Digital Transformation in Semiconductor

A Systems of Systems Approach to Achieving the Digital Enterprise

By Joe Dury, Devin Bedwell and Ted Farrington

KALYPSO

Introduction

Semiconductors are inherently a part of everyday society. Like electricity and water, the foundational elements of systems that semiconductors enable are now a fundamental part of modern life. From the computers we use to the cars we drive, the smart phones we carry to the appliances we use in our kitchen, all are enabled by semiconductors. These modern appliances have transformed our way of living, interacting and interfacing with each other while doing our daily routines.

The backbone of all of this is an ongoing digital transformation being empowered through global and local networks using the Internet of Things (IoT) protocols for collecting, storing and accessing the data and information. The storage farms for Google, Apple, Facebook, Amazon – which many of us don't even know about – rely completely on semiconductors to power them. This information and data enriches and changes our everyday lives.

it's no wonder semiconductor firms are rushing to this market opportunity and finding new ways of growing by capturing more of this value chain with an entire ecosystem of solutions. Leading semiconductor companies no longer just sell a chip – they sell total electronic solutions which include software, firmware, electronics, power management, development boards, material and even thermo-mechanical designs. Autonomous vehicles and overall electronic instrumentation in our cars and homes are driving this digital system shift.

The semiconductor firm's evolution from a hardware chip supplier to solution provider, however, is not an easy transition:

- Products require more complexity for both the silicon hardware and software solutions
- Market conditions demand ever-shrinking development cycles
- Market and customer demands evolve constantly
- The nature of some semiconductor applications, such as autonomous vehicles, is mission critical

These challenges, amongst others, raise the question:

Are semiconductor companies equipped to handle the total system requirements needed for an ecosystem of solutions that goes well beyond traditional hardware silicon chip?

Reflection: A Case in Point

In the late summer of 2016, a major smartphone manufacturer released the newest version of their phone. This much-anticipated phone featured a dual curved display, water resistance, and expandable storage, and was expected to be a major driver to this firm's revenue in the coming months. The company was also under competitive pressure to be first to the market, a market that was excited to see the next "must have" feature.

However, within days of the release, some users reported that the batteries in the new phones were exploding and catching fire while charging. Shortly thereafter, the corporation announced that they were delaying shipments for additional quality checks, and just a couple weeks later the phone was officially recalled. Yet, this wasn't the end of the troubles.

To show good will, the smartphone manufacturer started exchanging defective phones with a newer version that utilized a battery from a different supplier, and they released software upgrades to minimize the risk of defective phones and help identify the newer versions that were marked safe.

For a time, the crisis appeared to be under control until about 60 days into crisis, a passenger on a commercial airline on the ground in Louisville, Kentucky, started hearing a popping sound and his smartphone started smoking and eventually caught fire, prompting an evacuation of the flight. Investigators soon discovered that the phone was one of the newer versions that had previously been declared safe and a second recall was now required.

The problem continued to grow as additional reports were released showing that three of the replacement phones had similar issues. All major US wireless carriers suspended sales, and the manufacturer announced that it was permanently ending production of this new phone and recalled a total of 2.5 million handsets worldwide.

The cost of this design flaw was enormous. The stock dropped by over 6% on the day the company announced the phone was being scrapped. Guidance for operating profit was adjusted down by 33%, and revenue forecasts were slashed by *tens of billions of dollars*.

Perhaps even more critical was the hit to this firm's brand and overall marketing image. Aviation officials in United States and Europe issued a complete ban on this smartphone and the company was severely criticized for their handling of the crisis. Analysts warned that its' competitors won a gain in market share – just the opposite affect of why the phone was rushed to market. One survey revealed that 34% of current customers would not buy another phone from this firm because of the incident. In an extremely competitive market, the episode was disastrous.

Post mortem, this company deployed a team of 700 engineers to test 200,000 returned phones and examine an additional 30,000 batteries. They tested all aspects of the phone, including hardware, software, charging accessories, mechanical design, manufacturing processes, design, and usability. The research team found that the problem was caused by a faulty design by one battery vendor, and by a manufacturing defect from a second battery vendor[1].

For the first battery vendor, a design defect did not allow enough room for the heat seal around the battery and the internal battery components. This caused the electrodes in the battery to crimp and introduced the possibility of a short circuit (see Figure 1).

