor landscape can help manage resources in a more effective way.

5.1.11 Organizational Culture Fit

The V-Model suits traditional, hierarchical organizations that prioritize predictability, planning, and control. Hybrid approaches offer some flexibility; they benefit organizations that combine structured and exploratory practices many times in a complex matrix organization that might be too heavy. Lean Startup works best in innovation-driven environments that embrace uncertainty, encourage teamwork across different groups, and see failure as a learning opportunity.

5.1.12 Summary Comparative Analysis

This comparative analysis points to no single method being the best choice for every situation. The right development model depends on the technology's maturity, the system's complexity, the regulatory requirements, and the organization's context.

In the lithographic systems industry, a Hybrid Model with embedded TRLs appears to provide the best balance of risk control, system validation, and learning through iteration. However, Lean Startup principles work well for early-stage R&D, innovation in subsystems, or software components. At the same time, the V-Model is helpful for safety-critical modules that need strict documentation and traceability.

5.2 Radar Chart

To provide a clearer comparison of how the different product development models perform over the selected metrics in Chapter 4, this study grouped the eleven innovation metrics into five main categories: Planning, Iteration, Feedback, Documentation, and Adaptability.

Each metric was assigned to one or two categories based on its relevance.

- Planning consists of known sequence of activities that add value to achieve the vision; it condenses the following metrics Time to Market, Cost Efficiency, Design for Manufacturability (DfM), Resource Allocation, Risk Management, Organizational Culture Fit.
- Iteration reflects the efficiency of rework and short-cycle development, encompassing Iteration Cost and Validation Lead Time.
- Feedback measures the responsiveness to input, using Feedback Frequency and Validation Lead Time.
- Documentation includes traceability and risk-related governance through Documentation Traceability and Risk Management.
- Adaptability highlights the system's responsiveness to change, assessed through Change Responsiveness, DfM, and Organizational Culture Fit.

Each broader metric was calculated as the average of its related detailed metrics. All included metrics had equal weight, no matter if there was any overlap between categories.

The resulting values are shown below, in Table 5.2.

A radar chart (Figure 5.1) was used to visualize the relative the performance of the three models across the five sub-categories (innovation metrics as mapped above) in order to visualize these results.

Table 5.2: Aggregated Model Scores Across Defined Innovation Metrics

Category	**V-Model**	**Hybrid**	**Lean Startup**
Planning	3.0	3.8	4.0
Iteration	1.0	2.5	4.0
Feedback	1.0	3.0	4.5
Documentation	4.5	5.0	2.5
Adaptability	2.7	3.3	4.3

As anticipated, the Lean Startup model excels in dynamic, innovation-driven environments, as evidenced by its highest scores in iteration, feedback, and adaptability. In contrast, the V-Model's organized, linear methodology is consistent with its strong support in planning and its excellence in documentation.

This simplified radar synthesis highlights the strategic trade-offs inherent to each model and underscores the suitability of Lean Startup principles for agile, innovation-oriented product development in complex industries such as semiconductor lithography.

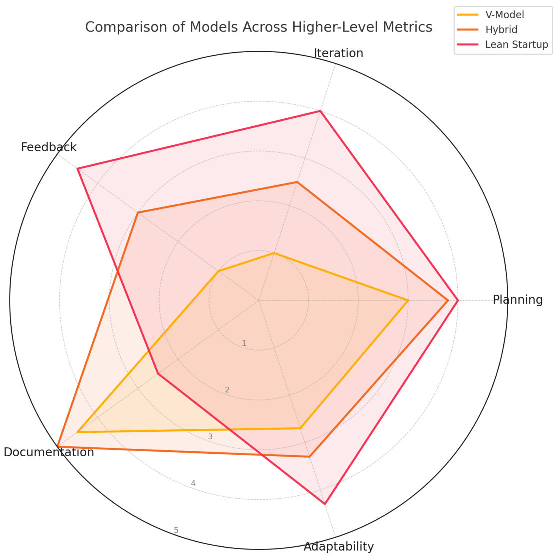

Figure 5.1: Comparative Radar Chart of Development Models Across Innovation Metrics

5.3 Simulated Comparative Analysis of Product Development Approaches in a Semiconductor Lithography Context

This section offers a structured simulation that contrasts the application of the V-Model and Lean Startup, two distinct product development methodologies, in a semiconductor lithographic systems environment.

This simulation examines variations in development cycles, risk responses, operational dynamics, and team formation. It offers a strong foundation for evaluating the potential effectiveness of Lean Startup techniques in a historically capital-intensive and high-risk sector.

