Semiconductor Supply Chain Efficiency: A Product Lifecycle Management -Powered Optimization Strategy

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***Abstract*— Semiconductors are one of the most indispensable components that shore up modern society, as is evident from their extensive presence in the majority of the products that we use every day and are dependent on. Being a key component of electronic devices, semiconductors enable improvements and progression in information and communication technology (ICT). It affects all round advancements affecting almost all the aspects of modern life - from computing, to communications, healthcare to transportation, military systems to clean energy, and several other applications. Semiconductors form an important part of our daily lives because of the role they play in the manufacture of electronic devices. This study scrutinizes existing literature to provide insight into the necessity of using Product Lifecycle Management (PLM) in the optimization of semiconductor supply chain and heightening of efficiency.**

***Keywords*—** *supply chain, supply chain efficiency, semiconductor, semiconductor supply chain, PLM, product lifecycle, product lifecycle management.*

1. Introduction

The critical components found in all modern electronic products are the semiconductors. Semiconductors are materials that lie between conductors and non-conductors or insulators in terms of conductivity. They are able to block or allow the current to flow through and in the process provide complete control over it [1]. Devices made of semiconductors, notably silicon, are essential components of most electronic circuits [2]. Silicon has appeared as the most vastly used material in semiconductors in the electronic industry and is paving the way for the digital era [3].

From medical devices to laptops and smartphones to automobiles, semiconductors find application in a wide array of products such as microprocessors, memory modules, and integrated circuits (IC) found in various devices [4]. A semiconductor provides conductivity between insulators or non-conductors such as ceramics and conductors (majority of metals) because of the effects of temperature or addition of any impurity called doping [1].

2. Literature Review

This article rummages through various resources available, on the subject matter, such as journal articles, academic resources, websites, books, newspapers, magazines, various infographics and websites to gain clarity into the concepts of semiconductor and its supply chain and evolution of product lifecycle management (PLM) in the semiconductor industry. The article provides an insight into the impact of PLM on semiconductor manufacturing and how this can be used to power optimization strategies that have become essential for the industry.

2.2 Understanding Supply Chain Efficiency

2.2.1. Supply Chain (SC)

Supply chain refers to the network of people and enterprises involved in the process of producing a product and delivering it to the consumers and includes raw material storage, work-in-process (WIP) inventory, and goods transportation from point of origin to the point of consumption [5]. Being an integrated function, a supply chain acts as

the lifeline of an enterprise. Hence, efficient supply chain management (SCM) has the capability to enhance business performance through the provision of superior customer value. Profitability and organizational efficiency can be enhanced through efficient SCM as it helps to better integrate firms and their suppliers by developing and nurturing strategic alliances and partnerships with the supplier [6],[48].

2.2.2. Supply Chain Efficiency

Efficiency measures the extent to which a supply chain's resources are used economically while providing a predefined or stated level of customer satisfaction [6]. In the new industrial era, where there is higher turbulence, such disruptive technologies as Big Data analysis, Internet of Things (IoT), BlockChain and additive manufacturing have emerged as the key drivers of transformation of supply chain [7]. This demands special attention to enhancing supply chain efficiency and balancing it with supply chain resilience. Supply chain efficiency will determine how effectively a firm is able to provide the right product to the right end-user, at the right place, in a timely manner and at the least possible cost, making the best possible use of resources at its disposal to manufacture and distribute them [8]. An efficient supply chain needs to be stable and insulated against the external changes as much as possible. Circumventing unpredicted harms is not easy and requires comprehensive understanding of the entire supply chain and the level of competitiveness that is faced by each and every element comprising that supply chain [9]. Product Lifecycle Management (PLM) makes it possible for a supply chain to become better competitive through an efficient collaboration between developers, manufacturers, suppliers, and customers at various stages of the lifecycle of a product [10].

2.2.3. Product Lifecycle Management (PLM)

Product Lifecycle Management, also called PLM, refers to the process of management of a product as the product moves through the 4 stages of its life cycle – i) introduction, ii) growth, iii) maturity, and iv) decline [11]. It involves managing the entire life cycle of a product commencing with the generation of an idea, followed by description of the concept, business analyses, product design and solution architecture and finally technical implementation, which leads to the successful entry into the market and the come the obvious stages - service, maintenance, and product improvement [12]. From the cradle to the grave – PLM takes care of every aspect of the life of a product [10] and hence the semiconductor industry could also benefit from it.