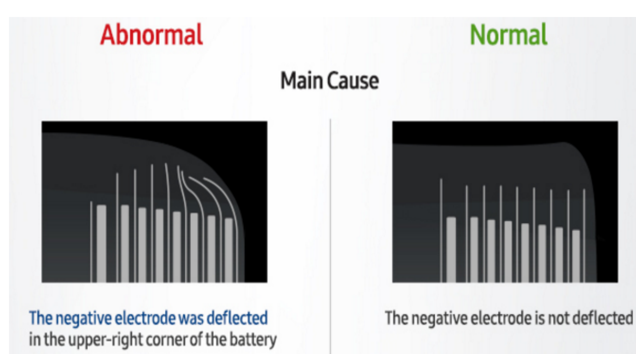

Figure 1 - Battery A Design Defect

1 https://www.usatoday.com/story/news/2016/10/05/samsung-galaxy-note-7-explodes-while-boarding-southwest-flight/91602698/

2 https://news.samsung.com/global/infographic-galaxy-note7-what-we-discovered

For the second battery vendor, a manufacturing defect caused penetration between the positive and negative electrodes through the insulation tape and separator in the battery (see figure 2). In both cases, the short circuit resulted in excess heat and eventually fire from the battery.

This case highlights a critical problem that semiconductor and electronics companies are now facing. Multi-domain models must be tested, validated and verified. These sub-systems in multi-domains are now spread across many different functions and disciplines, including electrical, mechanical, thermal, software, and material design. Each vendor likely received a specification, but one can ask questions such as, *"Was this failure mode anticipated and was it missing from the specification and, therefore, not tested?"* or *"Perhaps there were relevant entries in the specs that should have been found in testing, but the battery vendors did not sufficiently cover these tests. Were models created from the specs?"* Either these problems were thought of before design or there was a gap in the test or handoff of information processes.

Overall, legacy approaches and engineering processes are being stretched; solutions are no longer just a chip or a piece of software – they are a set of sub-systems that must all work together or the entire solution will fail. And failure is more costly now than ever before. With the advent of electronic driver assist features and driverless cars, the impact of a system failure will not only be counted in terms of dollars, but also with human lives. A problem such as the smartphone battery failure in a safety application could very well prove fatal for a company today.

Ensuring that the semiconductor "systems of systems" is correct is paramount in this new multi-domain world.

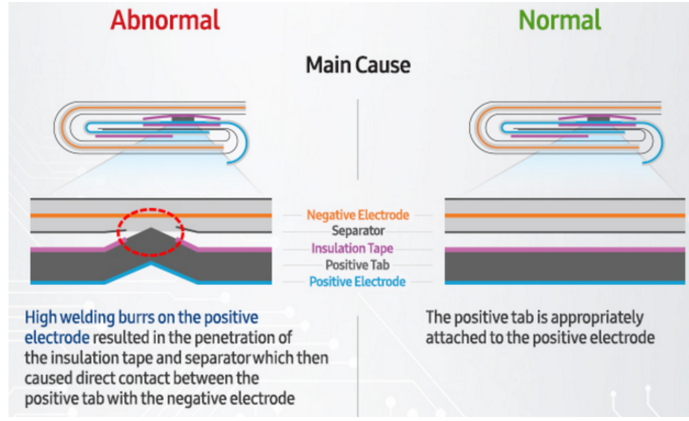

Figure 2 - Battery B Manufacturing Defect

System failures and a lack of systems of systems testing abound. As we experience product recalls now nearly everyday, we've become somewhat immune to them. In 2015, Takata, an automobile supplier to many Japanese car manufacturers, announced the recall of 34 million air-bags; one of the largest auto defects that continues to this day[3]. Takata was a leader in the automotive supplier industry, but quickly amassed over $9B in debt and declared bankruptcy in June 2017.

What are the lessons that can be applied to semiconductor solution development to avoid duplicating the occurrence of these types of issues?

- Where did the problem reside?
- Were there electrical requirements missing?
- Was this an interface between an electrical system and a mechanical system?
- Were there adequate design and simulation models?
- Was the data and product Intelligence across the supply chain leveraged to minimize the issue?
- Should it have been found in testing or simulation?
- Was there a correlation seen in reliability and characterization testing?