5.4 Team Definition and Composition in Lithographic Subsystem Development

Given the complex and multidisciplinary nature of lithographic systems, a representative team working on a new optical alignment subsystem for a next-generation wafer scanner was simulated. This subsystem is important for overall system precision, but allows for some separation from final machine integration during the early R&D stages. This makes it a good fit for a Lean Startup simulation. The organizational structure and team composition differ significantly depending on the chosen development model, affecting communication, flexibility, and risk management.

5.4.1 Team Setup Under V-Model

V-Model teams in semiconductor lithography are typically larger and hyper-specialized, with several experts dedicated to each technological domain. This division supports rigorous documentation, traceability, and compliance but can reduce flexibility.

Team Size: 12-17

Composition:

- Product Manager: Responsible for the overall scope of the project and the alignment of stakeholders.
- Process Engineering Team (3-4 specialists): Individually focused on resist chemistry, exposure parameters, and defect control.
- Optical Engineering Team (3-4 specialists): Divided into subdomains such as lens design, illumination optics, and metrology.
- Software Development Team (2-3 embedded and control software engineers): Working separately on sensor integration, system diagnostics, and factory interfaces.
- Quality Assurance and Compliance Specialists (2-3 people): Dedicated to safety, reliability testing, and documentation control.
- Manufacturing Integration Team (2 engineers): Responsible for factory automation and process monitoring interfaces.

This separation of roles enables deep domain expertise and thorough validation, but creates dependencies on formal communication channels and slower decision cycles.

5.4.2 Team Setup Under Lean Startup

By contrast, a Lean Startup-inspired team is intentionally smaller (as startups are), cross-functional, and designed for early experimentation. The focus is on fast hypothesis testing, prototype learning, and early-stage risk exposure.

Team Size: 6

Composition:

- 1 Product Lead (vision and customer problem definition)
- 1 Optical Engineer (light path and lens exploration)
- 1 Mechatronics Engineer (mechanical integration + electrical sensing)
- 1 Embedded Software Developer (rapid firmware prototyping)
- 1 Simulation Specialist (optical modeling and virtual MVPs)
- 1 Manufacturing Liaison: Ensures manufacturability and factory integration while providing direct feedback from production lines.

During the subsystem feasibility stages, this team has the authority to make design trade-offs and function somewhat independently.

5.4.3 Development Simulation: Lean Startup versus V-Model

To simulate the development of this optical alignment subsystem under each methodology, we detail how each team would operate through the key phases of the product lifecycle, particularly focusing on response to typical early-phase risks.

5.4.3.1 Lean Startup Scenario

- **Phase 1: Problem Discovery and Assumption Mapping**

  In order to comprehend alignment tolerances and user requirements, the Lean team starts with exploration workshops where they shadow integration engineers and system architects. Learning objectives are associated with hypotheses like "real-time lens auto-calibration could reduce drift errors by 30%."

- **Phase 2: Early MVP and Subsystem Prototyping**

  A mocked-up sensor rig, simulation-based alignment prediction, and off-the-shelf components are used to create an early "minimum viable prototype." Without complete mechanical integration, the goal of this MVP is to verify essential functionality in a sandbox testbed.

- **Phase 3: Build-Measure-Learn Cycles**

  The team refines the design and data assumptions through two to three feedback cycles with adjacent module designers and integration engineers. Important metrics are tested both physically and virtually, including alignment accuracy and thermal drift response.

- **Phase 4: Pivot, Preserve, or Proceed Decisions**

  The team investigates different sensor configurations and cooling techniques based on preliminary test results. This results in a validated design direction that still meets system accuracy thresholds while being 80% less complex than the initial assumed path.

- **Phase 5: Documentation and Transfer**

  In order to facilitate a more seamless transition into more structured development environments, lightweight design logs, validation summaries, and assumptions are collected into a "learning archive" that supports later handover to system integration teams.

5.4.3.2 V-Model Scenario

- **Phase 1: Requirements Elicitation and Traceability**

  The V-Model team works with experts in system engineering, marketing, and regulations to come up with full requirements specifications. These are turned into a hierarchical requirements matrix that includes functional, non-functional, and environmental areas.

- **Phase 2: Design and Interface Definition**

  There is a full design baseline that includes formal interface control documents (ICDs), tolerance studies, and reviews of how easy it is to make the design. Before a prototype can be approved, it must use high-fidelity simulations.