A key benefit of product lifecycle management is that PLM aids in establishing that a product is worth pursuing, or otherwise from the points of view of marketability and profitability [11]. An appropriate PLM plan can go a long way in increasing the productivity for a business and cut down the time that is consumed in getting a product to its market. Meticulous planning can also be helpful in the elimination or significant reduction in wastes as also minimization of risks faced by the company. Product lifecycle management also makes it possible for the companies to timely comprehend that a product has come to the end of its lifecycle and that it would be the logical and appropriate time to turn its attention to new innovations [12].

Though Product Lifecycle Management or PLM is a paradigm that is in its early stages, it is developing very fast. Manufacturers from a wide range of industries including automotive, aerospace and information & communication technology (ICT) are committing and investing a great deal of resources, time, money and effort, in investigation, planning, as well as implementation of solutions under the PLM projects umbrella. Providers of software solutions who have important PLM offerings are developing and nurturing relationships with academic institutions for the purpose of developing PLM into more than just an acronym that has previously been developed by groups to point solutions [11].

The conception and development trends of PLM systems are cutting-edge tools which support the work of engineers at every stage of any product lifecycle. They are specifically useful as also necessary for the design and development of products as they integrate several fields of technology (engineering), that is to say products that have electrical, mechanical, electronic, IT components, etc. The technological development and progress which is the outcome of the 4th Industrial revolution, has created new demands along with several opportunities for PLM systems [13].

2.2.4. .PLM for Optimization of Supply Chain

Massive scientific progression in and advancement in information and communication technology over the last few years have brought about complete change in the way most enterprises function. It has already been acknowledged that the perspective of competition is changing. It is now “supply chain versus supply chain” from “firm versus firm”. Because of this transformation the critical factor for deciding whether a company will be able to stay ahead in competition by building the competitive advantage, is the ability of that company to optimize

its supply chain [14]. The key is working toward building a collaborative relationship amongst various different partners that comprise its supply chain. Sharing of information for improving their performances and taking advantage of the benefits the flow in from the integration of the supply chain participants has thus become an absolute necessity for the modern enterprises, which has been instrumental to the development of a concerted product lifecycle management which is commonly referred to as PLM [15].

At present it has become necessary for businesses to make use of the benefits that can be derived from the integration of the supply chain and from sharing of information to ensure enhanced supply chain performance. It has been argued that effective Supply Chain Management (SCM) is a source of potentially sustainable competitive advantage for organizations [16]. higher efficiency is achievable in case this integration is made to happen during the early phase in the life cycle of a product especially during the process of development of the product [15]. This has resulted in the development of systems that can manage the technical data pertaining to the engineering process. It is in this context that the concept of product lifecycle management (PLM) was born.

2.3 Role of Semiconductors in Modern Life

Semiconductors, many a times referred to as "semis," or chips, are omnipresent when it comes to present-day technology and are universally present in variety of modern electronic devices from computers to smartphones to medical equipment and cars and even household appliances like washing machines and refrigerators and even gaming devices and electrical musical instruments. Due to the role they play in the fabrication of electronic devices, semiconductors have become incredibly important for the modern economy, driving both innovation and productivity across industries [4]. LED lighting displays, blood pressure monitors, rice cookers, and gaming devices, all have one thing in common – semiconductors, the powerful brain driving every modern technology [17].

A semiconductor is a substance that is usually placed between the conductor and insulator that manages and regulates the flow of electricity into an electronic device as per its power requirements. Consequently, it has become a popular and much needed component of electronic chips that are manufactured for computing devices and a wide array of electronic devices which includes solid-state storage devices [18]. It has become indispensable for the manufacture of automobiles, smartphones, computers as well as a large number of other electronic products, making modern life, as we know it, possible [19]. The research and further developments in semiconductor technology in the past half a century have enabled manufacturing of faster and smaller electronic devices which have superior reliability. One needs to just pause and think about our regular dependence on electronic devices and hence on semiconductors [20].

Silicon and other materials are processed in the manufacture of semiconductors which in turn is used in the production or assembling of various electronic devices which are reliant on electricity for their source of power to function. They need to control the flow of electricity while remaining powered up and hence demand semiconductors. The ever-increasing demand for chips or semiconductors is here to stay. Thanks to the Fourth Industrial Revolution (4IR) which is instrumental in changing the current manufacturing and production processes as an increasing number of businesses take to globalization. Global businesses are now being characterized by smart computers and connected devices. Smart invariably signifies connected devices, which in turn means higher use of chips. Semiconductors influence everything from smart homes, to high-speed connectivity, from data centers to modern automobiles [21].