3 *"Takata Doubles Airbag Inflator Recall to 34 Million Cars, Divulges Epic Failure Rates – News – Car and Driver - Car and Driver Blog". Retrieved 14 December 2015*

Megatrends and Opportunities Ahead

For 50 years, the semiconductor industry has had a long history of addressing and solving highly complex challenges. Products increase in complexity with every new generation and technology node. Many system on chip (SoC) semiconductor designs can involve billions of transistors and up to ten times that number for lines of software code needed to enable that hardware.

Adding the configuration for firmware, hardware options and software versioning; the ability for mass customization at scale; software traceability; and the convergence of safety and quality requirements, the complexity can seem unsurmountable.

However, semiconductors are the enabling technology for addressing the current megatrends that are now nearly constant in our lives:

- Electrification of nearly everything (e.g. being electronically controlled)
- Smart connected infrastructures supporting our communities and cities
- Autonomous vehicle operation transforming all forms of mobility solutions
- IoT-enabled networks in manufacturing, products or energy systems that monitor the entire system to predict and optimize performance while reducing failure
- Autonomous operations in both production and order fulfillment activities enabled by a network of data analytics and system processing to satisfy both known and likely demands

These megatrends certainly have an impact on semiconductor firms, including the following benefits:

- Keeping pace with faster technology cycles
- Achieving 0.25-1.00 PPM levels that customers demand
- Collaborating globally with real-time and accurate data
- Seeing the data at scale within manufacturing

Figure 3 depicts some of the key challenges companies need to overcome in order to meet market demands.

Figure 3 –Impact of Megatrends on Semiconductor Firms

- **Shorter technology cycles** are required to meet the market windows, which are either extremely short for consumer applications- and require execution excellence in R&D and production ramp-up- or extremely long for industrial and automotive applications, requiring stable forecasting from customers
- **Zero defects** are now expected as customers require very high quality, customized solutions and Application Specific Integrated Circuits (ASICs) for their products. In addition, increased reliability and regulatory standards require extra work and expense, which can delay a product launch.
  - Semiconductor companies have adapted to these challenges extremely well over the years, and deploy sophisticated tools, including Electronic Design Automation (EDA), Electrical and Mechanical CAD tools (eCAD/mCAD), Product Lifecycle Management (PLM), Manufacturing Execution Systems (MES), and Project and Portfolio Management (PPM) to mitigate these challenges

- Product complexity not only includes new technology nodes and product generations, it now includes software, electronic, and thermal design. Market windows are not only based on customer applications, they also include new market and regulatory requirements. The goal to simply reduce time to market (TTM) is no longer sufficient – time to market with high quality is now the standard. Former methods to reduce risk may have been sufficient in the past, but they are increasingly inadequate in today's landscape. Safety critical customer applications mandate defect levels as low as .5 PPM from product launch[4], even amid evolving technology nodes and increasing software and electronics design

- **Global supply chain collaboration** is required to meet market demands and support make and create functionality
  - Development teams are located across the globe to enable a 24-hour design cycle, increasing the need for global collaboration platforms, revision control, and coordination across several time zones
  - The global make function is no different, with silicon wafer manufacturing, wafer probe, back end assembly and test, and inventory banks scattered across the world

- **Unifying the data** at scale from conceptualization, development and realization requires integration of data sets not yet seen even in the most sophisticated design and manufacturing tools in the semiconductor ecosystem. Tying these sets of data into analytics can be used for:
  - Mining and rationalizing what's needed to make informed business decisions. It's similar to a data lake or warehouse but requires deep domain knowledge and data contextualization to be of value
  - Market leading solutions for analytics will address the entire digital enterprise and encompasses descriptive, diagnostic, predictive and prescriptive results

The challenge is quite clear to executives and business managers: it is harder to make the products customers demand with a more pronounced risk of failure.

The need for digital transformation with integrated data across design, validation, verification and testing – both in development and in the factory – is vital.

The winners will be those who embrace digital transformation across their own design methods, manufacturing processes and ability to track smart products in the field. The design factories, and actual factories or foundries, must follow and address this digital shift going forward.

4 http://www-g.eng.cam.ac.uk/robuspic/pub_present/ESSDERC06/6-ROBUSPIC-Workshop-ESSDERC06-VVonTils.pdf

Going Digital

As semiconductor complexity continues to grow, so do the demands on both the design and manufacturing supply chains. These supply chains are stressed further requiring companies to deploy "Design Anywhere, Build Anywhere" strategies across the globe.

