

CIMdata

2021 Market Analysis Report Series

Simulation & Analysis Market Analysis Report

June 2021



CIMdata, Inc.
3909 Research Park Drive
Ann Arbor, MI 48108
+1 734.668.9922
www.CIMdata.com

CIMdata®

About the CIMdata PLM Market Analysis Report Series

The CIMdata PLM Market Analysis Report (MAR) Series is a set of related reports that serve to document CIMdata's analysis of the product lifecycle management (PLM) market. The 2021 report series documents CIMdata's analysis of the global PLM market results for the 2020 calendar year. The CIMdata PLM MAR series includes:

CIMdata 2021 Executive PLM Market Report

Provides an overview of CIMdata's complete global analysis. Includes key charts on PLM market investment statistics through 2020, 5-year forecast of investments through 2025, and a summary of PLM solution providers' performance in 2020.

CIMdata 2021 PLM Industry Review and Trends Report

Mainly qualitative in nature; focuses on key issues facing the global PLM ecosystem of solution providers and end user organizations. Highlights changes that occurred in 2020, what effects those changes may have in the short and medium term, and what is on the horizon in the years to come.

CIMdata 2021 PLM Market and Solution Provider Analysis Report

Details measures of and forecasts for the overall PLM market, and key segments including tools, collaborative Product Definition management (cPDm), and digital manufacturing. The tools section has additional details on sub-segments including MCAD, CAM, S&A, EDA, and AEC; also includes CIMdata's estimates of PLM solution provider revenues for 5 years.

CIMdata 2021 PLM Market Geographic Analysis Report

Provides another view of the 2020 market results, by major geography. CIMdata's 2021 estimates and market forecasts for PLM and the major PLM market segments are provided for the Americas, EMEA, and Asia-Pacific. In addition, includes estimates and forecasts for the cPDm segment within specific European and Asia-Pacific countries and regions.

CIMdata 2021 PLM Market Industry Analysis Report

Provides another view of the 2020 market results, by industry segment. CIMdata's 2021 estimates and market forecasts for PLM and cPDm are provided for eight different industry sectors: aerospace and defense; automotive and other transportation; electronics/telecommunications; fabrication and assembly; process-packaged goods; process-petrochemical; utilities; and construction, infrastructure, and shipbuilding.

CIMdata 2021 PLM Market Country Reports

Provide country-specific views of the 2020 market results. Country reports are available for: Brazil, China, France, Germany, India, Italy, Japan, Russia, South Korea, United Kingdom, and the United States. The reports include estimates of spending by industry segment within each country, solution provider market presence within the country, growth of the top ten solution providers, revenue by

global mindshare leaders, market shares in each measured segment, and five-year forecasts.



CIMdata 2021 Simulation & Analysis Market Analysis Report

Details measures of and forecasts for the simulation and analysis (S&A) segment of the PLM market. The report also includes CIMdata's overviews of leading S&A solution providers and estimates of S&A solution provider revenues by geography and industry for 2020.

CIMdata 2021 Computer-Aided Manufacturing Market Analysis Report

Provides information about the worldwide market for Computer-Aided Manufacturing (CAM) software products and services during 2020. The report includes market size in terms of expenditures by user companies for CAM software products and related services, analyses of various technical aspects concerning the industrial use of CAM software and techniques, trends in the CAM software industry, market share of CAM providers by various measurements, reseller revenues, and other information related to CAM software providers.

Legal Use Notice

~ LEGAL USE NOTICE ~

This document is copyrighted © by CIMdata, Inc. and is protected by U.S. and international copyright laws and conventions.

The document and the data presented in it is licensed for the sole use of the original purchaser. Purchaser is granted an irrevocable, nonexclusive, worldwide, royalty free license to use this material internally. However, if the document is being purchased for a third-party, then the license is restricted to that third-party alone and may not be used by any other party including the purchaser.