- **Phase 3: Development and System Assembly**

  After the design reviews are done, custom parts are ordered, like a special optical mount that will take 10 weeks to arrive. Based on frozen hardware specifications, firmware is developed at the same time.

- **Phase 4: Verification and Validation**

  Verification happens through structured lab tests, alignment protocols, and traceability audits. Any changes must go through formal engineering change requests (ECRs), which could delay validation.

- **Phase 5: Risk Event—Supplier Delay**

  Considerable downstream delays are caused by a delay in the delivery of the optical mount. Switching to a standard part would necessitate re-testing, new compliance reports, and system-wide impact assessments because of the formal change control procedure.

5.4.4 Comparative Risk Response: Shared Scenario

To highlight methodological differences, both scenarios face the same risk—a 6-week supplier delay of a crucial optical component—to illustrate methodological differences (Table 5.3).

Table 5.3: Comparative Risk Response: Shared Scenario

Criteria	**Lean Startup Response**	**V-Model Response**
Planning Flexibility	Replaces with off-the-shelf prototype, documents trade-offs	Requires formal ECR, re-validation, and compliance review
Iteration Impact	Continues subsystem testing using simulated data or substitute hardware	Iteration halts until new part or re-design is approved
Documentation Overhead	Lightweight tracking of decisions in internal design logs	Heavy updates across requirement specs and ICDs
Feedback Continuity	Maintains user testing and learning via sandbox experiments	User input delayed until part is available
Adaptability	High—team adjusts scope and revalidates early assumptions	Low—team bound by frozen specs and formal processes

5.4.5 Insights from Simulation

In this simulation, basic trade-offs between the Lean Startup and V-Model approaches come into play in high-stakes, hardware-intensive domains:

- Lean Startup de-risks projects early with the help of virtual MVPs and modular testing, but traceability is compromised, and a cultural shift is more likely to be required in regulated environments.
- The V-Model ensures compliance and documentation rigor, which could hamper early learning and the ability to respond to supply chain volatility.
- A hybrid approach using Lean Startup in early-stage exploration and V-Model for system-level development could give the best of both worlds in terms of agility and control.

A summary of the simulation and the comparison between the two models can be seen in Table 5.4.

Table 5.4: Comparative Analysis summary

Aspect	**Lean Startup Team**	**V-Model Team**
Team Size	Small (7 members)	Large (15+ members)
Role Specialization	Cross-functional, multiple skills per person	Hyper-specialized, domain-specific experts
Communication Style	Informal, continuous, frequent	Formal, scheduled, documentation-heavy
Decision-Making Speed	Fast, decentralized	Slow, hierarchical
Adaptability to Risk	High; flexible substitutions and pivots	Low; formal change control required
Documentation Burden	Lightweight, evolving	Heavy, rigorously controlled
Iteration Cycle	Rapid, short sprints	Long, phase-gated
Innovation Enablement	Encourages experimentation and rapid learning	Emphasizes compliance and stability

5.5 Key Takeaways

The comparative analysis of the V-Model, Hybrid (V-Model + Waterfall + TRL), and Lean Startup methodologies in lithographic systems development shows the importance of matching development approaches to subsystem complexity, technology readiness, and company culture.

Hybrid methods, especially those using Technology Readiness Levels (TRLs), have become standard in the semiconductor capital equipment industry, with companies like ASML and Lam Research. They offer a practical balance between managing high-risk engineering, following regulations, and validating in stages. This model consistently performs well in risk management, design for manufacturability integration, and documentation traceability.

The V-Model is still useful for critical-path hardware systems that need strict traceability, safety checks, and system-level integration. However, its inflexibility can hinder development, especially in early phases or highly innovative areas.

Lean Startup methodologies work best in environments that prioritize agile learning, quick iteration, and early validation, such as subsystem innovation, software-in-the-loop simulation, and emerging technology pilots. Its advantages include shorter time to market, cost-effective iterations, and quick responses to changes.

Using Lean Startup selectively, especially in early-stage subsystem development or high-risk feasibility studies, is culturally acceptable and technically promising. Practices like minimum viable products, Build-Measure-Learn cycles, and working with customers are beneficial but must be tailored to the constraints of physical system development.

It is essential for organizations to be aligned. Lean Startup should support, not conflict with, existing processes around compliance, safety, and system integration. When integrated thoughtfully into a broader Hybrid development strategy, Lean principles can speed up innovation without undermining system-level integrity.

5.6 Summary

This chapter presented the research findings. No single development model performs better than the others in every situation; rather, their applicability varies depending on the situation, as the simulation and metric-based comparison make abundantly evident. Model selection should be in line with organizational priorities, risk exposure, and subsystem maturity in the development of lithographic systems, where both innovation and dependability are crucial.