2.4 Semiconductor Supply Chain

The supply chain for semiconductors is a complex mesh of companies that take part in designing, manufacturing, testing, packaging, and distributing these semiconductors [4]. Semiconductor supply chain involves various processes and steps that are necessary not just to keep it running but also to make it efficient [22]. Just like any other supply chain, this one also is a system that involves the synchronization of various stages, from procurements of raw materials and component parts to the sale of semiconductors to the final consumers [4]. Beginning with the System Companies, a semiconductor supply chain starts with, travels through electronic manufacturing services (EMS), IC Design, IC Manufacturing, IC Assembly & Test, End Consumers, circling back to the System Companies [22].

The ever-changing scenario of the networking industry is driven by supply chains which drive a host of daily tasks and lie at the root of manufacturing state of the art network infrastructure. The main function of the supply chain is to ensure that an extensive list of materials and individual components which are essential for manufacturing networking hardware thus guarantees smooth and uninterrupted connectivity

and strong performance across digital domains [23]. The procurement of electronic components is the first and foremost step of this endeavor and these can range from semiconductors to integrated circuits and also include resistors, capacitors, transistors and diodes. These components act as the building blocks of networking hardware devices, controlling power to intricate circuits to drive transmission and processing of data. Fabrication of semiconductors itself is an extremely complex manufacturing process. In today's world, thanks to globalization, supply chain operations have become not just cross-company but also cross- country. This has further complicated things due to higher dynamism so much so that the regular planning and scheduling solutions now frequently become impossible to employ [24].

Cables and connectors act as essential connectors which help with physical connections between varied networking infrastructure devices. These could range from ethernet cables, connectors, adapters and even patch panels to play a critical role in establishing and ensuring trusted communication routes facilitating the seamless flow of information within and across networks [25].

2.4.1. The Vulnerabilities

The production of semiconductors needs both advanced technology and a significant amount of investment and is hence much less dispersed and primarily huddled in a restricted number of countries and limited to few companies. These constraints result in a huge number of risks in semiconductor supply chains. The global pandemic caused by the COVID-19 virus, the trade conflict between US and China, the war between Russia and Ukraine, and several such other events in the recent past representing geo-political instability had increased the criticality of global semiconductor shortage and impacted a broad gamut of industries. To cite an example, automobile manufacturing companies have been forced to postpone or suspend their manufacturing plans in spite of higher demand for their products as their requirements for automobile components had been affected adversely because of this semiconductor shortage [19].

Semiconductors do have the potential to provide enhanced opportunities for all global industries but this increasing dependence on semiconductors also shows cracks as demand remains unmet due to supply falling short frequently. McKinsey Explainer has tried to shed some light on the actual reasons for the pandemic-era shortage of semiconductors. When the pandemic broke out in 2019, the industry was running at nearly full capacity (95% utilization) and the demand was being met just fine [26]. The COVID pandemic pushed most economic activities to home and online, raising the demand for smart devices, such as smartphones and PCs, manifold and the demand for semiconductors exploded in an unprecedented manner [27]. 2020 onwards the demand for semiconductors far surpassed its supply causing severe supply shortage all over the world [28, 47]. The pandemic highlighted the vulnerabilities of having a global supply chain and brought to light the need for localized manufacturing or nearshoring [29]. During the peak of the Covid-19 pandemic there appeared an acute shortage of semiconductor that affected almost every article of our daily lives, from cars to games consoles. However, as demand eased, its lopsided growth became evident and soon turned into a chip glut which resulted in some of the world's largest chip makers taking a hit [30]. The covid pandemic is not the only cause of this shortage. The semiconductor supply chain itself was constrained by several vulnerabilities and weak points that were only enraged by the covid situation [28, 47].

The global semiconductor industry is heavily dependent on Taiwan. The country produces more than 60% of the global semiconductor volume and more than 90% of the most sophisticated chips [31].