This document, or any portion of it, may not be copied, reproduced, stored in a retrieval system, transmitted in any form, posted on a public or private website or bulletin board, or sublicensed or provided to a third-party without the written consent of CIMdata, EXCEPT that, fully contextual quotations, totaling up to 300 words may be used under common "fair use" doctrine for marketing purposes by the original purchaser and clearly marked as "Copyright © by CIMdata, Inc." Charts created from or other reuse of data in tables or spreadsheets in this document may not alter or misstate CIMdata's estimates in a material way. Licensees may not create derivative works that alter or misstate CIMdata's estimates. Any republication of information from this document, beyond the limits stated above, must be approved by CIMdata, Inc., in writing.

No copyright may be obscured or removed from the document or portions of it.

This document was developed on the basis of information and sources believed to be reliable. This document is to be used "as is." CIMdata makes no guarantees or representations regarding, and shall have no liability for the accuracy of, data, subject matter, quality, or timeliness of the content.

CIMdata® is a Registered Trademark of CIMdata, Inc. All trademarks and registered marks of products and companies referred to in this document are protected.

Table of Contents

About the CIMdata PLM Market Analysis Report Series	i
Legal Use Notice	ii
Table of Contents	iii
Index to Figures	iv
Index to Tables	v
Introduction	1
Market Definition	5
PLM Solution Market Segments	5
PLM Market Analysis	8
Measuring the PLM Market	9
The Effect of Exchange Rates	9
Update on Mergers and Acquisitions (M&A)	10
Measuring PLM Market Growth	13
Forecast Assumptions	14
Simulation and Analysis Segment of the PLM Market	17
Trends Impacting the S&A Market	17
Overview	17
Segmenting the S&A Market	19
Technology Trends in the S&A Market	23
Overview	23
PLM Integration and Product Innovation Platforms	25
Digitalization and PLM	33
Digital Thread and Digital Twin	34
Model-Based Systems Engineering	38
Physics-Based System Simulation and Co-Simulation	46
Data and Model Interoperability Standards	46
Simulation Process & Data Management	51
Simulation, Analysis & Validation Governance	53
Cloud Computing and Software as a Service (SaaS)	54
Generative Design and Generative Engineering	56
The Democratization of Simulation	60
Solution Providers Respond to the Demand	62
Comprehensive S&A Platforms	64
Smaller but Key Emerging Players in MBSE	66
Current CIMdata SDS Consulting Practice Research	74
S&A Market—Results and Forecast	75
S&A Industry Analysis	77
S&A Geographic Analysis	78
Solution Provider Analysis	83

The S&A Competitive Landscape	83
S&A Providers Analysis.....	85
Major S&A Solution Providers	89
Ansys	89
MathWorks	92
Dassault Systèmes	93
Siemens Digital Industries Software	95
Altair	99
MSC Software (Hexagon)	101
ESI Group	104
Cybernet Systems	106
Autodesk	107
BETA CAE Systems.....	109
COMSOL Group.....	110
Analytical Graphics Inc.....	111
PTC	112
Gamma Technologies	113
Maya HHT (Heat Transfer Technologies) Ltd.	114
Simulations Plus, Inc.	115
Major S&A Solution Resellers	115
Conclusion	116
About CIMdata.....	116

Index to Figures

Figure 1: CIMdata’s Product Innovation Platform Model	2
Figure 2: PLM Market Sub-Sector Sizes (US\$ Millions).....	3
Figure 3: PLM Market History and 5-Year Forecast	4
Figure 4: PLM: Connecting the Model-Based Domains Enables the Lifecycle Digital Thread	18
Figure 5: CIMdata’s Modeling & Simulation Platform is at the Core of the Product Innovation Platform	26
Figure 6: Engineering Domains and Models are Loosely Connected Today Across the Enterprise Product Development Process	29
Figure 7: Key Elements of the Systems Modeling & Simulation Platform	31
Figure 8: Key Capability Elements of CIMdata’s Enterprise Application Architecture (EAA) Model.....	33
Figure 9: Digital Twins Integrate Data with Engineering Models	35
Figure 10: Waves of Digital Transformation	36
Figure 11: Digital Twin Adoption Plans.....	37
Figure 12: Digital Twin Adoption Plans.....	37
Figure 13: Business Benefits Expected from Digital Twins	37
Figure 14: Digitalization Enables Model-Based Systems Engineering Across the Entire Lifecycle	40
Figure 15: The Boeing Diamond.....	40
Figure 16: Complexity Issues Cut Across Industries	41
Figure 17: The Majority of Lifecycle Costs are Committed Early in the Product Development Process	42