Depicted in Figure 4 is an overview of the challenges being placed on today's semiconductor firms.

Figure 4 – Business Challenge Overview on Semiconductor Firms

Addressing these challenges will enable companies to deliver innovative products and solutions that meet the ever-demanding market requirements in the semiconductor industry. Leading companies are adopting the following practices to make this a reality:

- Creating a **digital thread** throughout the entire lifecycle of a product
- Leveraging the activities to realize a true **digital twin**
- Obtaining s**mart connected operations** (SCO) to address data analytics

The digital thread ties all of the functions and their respective data together, from requirements through design, all the way to manufacturing and the field. The standardization of the data and its connecting points will allow for multi-domain modeling and multi-physics analysis that will ultimately test and validate the system of systems performance into one unified platform, and enable collaboration among all stakeholders within engineering, operations and manufacturing. This includes true device level traceability through design, manufacturing, supplier sites and unique process data.

The digital twin allows the enterprise users to simulate the entire supply chain, from requirements collection and design to factory layout, capacity, scheduling, processing, manufacturing and the field. The goal is to save time and learn before committing physical assets. The digital twin begins at the requirements stage, transitions through system and component design, factory layout, capacity analysis, process definition, manufacturing and beyond. It's one piece of the threading needed.

Smart connected operations (SCO) addresses the volumes of data and associations of what is known and unknown, resulting in additional operational insights developed at scale. Detailed in Figure 5 is a SCO framework for addressing the data analytics challenges by utilizing data for unified dev/ops info (e.g. digital twin) through deeper monitoring and automated measurement to optimize the process of producing products. The desired business result and smart operations strategy are vital boundary layers to a successful outcome for SCO .

Smart Connected Operations

SCO introduces many operational use cases that provide value to a firm. Leveraging monitoring and measurement data can help increase operational efficiency and throughput, and reduce overhead.

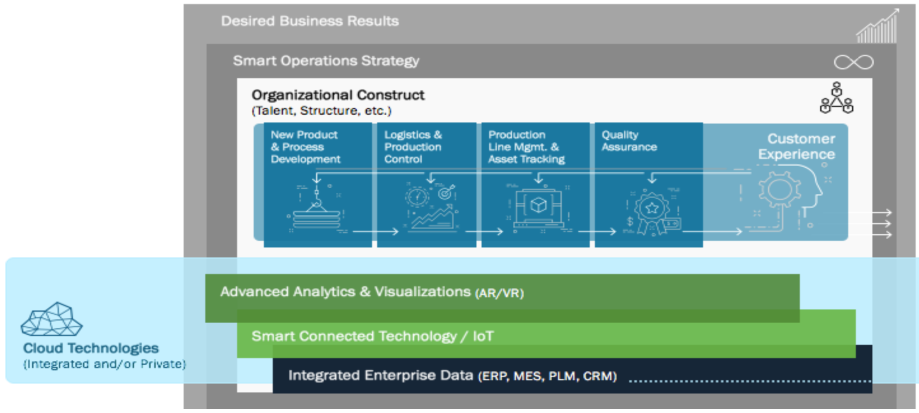

Figure 5 – SCO Framework for Addressing Data Analytics

Improve machine availability	Use real-time alerts, notifications and tracking of machine problems to avoid unplanned stops (breakdowns) during scheduled production time
Real-time monitoring of operational KPIs	Leverage dashboards for real-time monitoring of critical indicators and operational metrics to enable quicker response times to potential problems
Improve machine performance	Use smart connected equipment to operate most effectively and deliver greater performance rates
Inventory and Material Tracking	Collect and transmit data on inventory, die banks and raw material to provide greater access to data and enable reordering, logistics optimization and inventory maintainence
Improve machine output quality	Use real-time connectivity of industrial assets to improve the quality of output when the product/equipment is in operation and to flag possible excursions for further review
Predictive Analytics of Machine Health	Collect historical data from IoT sensors on machines, apply algorithms to uncover warning signs of costly failures and proactively schedule maintenance prior to malfunctions
Worker Health and Safety	Digitally map geo-fenced boundaries that use IoT sensors to send notifications to employees when hazardous zones or equipment is nearby
Track Worker Efficiency	Input project data planning to forecast the operational timeline for facility projects, automatically time employee work times by sensor tech and report against expected project timeline
Asset Finding	Manage a dashboard console view of all locations of machinery, assets and workers; improve worker efficiency with auto-guidance and notifications of asset locations related to current tasks
Workplace Safety Planning	Track safety procedures, compliance and incident reports throughout worker performance data, project data, machine variations and maintenance, and location-based data in the facility to improve safety environment