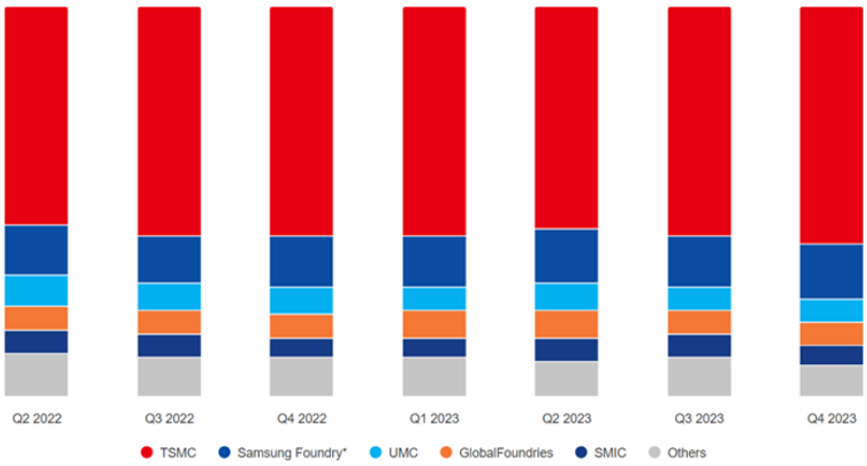

Figure 1: Global Foundry Revenue - Market Share Q4, 2023 [32]

In the last quarter of 2023, TSMC retained its leadership position in the foundry sector, controlling an impressive 61% market share on the back of restocking of smartphones and robust demand from AI [32]. This concentration makes the supply chain further vulnerable especially in situations such as natural calamity which usually strikes a region but very rarely the whole world alike. An example is the recent earthquake which caused a stoppage of certain chipmaking by Taiwan Semiconductor Manufacturing Co. or TSMC, the main contract chipmaker to Apple Inc. and Nvidia Corp., and evacuation of its plants to avoid large scale damage and casualties [33].

2.4.2. Semiconductor Supply Chain Efficiency

Advanced technology or presumed sophistication are not the only attributes that make Semiconductors or chips crucial. Their wide reach in terms of the range of their application, determine the manner in which they influence the modern world. Every critical aspect of modern life – from mobile communications using smartphones to the use of battery-operated vehicles (BoVs) that help to address environmental issues, cannot run without this minute yet mighty component [34].

Due to their shortages and other vulnerabilities, it has now been recognized that flexibility and multiplicity of supply channels have become the crucial and critical approach to ensure economic security, supply risk mitigation and resolution of other pressing issues. The most notable and glaring risk, in the present day, is the dependence on a select group of countries and companies, which manufacture semiconductors. These and several other external factors create great challenges which the companies can only circumnavigate with novel and sophisticated semiconductor sourcing and procurement strategies [19]. Besides Taiwan Semiconductor Manufacturing Co (TSMC) and Foxconn, the two Taiwanese tech companies who are finally realizing the need for overseas expansion, materials and plant builders, suppliers of chip and electronics tools, are also attempting to expand internationally as their top clients look to spread out [35].

Supply chain management or SCM assumes huge importance in the semiconductor industry. Fabrication facilities for semiconductor wafer require significant capital outlays, generally Billions of dollars). Along with that the facilities for assemblage and testing are relatively expensive with the cost of certain individual testers running into a few million dollars. The products manufactured in these facilities, both in the form of integrated circuit (IC) chips and in the form of wafers, are of significantly high value. A single unit of processor chip can be as expensive as a few hundred dollars. Such high capital investments along with the expensive nature of the products, has made it crucial for the semiconductor manufacturers to maintain significantly elevated levels of utilization of the equipment alongside maintaining minimal inventory and efficient supply chain management can be of immense help in the achievement of these goals and make sizable savings available for the semiconductor industry [36].

Companies need to put more stress on environmental factors, social practices, and the overall economy to drive a more sustainable supply chain for semiconductors. Improving the process of manufacturing and its quality and at the same time reducing environmental impact coupled while protecting labor rights will help in making the semiconductor supply chain more robust and sustainable in the future. It becomes imperative to devote time to understand the semiconductor supply chain so that one gets more insight into their impact on the technology industry [22].

2.4.3. The Evolution of PLM in Semiconductor Manufacturing

The adverse impact of multi-pronged disruptive forces is posing a big challenge for current semiconductor manufacturing companies. The dynamic market demand has made it imperative for the semiconductor companies to redesign their business models. Tremendous pressure on the semiconductor industry has been created by such factors as the needs of the market that is hyper-fragmented in nature and needs getting rehashed and defragmented at various levels, rising costs of design and development, increased product complexity and dwindling average sales price coupled with the persistent need for innovation to maintain the viability of the business and its competitive edge. In the face of formidable or deterring design challenges, faster or shorter product life cycles and increased supply chain complexity, it is no rocket science why there are frequent misses when it comes to launch dates or new or improved products, development budgets and product quality [37].