Figure 18: MBSE Links Requirements with the Model-Based Design and Engineering Domains	43
Figure 19: Engineering Domains are Supported by Many Overlapping MBSE Solutions	46
Figure 20: Implementation Issues in MBSE	47
Figure 21: MBSE Emerging Standards Landscape	50
Figure 22: MBSE Emerging Standards Landscape	51
Figure 23: Business Value Comes with Adoption Maturity	54
Figure 24: Moving S&A to the Cloud	55
Figure 25: Component Design Process	57
Figure 26: Generative Design Process	57
Figure 27: A Collaborative Effort to Integrate Systems Engineering Data & Processes with S&A Tools	68
Figure 28: S&A Revenue—History and Forecast	76
Figure 29: Distribution of S&A Revenues US\$ (Millions)	76
Figure 30: History of S&A Revenues by Segment	77
Figure 31: S&A Revenues by Industry Segment US\$ (Millions)	78
Figure 32: History of S&A Revenues by Industry Segment	78
Figure 33: Geographic Distribution of Worldwide S&A Revenues US\$ (Millions)	79
Figure 34: History of Geographic Distribution of Worldwide S&A Revenues	80
Figure 35: Distribution of S&A Revenues within the Americas Region US\$ (Millions)	80
Figure 36: History of Distribution of S&A Revenues within the Americas Region	81
Figure 37: Distribution of S&A Revenues within the EMEA Region US\$ (Millions)	81
Figure 38: History of Distribution of S&A Revenues within the EMEA Region	82
Figure 39: Distribution of S&A Revenues within the AP Region US\$ (Millions)	82
Figure 40: History of Distribution of S&A Revenues in the AP Region	83
Figure 41: PLM Leaders' Revenue by Market Segment	84
Figure 42: S&A Revenues by S&A Application Segment	85
Figure 43: S&A Revenues	86
Figure 44: S&A Leaders' Revenue Histories	86
Figure 45: S&A Leaders Distribution US\$ (Millions)	87
Figure 46: S&A Leaders' Software and Services Revenue	87
Figure 47: S&A Leaders' Revenues by Company Size US\$ (Millions)	88
Figure 48: S&A Leaders' Revenues by Geography	88

Index to Tables

Table 1: Mapping the PLM Segments	6
Table 2: Definitions of PLM Segments	7
Table 3: Average Exchange Rates for Currencies Used in the MAR	10
Table 4: S&A Application Domains	20

2021 Simulation & Analysis Market Analysis Report

Introduction

This report presents CIMdata’s analysis of the global simulation and analysis (S&A) market, including 2020 revenue results and revenue forecasts for 2021 through 2025 by industry and geographic segmentation. S&A is one of the fastest growing segments of the overall product lifecycle management (PLM) market tracked by CIMdata and one that is also growing in importance in supporting product and process development.

CIMdata defines PLM as a strategic business approach that applies a consistent set of business solutions in support of the collaborative creation, management, dissemination, and use of product definition information across the extended enterprise. PLM spans from product concept through life and integrates people, processes, business systems, and information. In today’s market, these capabilities are increasingly delivered by a product innovation platform that supports lifecycle activities across more business functions than just engineering and manufacturing. The platform enables the product information backbone for a company and its extended enterprise, as shown in Figure 1. It enables a set of lifecycle processes and incorporates best practices, methods, and processes. It also includes a set of lifecycle optimization techniques that span multiple disciplines.

Figure 1:
CIMdata's Product
Innovation Platform
Model



CIMdata uses the term “product” in a broad context. A product can be a physical item, a system, and/or a service that is defined, delivered, and supported. This definition includes discrete products such as automobiles, toys, medical devices, and airplanes. It also includes formulated products developed by the food and beverage, pharmaceutical, and process industries. CIMdata’s definition for product also includes large-scale plants and facilities, such as oil rigs, petrochemical facilities, airports, roadways, telecommunication grids, and other infrastructure items.