Early-stage innovation, feasibility testing, and quick learning in less regulated parts or software-driven subsystems are areas where the Lean Startup methodology excels. Complex, safety-critical modules that require rigorous validation and documentation can still use the V-Model. It seems that hybrid models, especially those that incorporate TRL frameworks, provide a useful middle ground between control and agility by offering both formal oversight and early feedback.

A useful, comparative framework for evaluating development tactics in high-stakes semiconductor environments has been established in this chapter.

Chapter 6 will interpret these findings in relation to existing literature, explore practical implications for industry use, and discuss possible risks and ways to manage them.

Chapter 6

Analysis and Discussion

This chapter presents a detailed look at the empirical results from Chapter 5. It emphasizes the effects of using Lean Startup methods in research and development and product development in the semiconductor lithography R&D industry and how these principles can complement (instead of replacing) traditional product development models.

The analysis looks at the practical limits of developing lithographic systems and the potential benefits of using feedback-driven, iterative practices.

It focuses on how Lean Startup framework can work alongside traditional development models like the V-Model, Waterfall, and Technology Readiness Levels (TRLs) through a mixed development approach.

This analysis and discussion is grounded in comparative scoring, literature-backed modeling, and simulation-based evaluation of development frameworks introduced in Chapter 4 and applied in Chapter 5.

The chapter is divided into six main sections as listed below:

- Challenges in Current R&D and Product Development Practices (6.1).
- Applicability of Lean Startup in hardware-focused environments (6.2).
- Proposal and analysis of a Hybrid Product Development Framework (6.3).
- Organizational and cultural considerations (6.4).
- Implications for industrial implementation (6.5).
- Summary (6.6).

6.1 Challenges in Current R&D and Product Development Practices

The methodological framework for examining how Lean Startup can accelerate innovation in lithographic semiconductor systems was described in this chapter.

By comparing Lean Startup with the V-Model and a Hybrid methodology that uses structured innovation metrics, the study takes a comparative and simulation-based approach. The key challenges were identified:

- Delayed feedback and slow learning cycles, especially during integration after significant investment.
- Limited Design for Manufacturability (DfM) considerations in the early phases, which cause rework later on.
- High costs and complexity of iteration, making frequent prototyping difficult.
- Unlimited budget that allows engineers to over-engineer and compromise simple scalable designs.
- Insufficient customer engagement during the initial development phase, resulting in poor product-market fit.
- Organizational inflexibility, where engineers deal with too much oversight and divided team structures.
- Low adaptability: Phase-gated models are unable to react swiftly to evolving customer demands or new technical discoveries.
- Documentation burden: During the early stages of design, teams may be less flexible and experiment more slowly due to compliance-heavy procedures.

These issues highlight a larger conflict in the industry: the need to maintain control, quality, and compliance while also being able to adapt quickly, learn rapidly, and innovate effectively. This conflict is hard to resolve using only traditional, phase-gated models like the V-Model or even Waterfall combined with TRLs.

These findings highlight a tension between control-oriented development models, designed to manage complexity and compliance, and the need for adaptability and early-stage learning to foster innovation.

6.2 Evaluating the Applicability of Lean Startup in Hardware-Centric R&D

Lean Startup emphasizes Build-Measure-Learn cycles, early customer feedback, and minimum viable products (MVPs). It offers a strong alternative for speeding up innovation. However, using it directly in semiconductor hardware development has significant challenges:

- The high cost and time required for physical prototyping, especially in precision systems like lithography.

- The serious consequences of failure in system-level experiments, which can damage cleanroom-integrated equipment.
- Strict documentation and compliance requirements that Lean Startup often overlooks, but are crucial in regulated or supplier-driven settings.

Despite these challenges, the simulation-based scenarios in Chapter 5 show promising use cases where Lean Startup can be effectively applied:

- Subsystem-level innovation, where localized MVPs can lower risk without affecting the entire system.
- Simulation and digital twins as good substitutes for physical prototypes.
- Concept validation in early-stage R&D, where Lean Startup can help test assumptions, gather customer feedback, and prioritize features before finalizing the architecture.

The findings point that Lean Startup might not be suitable for every stage but is very useful when focused on the early, exploratory parts of the product development lifecycle, especially for new or high-risk subsystems.