3. PLM-Powered Optimization Strategy

PLM has an important role to play in helping the developers and sometimes even the manufacturers, through the creation of the next version of products in manners which are better efficient and at the same

time more cost-effective. Product managers will use various strategies to manage this process [12]. A key concern in the modern world is energy efficiency. Projects, processes and products need to be energy efficient as conservation of energy is one of the issues hogging the limelight due to the fast drying up of non-renewable energy resources. Recycling is the need of the hour and hence PLM is gaining more and more importance.

Energy efficiency improvements are being explored at multiple levels and this is possible by designing for environmental impact lessening, re-use of wasted energy, modernizing legacy systems and analyzing product lifecycles from extraction of the raw material to finished products through the implementation of the best technologies available and also through the improvement in efficiency of materials [38]. Implementation of these methods on a large scale can result in the improvement of energy efficiency by approximately 15% - 30%. Any further improvement, however, would depend on adapting to breakthrough technologies and vital alterations to the core process [39]. The available literary works highlighted the major technologies that can be great facilitators when it comes to supporting this endeavor and include big data analytics, digital twin, Internet-of-Things (IoT), artificial intelligence (AI), advanced robotics as also cloud computing [40, 41]

The modern manufacturing environment is transitioning quicker than ever before. Novel technologies have made it possible for the manufacturers to speed up their processes pertaining to designing, manufacturing, and distributing their products without compromising on the product quality. Such transformation has resulted in certain industry insiders believing that product lifecycle management (PLM) is likely to expand into the fields of design of electronics and semiconductors along with customary manufacturing industries such as automotive, construction equipment, oil & gas, aerospace, etc [42].

Semiconductor business performance is augmented significantly, by the deployment of PLM, through the leveraging of product information across the organization, which enables the processes of working in concert. Product lifecycle management assists companies in providing a boost to their principal business drivers which include but are not restricted to product development, collaboration for product design, operations management, management of supply chain and of product requirements, sourcing of strategic raw materials and utilization of total resource [43].

It can, therefore, be said that PLM is essential for the strategy of digital transformation. It constitutes the principal business strategy that empowers digital continuity across the business organization – from the conception of a product to its launch. Investment in advanced and more sophisticated PLM solutions is considered to be a cautious and wise step for maintaining the flexibility and focus of the business infrastructure. Such a structure of a business would make it proficient at propelling businesses growth and responding to a dynamic business environment characterized by fast-changing market requirements. Semiconductor companies always remain under tremendous pressure as they need to guarantee faster time to market. Hence for them an unambiguous PLM strategy that is well communicated and stated is absolutely necessary. The participants would be clear on the desired outcomes and the respective roles that they would be playing achieving the declared goals.

Product lifecycle management or PLM has always remained separate from the semiconductor industry. Manufacturers in the semiconductor industry lived in their own silo, and considered PLM to be more of a discipline that find use in mechanical design and industries involved in complex product development for example defense and aerospace products, sophisticated and intricate automotive and airplane design, and very machinery that are configurable and complicated [42]. However, with the changing facet of modern civilization, they are being increasingly pressurized for becoming integrated. Automotive industry, IoT, medical care, computing, smart and mobile communication, and other industries have come to realize that this integration is the single way in which these organizations will be able to manage the varied aspects of their business. Semiconductors stand out as a large black box in that methodology – the essential part in almost every article of modern use [44].

The technology industry is steered by a combination of 2 processes - top-down and bottom-up. Bottom-up tends to be increasingly popular in modern tech companies that are driven by innovation and employee engagement, where speed and agility are considered to be more important compared to being timely and being inexpensive or economical [45].

The top-down processes are generally seen to be prevalent in case of sizable industrial development and large systems, and they are fast turning out to be

the chosen method of controlling products within a company — particularly when handling portfolios that are significantly large [44]. The decision-making process being centralized, the senior level leaders and managers generally make decisions with little or no input from their subordinates and the decision is simply communicated to them. This leaves no room for any significant innovation or any novel product development and hence is not conducive for large scale integration of processes [45].

There are several steps that are involved in the process of manufacturing of electronic goods and semiconductors, each of which needs to be carefully controlled in order to make sure that they yield high-quality results. For example, there is an increasing demand for miniaturization. An increasing number of consumers now demand smaller size, yet more powerful electronic devices which require ever-smaller transistors. This has increased the complexity of the manufacturing process manifold [46].