CIMdata partitions the PLM market into three primary segments:

- *Tools*: Create, analyze, and simulate products and plants and associated documentation, including mechanical computer-aided design (MCAD); simulation and analysis (S&A); electronic design automation (EDA); architecture, engineering, and construction (AEC); and “Other Tools,” such as application lifecycle management (ALM).
- *collaborative Product Definition management (cPDM)*: Manages the complete product or plant definition lifecycle, including all of the mechanical, electronic, software, documentation and other components and the processes that are used during the lifecycle (including product development, manufacturing planning, test process and data management, in-service operation, and maintenance). cPDM includes Comprehensive Technology Providers and Focused Application Providers (who supply solutions such as visualization and collaboration, enterprise asset management, quality management system, service lifecycle management, and content and document management). CIMdata’s measurement of the cPDM segment also includes revenues

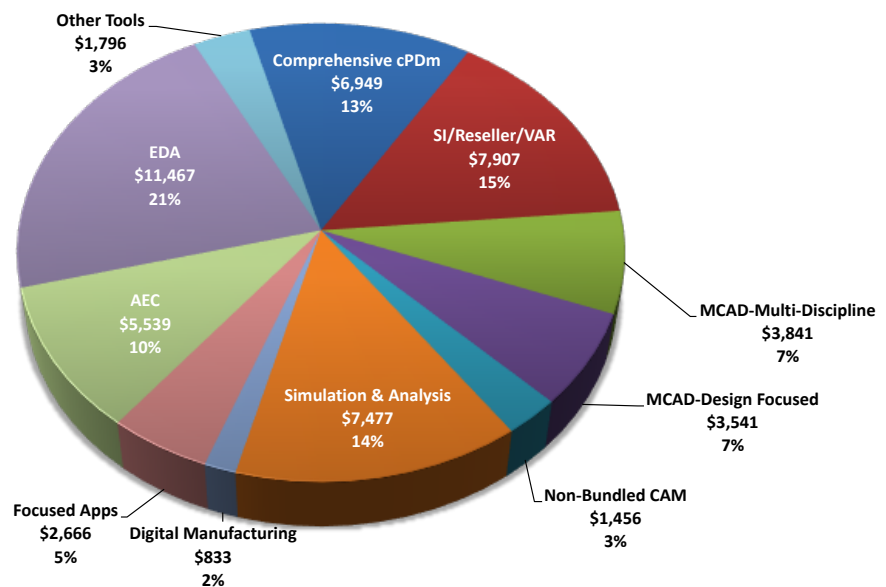
from systems integrators (SIs), value-added resellers (VARs) and other resellers that focus on implementing these solutions.

- *Digital Manufacturing*: Supports the definition of the processes used to produce a product, including simulation and analysis of those processes, and the manufacturing environments used, including production equipment and lines.

All of these segments are supported by systems integrators (SIs), resellers, and value-added resellers (VARs).

The PLM Economy grew strongly in 2019 as measured in our PLM market analysis, and heading into 2020 CIMdata expected the market growth to continue. Then the COVID-19 pandemic gripped the world. In calendar year 2020, the PLM market grew to \$53.5 billion overall (3.8% growth over 2019). Of that, 65.7% (\$35.1 billion) was invested in Tools while 32.8% (\$17.5 billion) was invested in cPDM, and 1.6% (\$833 million) was invested in Digital Manufacturing. Tools and cPDM investments increased 5.4% and 0.2% respectively over 2019. Digital manufacturing revenues decreased by 6% in 2020 to \$833 million. To provide a better understanding of the composition of the 2020 results, Figure 2 presents the various sub-segments of the overall PLM market and their relative sizes.