Table 1 – Smart Connected Operations Benefits to the Enterprise

With a digital thread, digital twin and SCO approach, the end solution creates a value stream of visualizations and information linkages throughout product development, order processing and manufacturing, which means:

- The digital and physical worlds are linked by the manufacturing master data model and the common plant model - and provide a mastery of data and information insights within and across systems
- Operations are simulated before any physical assets are involved
- Feedback from all relevant production execution systems creates a nearly real-time image of the digital twin of product, process and resources
- Decisions are made based on real-time data
- The ability to analyze engineering simulation and emulation data along with manufacturing "big data" via a true machine learning model is created

A Single, Multi-Domain Solution

The semiconductor market is growing despite the absence of a single solution across multiple domains and setting the standard in terms of decreasing time to market in a competitive environment. It has evolved to a hybrid-make function model with outsourced contract manufacturing (i.e., wafer foundries and subcontractors for assembly and test) or with internal factories augmentation, driving down cost and creating additional opportunities for all to achieve better results.

Yet, this has caused some reduction in the validation phase by eliminating testing cycles when bringing a product from engineering to market.

More complex products and shorter design cycle times mean less time to validate more information. This can be solved with more comprehensive total system requirements, more robust and complete models, paralleled simulation of larger universes of experiments, and better analytics to catch problem indicators earlier. The complexity and overall risk is growing faster than the solutions and tools available today to help calculate business decisions and assess risk in algorithmic ways.

As such the industry must demand help from its tool providers to support the development of advanced, multi-domain models, simulations and emulations, including:

- Full systems engineering approach
  - Tying hardware domains of electrical, thermal, mechanical, etc. together
  - Uniting software and hardware in some HDL/VHDL manner as the industry did with its hardware
- Unification of MCAD and ECAD worlds
  - Design error margining measurement across the product lifecycle
  - From design through manufacturing and into product utilization in the field
- Using techniques such as "smart tagging" which will drive even tighter design and manufacturing alignment

The financial incentive is measured by faster time to market and increased confidence in products that do not fail in the field. Tying together all of the design data models and their results by leveraging and evolving today's systems of PLM, ERP, CRM, MES, mCAD and eCAD work into a harmonized solution with each function managing, sharing and tying the appropriate data to the full requirements throughout the product lifecycle will help drive the vision forward.

For example, consider a semiconductor company offering technology to support the growing automotive electronics market and address the desire for heated/cooled seats in personal vehicles. According to WardsAuto, only 11% of cars now have self-heating and cooling seats. These products will:

- Include a complex and comprehensive set of requirements for electromechanical systems and safety
- Be used in a wide-range of conditions
- Have multiple supply chain partners
- Be sold to multiple automotive and tier one suppliers, leading to product variability to address application-specific needs

This product is a system of systems that requires multi-domain models, unified design and simulation of the product in multiple environments, and much more. Garnering market share in these product arenas can grow the revenue lines by two to three times, and when addressed with the systems approach, the profitability line will be at same level or greater.

Systems Engineering: A Construct for Tying the Data Together

A systems engineering approach is the next step in strategically uniting all of these constructs together, attacking system of systems complexity and enabling successful delivery of higher quality solutions for the market.

A successful approach for developing these systems involves focusing on customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design, validation, verification, and release throughout the production/manufacturing lifecycle.

The graphic depicted in Figure 6 illustrates a construct for this approach, which is adapted from the ISO/IEC/IEEE 15288:2015 standard. ISO 15288 establishes a common framework of process descriptions for describing the lifecycle of systems created by humans, defining a set of processes and associated terminology from an engineering viewpoint. These processes can be applied at any level in the hierarchy of a system's structure.

Semiconductor firms that adopt a systems engineering approach not only enable the digital thread throughout the lifecycle of a product, they also leverage their investments to realize a true digital twin and succeed with SCO to address their data analytics needs. In addition, they can also impact the market needs of their software suppliers in this space, particularly EDA, PLM and data analytics solution providers. Gartner recently stated the new focus on digital twins will ultimately drive the business impact of IoT by offering a powerful way to integrate information for both assets created and processed.[6]

This digital work should involve the organization areas depicted in Figure 7. This is more than a technical leadership challenge; it requires executive leadership as well as involvement from the organization's solution providers (EDA, CAD, PLM, MES, etc.). Without this level of buy-in, the effort will stall.