Development of semiconductor hardware and software have always been under the bottom-up classification, despite the fact that they have ushered in way more formalism than was present in the past. Software continues to undergo transformation due to the incorporation of Agile methods. Management of requirements, verification management, revision control and tracking of bugs are all in position and prepared to be extended over time. For several sections of the development and manufacturing cycle, there exist feedback loops which makes it possible to feed back the systemic issues through the process and hence creates the room for correction [44]. One of the key reasons why PLM is now being brought into the electronics and semiconductor space is that it provides much better visibility in the top-down design [42].

The increasing application of chips in the automotive, medical and military specifications and aerospace industries have given rise to new-fangled requirements to which have now been added to the flows of development, and while frequently it is considered to be a burden by the semiconductor development teams, there has been an ongoing process of incorporation of PLM processes and this incorporation is being treated as a prerequisite for acquisition of business [44]. Rough the implementation of PLM, semiconductor companies will be able to realize important benefits, which includes a single and compact version of the truth for every data relate to every product being handled; higher cooperation and better collaboration, superior control of product design and its communication, information pertaining to development and engineering change order; better quality of chips, improved design, development productivity and manufacturability of integrated circuits; improved design and low or zero rework by getting together input from a number of parties early in the product development process; reduction
in cycle times and the time taken to bring the products to the market through the standardization of tools and processes, etc. [37].

Figure 2: Importance of PLM in Semiconductor Industry [37]

Slowly but steadily enterprises are going digital. It is an obvious and unavoidable transformation every enterprise will have to go through. Digitalization is what they will all have to embrace eventually. A digital enterprise will see all its processes for instance product design, production processes, support & services, and consumer experiences being connected via a digital thread. This essentially

translates into huge and growing demand for semiconductors. The global semiconductor market was worth $ 618 billion approximately in 2022, and is anticipated to reach $ 1 trillion by 2030 [19]. At every step a huge volume of data is being exchanged.

Due to the fact that every stage of production also involves the exchange or communication of a huge volume of data, Data Management capabilities are frequently considered to be the key element for the efficiency of the PLM system, which makes up the principal semiconductor product record. T is possible to use the functionality for this product record for logically linking each one of the information pertaining to a product and handling the fluctuations in that information over a period of time, providing a single version of authentic data across the entire value chain consisting of clients, workforces, partners, vendors and suppliers. It becomes necessary to capture technical specifications, design definitions, production schedules, test reports, sourcing plans, quality inspections, etc..

PLM solutions provide the organizational structure and the framework for the implementation of the digital twin, which is rapidly transpiring into an integral part of the global digital transformation [37]. PLM integration makes better collaboration possible amongst design, engineering, and manufacturing teams. Through the provision of a single source of authentic data for the product, teams will be able to work together in a better efficient manner while reducing errors and refining efficiency [46].

4. Conclusion

Semiconductors are vital components in modern electronic devices, regulating power flow and enabling the functionality of ICT and smart devices. The growing demand for sophisticated, small-sized devices has increased the need for advanced semiconductors. Manufacturing these components is complex, involving multiple stakeholders, where even minor errors can lead to significant financial consequences. Innovation is essential in this industry, driven by globalization and the shift to digital business models, particularly accelerated by the COVID-19 pandemic. The continuous improvements in semiconductor technology ensure that their demand remains strong as they evolve to meet changing client needs.

The semiconductor supply chain is intricate, involving design, manufacturing, testing, packaging, and distribution. This complexity brings challenges such as demand-supply mismatches, custom specifications, and regulatory issues, making the supply chain susceptible to disruptions from internal and external factors like manufacturing constraints, natural calamities, and global trade disputes. The COVID-19 pandemic highlighted these vulnerabilities, causing chip shortages and surpluses, emphasizing the need for better supply chain management. Effective management ensures chip quality and stability in operations, addressing the dynamic demands of the market.

Product Lifecycle Management (PLM) is crucial for streamlining the semiconductor manufacturing process, improving efficiency, and managing disruptions. PLM oversees the entire product lifecycle, from design to market introduction, growth, maturity, and decline. Combining PLM data with real-time data from IoT technology enhances supply chain performance and product optimization. In the data-driven world, PLM helps identify operational weaknesses, ensuring superior customer satisfaction and product quality. As semiconductors remain essential in everyday devices, PLM reinforces their efficiency, necessitating further study to maximize its benefits in the semiconductor industry.

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