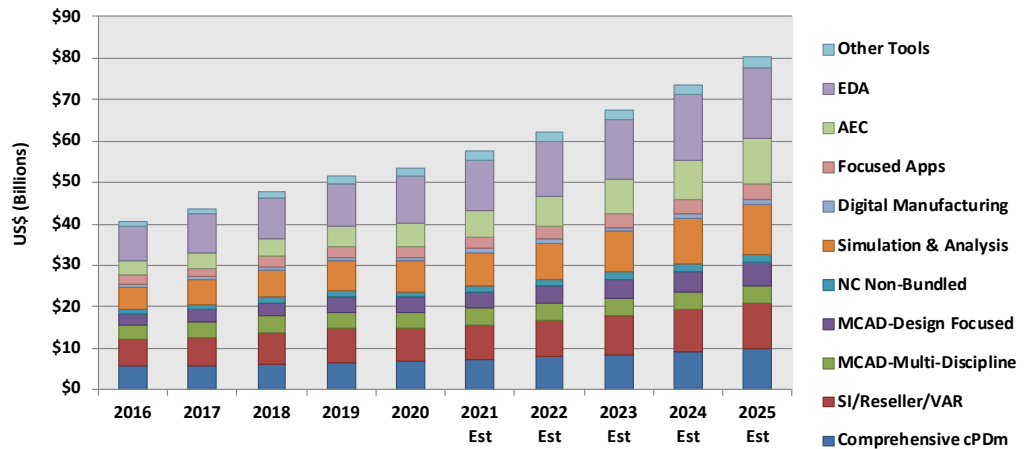
Figure 2:
PLM Market Sub-Sector Sizes
(US\$ Millions)



The PLM market became more vibrant in the third and fourth quarters of 2020 and finished above our forecast of -1.7% over 2019. The biggest forecast miss was in the electronic design automation (EDA) segment, whose providers had enough visibility into recurring revenue and sales pipeline to never lower guidance. The two EDA leaders actually raised their guidance in Q3 2020. The PLM Economy quickly returned to growth after the Great Recession, and it is showing signs of a return to normal based on a strong second half of 2020 and the guidance of many large contributors to PLM market growth. But the virus is still not tamed and will, as a result, continue to impact global trade and value chains for some time to come. CIMdata expects the PLM market to come back quickly to the growth level of the

last few years. How long will it take? The global trends driving PLM growth, like smart, connected products, Industry 4.0, adoption of cloud-based solutions, and the use of new materials and manufacturing processes, to name a few, remain and likely will get stronger in response to this crisis that emerged in early 2020. As a result, CIMdata forecasts the cPDm market to grow by 6% in 2021 to approximately \$18.6 billion (Figure 3). The Tools segment of PLM is forecast to grow by 8.3% in 2021 to \$38 billion, and Digital Manufacturing is forecast to grow by 5.3% to \$877 million. The overall PLM market is forecast to grow by 7.5% in 2021.

Figure 3:
PLM Market History
and 5-Year Forecast



Note that the revenue data presented in all figures in this report are CIMdata estimates of PLM revenue.

CIMdata’s analysis shows continued PLM growth after this crisis subsides in traditional industries such as automotive and high-tech electronics, as well as in industries that have not historically been major PLM investors—food and beverage, retail and apparel, financial and investment services, and government. Additionally, industries such as utilities, petrochemical, construction, and infrastructure are continuing to invest in PLM strategies and solutions. Some companies in these segments will pause their investment in response to the financial crisis and low natural resource prices, while others will take advantage of the crisis to make needed investments and changes in their businesses.

cPDm had low growth in 2020 reaching \$17.5 billion, up only 0.6%. Investments in comprehensive cPDm software—defined as new licenses, right-to-use fees, subscriptions, and software-related maintenance—grew in 2020, up 8.3% to \$7.8 billion from \$7.2 billion in 2019. Services decreased 4.8% to \$9.7 billion, down from \$10.2 billion in 2019.

Looking toward 2025, CIMdata forecasts the PLM market to grow at a compound annual growth rate (CAGR) of 8.5% to \$80.3 billion. CIMdata forecasts that the AEC segment will be one of the fastest-growing segments of the PLM market with a 14.7% CAGR to \$11 billion in 2025. The Tools segment is forecast to grow at 9.3% CAGR over the next five years to \$54.7 billion in 2025. The cPDm segment is expected to grow at a 6.9% CAGR over the next five years to \$24.5 billion in 2025. Digital Manufacturing is forecast to grow at a rate of 6.8% over the next five years to \$1.2 billion in 2025.