6.3 Toward a Hybrid Development Framework

The comparative analysis in Chapter 5 showed that no single development model, neither V-Model, Hybrid, nor Lean Startup, can meet all innovation needs in this industry. Instead, a Hybrid Model emerges as the best option. This model combines the exploratory flexibility of Lean Startup with the structured discipline of TRL-based, phase-gated systems.

6.3.1 Benefits of the Hybrid Approach

- Flexibility at the front end: Lean Startup methods like MVPs and iterative testing can safely be used during feasibility studies, early-stage prototyping, and software-in-the-loop evaluations. For example, an R&D team exploring a new wafer handling system for an EUV lithography machine could create a software-in-the-loop simulation MVP of the robotic arm mechanics using physics modeling. Instead of building an expensive prototype, the team tests control algorithms, motion precision, and integration assumptions in a virtual testbed. This setup allows for quick changes based on test results and feedback from field engineers.
- Structure and traceability in later stages: TRLs and the V-Model ensure thorough validation, quality control, and design documentation, which are crucial for scaling and integration. For instance, once the wafer handler design passes early feasibility checks and customer evaluation in a simulation environment, it moves into later TRL phases for formal hardware prototyping and integration testing. Here, the V-Model directs development through detailed system requirement specifications, design reviews, verification matrices, and supplier documentation. This ensures compatibility with ISO cleanroom and reliability standards.

- Accelerated risk mitigation: Early Build-Measure-Learn cycles highlight high-risk assumptions early on. This allows for changes or design simplifications before making a full-system investment. For instance, a team designing a new lens module for a next-generation lithography scanner conducts a series of quick experimental loops to test thermal stability under extreme UV exposure using a simple lab setup. These MVP experiments show that a certain coating degrades faster than expected—a risk that might have been overlooked until late-stage integration in a traditional V-Model process. The team can pivot early, choosing a more durable material before expensive production tooling begins. .

This layered approach creates two types of innovation workstreams:

- Exploratory tracks focused on learning, iteration, and design freedom.
- Execution tracks focused on scalability, compliance, and productization.

6.3.2 Model Integration Considerations

To implement this hybrid framework, several practices are recommended:

- Stage-gated transitions: Define clear handoffs between exploratory Lean Startup activities and formal TRL milestones.
- Use of digital alternatives: Digital twins and high-quality simulation environments can reduce the need for expensive physical MVPs.
- Tailored performance KPIs: Separate metrics for exploratory and execution phases, such as learning velocity and compliance readiness.
- Traceable MVPs: Encourage lightweight but documented MVP iterations to keep transparency and regulatory traceability.

This approach allows Lean Startup to integrate with existing frameworks instead of competing with or replacing them.

6.4 Organizational and Cultural Considerations

Adopting Lean Startup, even in a hybrid form, requires not just changes to methods, but also big shifts in mindset, governance, and structure.

6.4.1 Cultural Shifts

- From certainty to learning, traditional engineering environments reward predictability and control. Lean Startup requires a tolerance for early failures and experimentation.

- From output to outcomes, Lean Startup methods measure success by validated learning and reduced uncertainty, not just deliverables.
- Cross-functional collaboration, Lean Startup thrives in multidisciplinary teams. It breaks down barriers between systems engineering, software, marketing, and customer-facing roles.

6.4.2 Governance and Leadership

- Dual-mode governance: Leaders must support flexible innovation and strict execution processes at the same time.
- Empowerment at the edges: Teams should have the freedom to test hypotheses without bureaucratic limits, particularly during early R&D phases.
- Change management: Adopting a Lean Startup mindset will need retraining, support from leadership and possibly changes to internal KPIs and performance evaluations.

These organizational supports are just as important as the methodology itself for ensuring successful adoption.

6.5 Implications for Practice

The findings of this study suggest several practical implications for companies looking to improve R&D innovation in semiconductor lithography:

- Using Lean Startup effectively at the start of development can make risks clearer, lower the chances of not meeting customer needs, and speed up the launch of new subsystems and technologies.
- Combining different development models allows organizations to balance being quick and flexible with the control and structure needed for critical, high-reliability systems.
- Investing in supportive infrastructure, such as simulation environments, digital twins, and rapid prototyping platforms, is vital for making iterative development work in a hardware-focused setting.
- Managing organizational change will be important. This means getting leadership support, redefining key performance indicators for early-stage innovation and encouraging collaboration that brings together R&D, manufacturing, marketing and customer support.
- It would be beneficial to look into dual governance models. In these models, teams in early phases can use Lean Startup methods, while late-phase development can follow TRL and V-Model guidelines.