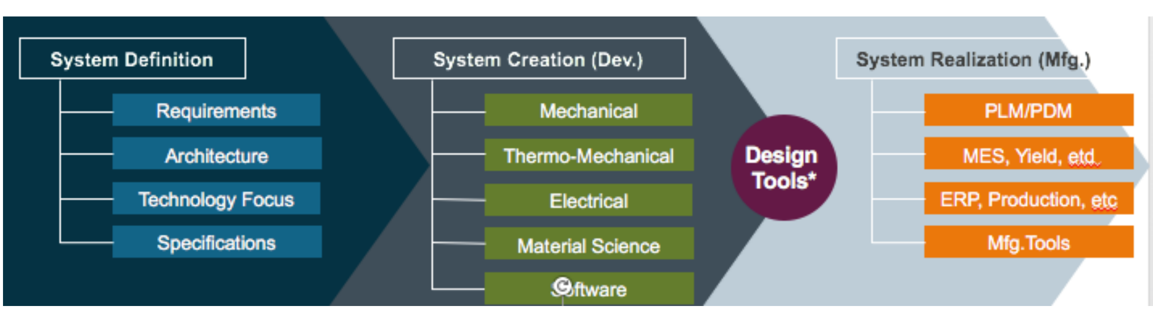

Figure 6 – Systems Engineering Approach (i.e., Systems of Systems)

5 Gartner's August 15, 2017 Report entitled "Digital Twins Will Impact Economic and Business Models"

Similar to the unified roadmap for tool development accomplished by Sematech in the 1980s and 1990s, before the end of the 2020s the industry will need to focus on their common needs and each firm will need to push for:

- Investing in stronger integration of ECAD with MCAD data management along with FEM (Finite Element Modeling) tools for thermal issues to begin to create a total MBE (Model Based Enterprise) solution
- Addressing the smart factory with ties to simulation and emulation through Augmented and Virtual Reality (AR/VR) by utilizing 3D data to simulate or overlay reality with digital information by connecting enterprise IT – especially PLM systems used to handle CAD models – and leveraging data analysis capabilities for additional insights at scale
- Exploring stronger integration between MES tools in manufacturing and PLM tools in engineering to address zero defect challenges and regulatory requirements
- Driving Overall Equipment Effectiveness (OEE) improvements previously unseen via Product Lifecycle Intelligence (PLI) and the analytics across PLM, ERP and MES data sources
- Understanding how to pull in firmware (embedded software) and overall software development into hardware toolsets for the product development process and product record
- Investing in enhancing quality management systems to address zero defect and deviation management requirements and to integrate pre- and post-market quality data into the design process

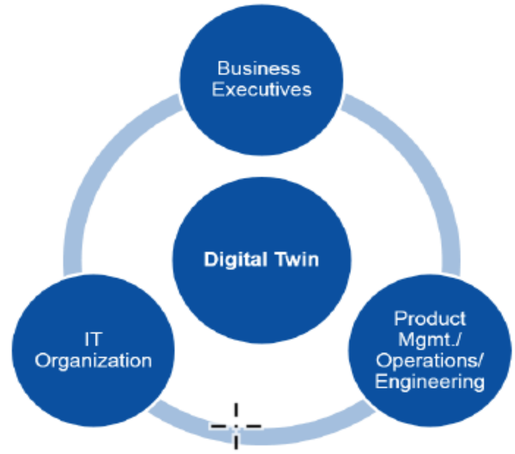

Figure 7 – Key Organization Components for Digital Twin Development). Source: Gartner, August 2017.

Analytics: The Return on the Data

It's been said that data in the 21st century is like oil in the 18th century – an immense and untapped asset that is extremely valuable. Collecting data is only part of the story; what you do with the data is what's important.

Analytics extract valuable insights from data assets/ Many companies use analytics to tap into data assets and hire data scientists to analyze the data and react to problems, but the real value is in using analytics to proactively address problems in the future. This includes two types of analytics:

- Predictive analytics to predict future events
- Prescriptive analytics to prescribe solutions to future events

Table 2 highlights several representative use cases that highlight the value of predictive and prescriptive analytics.