Market Definition

As mentioned in the Introduction, CIMdata defines PLM as a strategic business approach that applies a consistent set of business solutions in support of the collaborative creation, management, dissemination, and use of product definition information across the extended enterprise from concept through life—integrating people, processes, business systems, and information.

PLM incorporates a full suite of best-practices methods and enabling technologies such as product data management (PDM), computer-aided design (CAD), collaboration, visualization, digital manufacturing, and S&A. It focuses on the complete product definition lifecycle and addresses the extended product or plant definition supply chain of original equipment manufacturers (OEMs), subcontractors, suppliers, partners, and customers. PLM is not just a technology; it is focused on solutions to broad industry problems, not on characterizing a type of solution offering. PLM utilizes multiple types of technologies and methods, and it intersects with many technologies and methods.

PLM business solutions are focused on solving specific business problems; examples include, “managing the change process in the supply chain environment of an electronics manufacturer,” and “supporting the project management activities across the extended enterprise.” These solutions are delivered through a combination of foundation technologies, enabling applications, established methods and processes, and implementation approaches.

For more information on how the PLM market is evolving in response to global trends in technology and manufacturing, see the *CIMdata’s 2021 PLM Industry Review and Trends Report*, a module in the CIMdata PLM MAR series. Please see the CIMdata reports website for more details: http://www.cimdata.com/publications/reports_purchase.html.

PLM Solution Market Segments

PLM manages the complete product or plant definition lifecycle. This includes all of the mechanical, electronic, software, and documentation components and processes that are used during the lifecycle including product design, engineering change management, in-service operation; maintenance; and end of life decommissioning, recycling, remanufacturing, disposal, and other processes. Effectively managing these intellectual assets is essential in creating a true competitive advantage and achieving bottom-line business benefits. Technologies such as PDM, collaboration, visualization, digital manufacturing, and enterprise application integration (EAI) enable PLM; supporting the extended product or plant definition supply chain of OEMs, subcontractors, suppliers, partners, and customers.

For market research and analysis purposes, CIMdata divides the PLM market into three primary segments:

- collaborative Product Definition management (cPDm)
- Tools
- Digital Manufacturing

All of these segments are supported by systems integrators (SIs), resellers, and value-added resellers.

Table 1 lists the components of each segment and two views of the PLM market: Mainstream PLM and Comprehensive PLM. Unless stated otherwise, any reference to the PLM market and revenues is for the Comprehensive PLM view.

Table 1: Mapping the PLM Segments

Segment	Sub-Segments	Mainstream PLM	Comprehensive PLM
cPDM			
	cPDM Comprehensive Technology Providers	X	X
	cPDM-Focused Applications	—	X
	SI/Reseller/VAR	X	X
Tools			
	MCAD Multi-Discipline (MCAD-MD)	X	X
	MCAD Design-Focused (MCAD-DF)	X	X
	Computer-Aided Manufacturing (CAM)	X	X
	Simulation & Analysis (S&A)	X	X
	Other Tools	—	X
	EDA	—	X
	AEC	—	X
Digital Manufacturing		X	X

This broad definition of PLM has evolved to address complete products that include mechanical, electronics, software, and documentation elements.

To more effectively analyze and report on the overall PLM market, the market and its providers are divided into a number of categories as listed in Table 2.