6.6 Summary

This chapter provided a detailed look at how Lean Startup methods, originally designed for software startups, can be effectively applied to the complicated and heavily regulated field of lithographic semiconductor research and development.

It highlights where Lean Startup works well, especially in early exploration, subsystem validation, and learning-focused iterations, while also acknowledging the essential role of traditional models. This positions the Hybrid Model as a sensible and realistic approach to innovation.

To achieve faster learning, better user feedback loops, and lower iteration costs—while maintaining system integrity and compliance—more is needed than just changing methods. It requires organizational cooperation, smart simulation investments, and cultural change.

The next chapter shares the study's conclusions and recommendations. It combines theoretical ideas and practical insights to offer advice for both researchers and practitioners who want to encourage innovation in high-tech, hardware-focused industries.

Chapter 7

Conclusions and Recommendations

This chapter brings together the results and insights from Chapters 5 and 6. It highlights the organizational implications of using Lean Startup framework in semiconductor lithography research and development. It offers a set of findings and suggestions suited for industrial use, drawing on the simulation-based analysis and conceptual comparisons.

This chapter concludes the thesis by summarizing the main findings and discussing their practical effects on research and development in the semiconductor lithography industry. It also provides practical recommendations to industry practitioners. It looks at how Lean Startup principles, when applied selectively, can improve innovation without sacrificing the rigor required by traditional models like the V-Model, Waterfall and TRLs.

The chapter includes the following:

- Section 7.1 summarizes the key findings of the study.
- Section 7.2 presents the main conclusions from the analysis.
- Section 7.3 offers practical recommendations for industry implementation;
- Section 7.4 discusses the wider impact of using a hybrid development model.
- Section 7.5 provides a final summary to conclude the chapter.

Together, these sections reflect on how companies can adjust their R&D strategies to better balance agility, compliance, and innovation.

7.1 Summary of Key Findings

The results acknowledge that traditional, highly structured, and controlled product development processes that are a characteristic of semiconductor lithography face a large pressure to become more agile and responsive. Key challenges identified include (as discussed in Chapter 6):

- Delayed feedback loops: Iteration usually happens at the end of the process, which raises the possibility of rework and risk.

- Limited early customer engagement: Even if a product is technically successful, it may not meet user needs.
- Experimentation and quick learning are hampered by slow and expensive physical prototyping.
- Low investment in simulation tools: Virtual testing environments and digital twins are not used to their full potential.
- Agility vs. regulatory requirements: Lean Startup's emphasis on quick iterations frequently clashes with traceability and documentation, which are necessary for compliance.

Against this landscape, Lean Startup methodologies, which focus on fast Minimum Viable Product (MVP) development, ongoing customer feedback, and tested learning, provide strong innovation benefits. However, they need careful adjustment. The evidence in this study suggests the following:

- Lean Startup can be effective when targeted at early R&D phases such as subsystem or even critical modules prototyping, concept exploration, and high risk component development. Lean Startup could be applied effectively when used in the early research and development phases, such as subsystem prototyping, concept exploration, and risky component development.
- Digital twins and simulation tools could serve as substitute for real prototypes, allowing for quicker iterations and more frequent learning cycles.
- For system-level robustness, traceability, and regulatory compliance, the rigorous discipline of traditional frameworks (such as the V-Model and TRLs) is still essential. Lean Startup offers a fast way to prove a concept and make it into a desirable product but does not offer solutions for scalability and volume production (which are requirements semiconductor litographic systems development).
- A hybrid development model provides a useful balance by fusing traditional development frameworks with Lean Startup practices. It enables businesses to be flexible without sacrificing control.

7.2 Conclusions

This research reveals several important conclusions about how Lean Startup can be applied in semiconductor lithography R&D:

- Lean Startup complements traditional models instead of replacing them. An hybrid approach allows companies take advantage of Lean Startup's iterative and customer-focused benefits during low-complexity and very high-uncertainty phases. It also ensures that they maintain the thorough validation and documentation needed for complex system integration and scalability.

- Early-stage flexibility speeds up risk reduction and innovation. By including rapid feedback loops and MVP testing at the beginning, organizations can spot key technical and market risks early. This helps avoid costly surprises later on and ensures product features better match customer needs.

- Organizational culture and governance play crucial roles. Moving away from certainty-driven engineering mindsets to embrace uncertainty and experimental learning requires a thoughtful cultural shift. Leadership must support dual governance models that foster simultaneous exploration and execution.