Problem	Predictive Use Case	Prescriptive Use Case
Production test yields	Analyze production data to determine which parametric values, design sensitivities and fabrication variations affect production test yields and predict future test yields	Modify key parametric targets, design nodes and fabrication processes to optimize first-time production yield based on data from previous products
Quality	Predict the likelihood of failure based on analyzing design, manufacturing or test parameters of previous failures	Reduce the likelihood of failures by modifying design, manufacturing or test parameters
R&D Cycle Time	Predict R&D cycle time based on factors from previous R&D projects	Optimize R&D cycle time by designing R&D projects that address factors that affect cycle time

Table 2: Representative Predictive and Prescriptive Analytics Use Cases

Product Lifecycle Intelligence (PLI): A Methodology for Data Analysis

The data from SCO, PLM, ERP and other systems can quickly become overwhelming. Product Lifecycle Intelligence (PLI) is an emerging way to turn data into actionable information and can be seen as an evolution of product data management (PDM) and PLM.

PLI is an application of machine learning and advanced analytics that mines existing data from enterprise systems for insights (as shown in Figure 8). Enterprise data represents a unique opportunity for machine learning and advanced analytics because the data is structured, analysts are familiar with it and it's often shared across systems. This includes product development, production and market data within PDM, PLM , CAD, QMS; other business systems including ERP; and other manufacturing platforms such as MES and yield tracking systems.

Leveraging machine learning and advanced analytics, PLI helps organizations predict the impact of product development decisions on key business performance metrics such as demand, cycle time, cost, quality, regulatory compliance, manufacturing and supply chain efficiency.

A cradle-to-grave PLI capability could have uncovered the root causes of problems described earlier in this paper faster and with greater specificity.

PLI can also improve the product development process by leveraging all previous research and market responses to generate new ideas and kill bad ideas faster, eliminating the excuse for reproducing redundant results. Many firms have little or no "corporate memory" and PLI can ensure every experiment and product launch contributes to the corporate fund of knowledge.

Conclusion

The semiconductor industry has always had the products, designs and factories of the future. This will continue over the next 10-20 years so long as data becomes interconnected at scale across all areas of planning, design, development and production. The harmonious digital enterprise can be realized with smart machines, intelligent data analytics, dynamic systems for smart products and smart factories, global teams of engineers and production workers, and a single collaboration environment across the entire ecosystem.

The semiconductor industry led the first wave of the digital revolution and now it's time to take the next step forward. **Is your firm doing what it needs to do to realize the benefits of the digital transformation?**

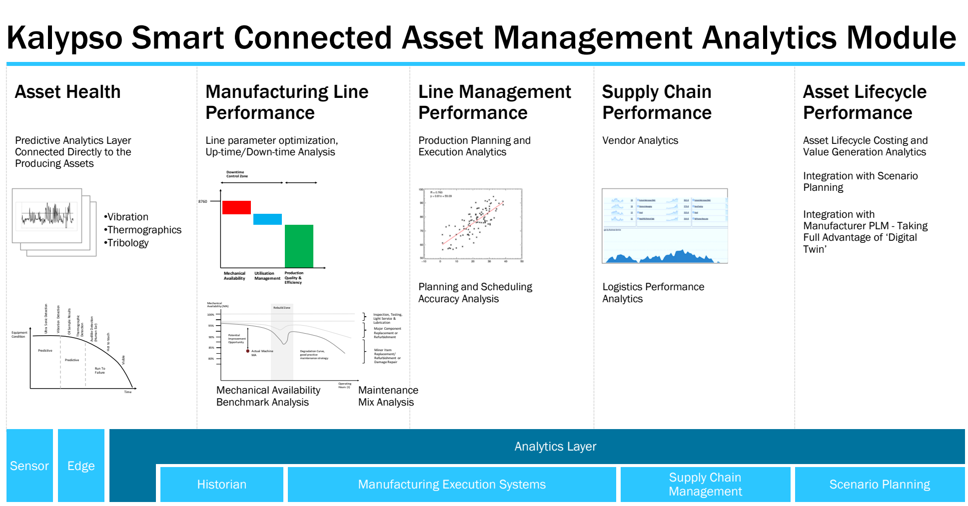

Figure 8 – An Overview of Analytics for SCO