- Technology infrastructure is essential for effective implementation. Without investment in simulation, digital twin technologies, and modular prototyping environments, it becomes challenging to achieve Lean Startup's potential in hardware-intensive areas. Modular prototyping is one of the examples that could be implemented, for instance, create a proof-of-concept stage that could print wafers only once but demonstrate the requirements from the customer.

- Cross-team collaboration helps break down barriers by getting marketing, development and engineering, and customer-facing teams involved early in the development process. This teamwork improves the relevance of innovation and reveals useful user insights that might otherwise be overlooked.

- Forming teams with varying skills helps bring in different viewpoints, leading to more creative and balanced ideas. By bringing together knowledge from different areas early on, these teams can question assumptions, balance technical goals with practical limits, and lessen the risk of over-engineering solutions. This teamwork encourages quicker, customer-focused design decisions and speeds up innovation while remaining practical and cost-conscious.

These conclusions confirm that Lean Startup principles can lead to significant improvements in R&D speed, cost efficiency, and innovation quality in the case of being carefully adapted and integrated into the semiconductor lithography development product lifecycle.

7.3 Recommendations for Industry Practice

From these conclusions, specific recommendations arise for companies to consider when looking to update their R&D strategies:

- Adopt Lean Startup methodology cautiously and surgically. Utilize Lean Startup methods primarily for early development tasks such as concept validation and subsystem prototyping.

Avoid using these techniques widely across system-level phases as the risk and expense may be too great.

- Create a hybrid governance structure by defining clear stage-gate procedures that, at the early gates, allow Lean Startup's iterative cycles and, at the later gates, enforce traditional validation standards. This parallel workstream governance provides flexibility while ensuring regulatory compliance.
- Make investments in enabling technologies: Give digital twins, and simulation platforms top priority. These tools speed up feedback cycles and reduce the need for expensive physical prototyping.
- Update incentives and performance measures. Put more emphasis on learning speed, risk reduction milestones and customer engagement metrics rather than output-based KPIs like the quantity of features delivered. Modify incentive schemes to promote trial and error (fail fast learn fast) and demonstrated learning.
- Promote collaboration across different fields and teams. Encourage regular meetings between R&D, marketing, application engineers, and customers. This will help everyone understand each other better and allow for quick feedback.
- Help leadership in managing cultural change by providing senior leaders with the tools and training they need to manage parallel workstreams of innovation and execution, strike a balance between flexibility and discipline, and cultivate an experimental organizational mindset.
- Develop or explore lightweight documentation practices (including the usage of different tools for requirements management). Create documentation and version control systems that are good enough for tracking changes, but do not create too much extra work during early MVP iterations.

7.4 Implications and Industry Impact

The successful adoption of a hybrid model gives semiconductor lithography companies the identified benefits:

- Improved time to market by allowing earlier detection and resolution of design and market risks.
- Improved product-market fit through continuous customer engagement and iterative validation.
- Optimized resource use by directing expensive prototyping efforts toward validated concepts.

- Increased organizational agility without compromising compliance or quality, helping firms respond effectively to fast-changing market demands and technological shifts.
- Encouraging collaboration between different fields and sectors boosts idea generation. It leads to more innovative and practical solutions by combining various perspectives and expertise.

In the end, employing a hybrid development framework with Lean Startup components may help businesses stand out in the cutthroat semiconductor systems sector. Businesses will be able to innovate more quickly and consistently with this approach.

7.5 Summary

This chapter summarized the key conclusions and converted into practical suggestions for the semiconductor lithography sector. It emphasized that although Lean Startup techniques have obvious advantages, like quicker learning, lower risk, and better product-market fit, they work best when used sparingly, particularly in early-stage research and development. The best method for maintaining a balance between agility, compliance, and quality was a hybrid development approach that combined Lean Startup with structured models such as the V-Model, Watefrall and TRLs. Multidisciplinary cooperation, parallel workstream governances, simulation tools, and leadership support for cultural change are important facilitators.

Chapter 8 discusses the limitations of the study and suggests areas for further research. It looks at topics that need more research to improve the scalability and usefulness of LS in the context of a hybrid product development model.

Chapter 8

Limitations and Future Work

This chapter considers the study's limitations and identifies possible directions for further investigation. It expands upon the findings and suggestions made in the preceding chapter.

Recognizing limitations is essential to contextualize the findings and to enhance the robustness and applicability of the proposed hybrid product development framework in semiconductor lithography R&D and potentially other hardware-intensive sectors.

This chapter is structured into three main sections.

- First, it discusses the limitations of the study (Section 8.1), including issues related to scope, methodology, and practical implementation.
- Second, it proposes several directions for future research (Section 8.2), with a focus on quantitative validation, broader industry application, enabling technologies, cultural transformation, and continued refinement of the hybrid framework.
- Finally, a brief summary recaps the key takeaways (Section 8.3).

8.1 Limitations of the Study

Although this study offers insightful information about LS methodologies in the semiconductor lithographic industry, it is important to recognize some limitations to put the results in perspective. These limitations could affect the interpretation of the results and generalization while pointing out areas that require more investigation.

8.1.1 Scope and Generalization

The semiconductor lithography field was the specific focus of this investigation. Although this situation offers a complex and pertinent environment for investigating hybrid R&D methodologies, it also restricts generalization.

Other hardware-intensive industries might not be subject to the particular operational, technological, and regulatory constraints associated with the development of lithographic systems.

Therefore, even though the hybrid model is conceptually transferable, its direct applicability in other industries, like aerospace, automotive, or medical devices, needs to be carefully evaluated.

8.1.2 Methodological Constraints

Instead of being empirical, this study was conceptual and simulation-driven. Although this method allowed for a examination of development models and speculative use cases, it lacked live project tracking and pilot program validation. As a result, even though the conclusions are based on theory and logic pertinent to the industry, they have not yet been put to the test in real-world applications.

Furthermore, assumptions about customer feedback cycles, team dynamics, and governance adoption were based on simulation modeling and literature rather than empirical observation because there was no primary data collection from end users, customers, or company stakeholders.

8.1.3 Implementation Challenges

Despite providing a structured integration of Lean Startup and conventional frameworks, the suggested hybrid model may face organizational resistance when put into practice.

Governance structures are usually strict in semiconductor environments, and formal, evidence-based justification is usually required before changes are adopted. A detailed transition plan, a framework for change management, or a long-term analysis of transformation results are not provided by this study.

Furthermore, the framework does not yet cover how quality assurance, regulatory traceability, and performance metrics can be modified or updated to compliantly support hybrid workflows.

8.1.4 Assumptions and Time Constraints

TIt was not possible to test or quantify real performance impacts like shorter time-to-market, better product-market fit, or cost efficiency because of the thesis's constrained timeframe and academic scope.

Although theoretically modeled, these anticipated benefits have not yet been measured. This drawback highlights the necessity of further empirical testing of the hybrid approach in actual development settings.

8.2 Directions for Future Research

This section highlights important areas for expanding the current study and confirming the proposed hybrid development framework. The research offers a solid conceptual base, but more investigation is needed to support wider use in the semiconductor lithographic industry.

8.2.1 Quantitative Validation

The collection and analysis of performance data from actual projects using hybrid development frameworks should be the main focus of future research.

Quantitative proof of the model's efficacy and business impact can be provided by metrics like development cycle time, customer satisfaction, iteration costs, defect rates, and compliance performance.

8.2.2 Expansion Across Hardware Domains

Examining the hybrid framework's applicability in other hardware-focused sectors, like medical devices, automotive, or aerospace, would test its viability and assist in adapting Lean Startup concepts to various engineering contexts.

8.2.3 Digital Tools and Enablers

Further research into digital tools like simulations, digital twins, and collaborative platforms can show how technology can lower the cost and time of prototyping (and creation of MVPs).

This makes iterative approaches more practical in complex hardware settings.

8.2.4 Organizational Change and Culture

Studies that look into the cultural and organizational changes needed to successfully integrate Lean Startup practices within established R&D units are essential.

This includes leadership behaviors, changes in performance measurement, and strategies for managing change.

8.2.5 Inclusion of Senior Stakeholders

A key area for future research is the involvement of higher-level decision-makers, including Vice Presidents (VPs), Executive Vice Presidents (EVPs), and strategy directors. Their insights are vital for understanding organizational readiness, risk governance, and strategic alignment.

Including their input in future studies, can improve the relevance of the hybrid model and identify barriers or enablers at the policy and portfolio levels.

8.2.6 Hybrid Model Evolution

Ongoing improvement of the hybrid framework, including the integration of emerging agile methods and regulatory compliance tools, will ensure it stays in line with changing technology and market needs.

8.3 Summary

The limitations of the current research have been emphasized in this chapter, along with the areas that require more thorough studies and context. It has offered next steps for the research to advance the knowledge of hybrid product development techniques in hardware-intensive sectors. The theoretical concepts can be improved and practical application of Lean Startup adaptations by filling in these gaps. In the end, this will result in more inventive, effective, and robust product development in semiconductor lithography and other fields.

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