Table 2: Definitions of PLM Segments

Category	Title	Description
1	Comprehensive cPDM Solution and Technology Providers	Systems that provide a full range of cPDM functionality, have demonstrated scalability, whose products can be distributed across multiple server networks, and have a track record of selling products for use throughout an enterprise. These suppliers typically develop broad product suites that address the full lifecycle of products and plants.
2	System Integrators, Resellers, VARs	Services and products provided by independent suppliers focused on selling and/or implementing PLM solutions based on technologies primarily supplied by other companies. Suppliers in this category do not develop core PLM technologies; however, they may integrate multiple products and technologies and add their specialized expertise, e.g., industry knowledge, to create focused PLM business solutions. It also includes companies that resell other companies' products.
3	cPDM-Focused Applications	Systems that address specific business or functional areas, and thus are focused on a sub-segment of the overall PLM market. These software products are often integrated with broader-based PLM solutions within customer implementations to form a full PLM environment. Examples of these applications are: independent view and markup packages, content management systems, enterprise asset management, portfolio management solutions, quality management systems, strategic sourcing systems, and others.
4	Digital Manufacturing	Systems that support definition of the processes used to produce a product, typically also supporting simulation and analysis of those processes and the manufacturing environments used to produce the product including production equipment and lines.
5	Multi-Discipline MCAD (MCAD-MD)	Full-functioned mechanical computer-aided design (MCAD) systems that support drafting, 2D and 3D geometric modeling, solid modeling, surface modeling (including Class A surfaces for automotive), constraint- and feature-based design (or similar functionality such as relational design), integrated engineering analysis, integrated CAM including Numerical Control (NC) programming, and other product development capabilities.
6	Design-Focused MCAD (MCAD-DF)	Systems characterized by fewer specialist packages, e.g., wire harness design, CAM, and esoteric analysis, than MCAD-MD systems with these capabilities typically made available by third-party developers. These solution sets are typically integrated with a local CAD data manager that provides a small subset of the capabilities typically found in enterprise-capable cPDM solutions. Design-focused MCAD systems typically offer only basic solid modeling and 2D drawing capabilities without any data management (i.e., they are file-based systems).
7	Non-Bundled CAM	Non-Bundled CAM includes companies such as Autodesk, SolidCAM, Hexagon, NDES, etc. It does not include the CAM revenues of Dassault, PTC, or Siemens (those are included in their MCAD estimates).
8	Simulation & Analysis	Simulation & Analysis includes a wide range of 0D/1D/2D/3D technologies such as structural and /fatigue analysis, thermal analysis, dynamics, acoustics, multi-body simulation, computational fluid dynamics, materials characterization, systems modeling and simulation, design optimization/DoE/robust design, simulation results visualization, empirical data analytics, general math-based calculations, simulation process and data management, and others designed to enable engineers to simulate real world functional behavior via digital modeling and simulations to perform "what-if" scenarios, explore and evaluate alternative design and technology concepts, and gain deeper insight into system behavior during new product development; perform final performance validation of the "as built" product as well as to optimize the performance of products and systems in real world operations (e.g., supporting digital twins).
9	AEC	Architecture, engineering, and construction (AEC) software solutions are used to design, engineer, build, and operate large constructed assets such as roadways, bridges, buildings, industrial process and power plants, and utility networks. They include solutions for 2D design and 3D modeling, constraint- and feature-based design, piping, process and instrumentation diagrams (P&ID), integrated engineering analysis, data management, collaboration, estimating, catalogs, project management, and specifications.
10	EDA	Electronic Design Automation (EDA) includes tools for designing, analyzing, simulating, and producing electronic systems ranging from printed circuit boards (PCBs) to integrated circuits.
11	Other Tools	Other tools include technical publication systems, software engineering (ALM—Application Lifecycle Management), requirements management, systems engineering, DevOps tools, Agile tools, and others tools associated with the development, support, and maintenance of products.

Providers of Category 1 systems form the hub of the PLM markets, developing the core technologies upon which PLM solutions are built. The comprehensive cPDM solution and technology providers (e.g., Aras, Autodesk, CONTACT Software, Dassault Systèmes, Oracle, PTC, SAP, Siemens Digital Industries Software, and many others) provide core cPDM functional capabilities, often including broad suites of technologies as well as consulting and implementation services focused on providing full solutions to address major industry problems for their customers. Siemens PLM Software changed their name to Siemens Digital Industries Software in 2019 and will be referred to as Siemens in this report. Other Siemens AG corporate entities will be referred to by their full names when necessary.

Category 2 solution providers are typically a *delivery* mechanism, creating and/or implementing solutions for a specific customer. Independent systems integrators, resellers, and VARs (e.g., Accenture, CENIT, DXC Technology, Deloitte Consulting, IBM, Tata Consultancy Services (TCS), and T-Systems) are included in Category 2 and provide services such as implementation and process re-engineering. Some resell PLM products and may create added-value capabilities built on the technologies they provide. These providers support all domains of the PLM market—Tools, cPDM, and Digital Manufacturing.

Category 3 providers *enhance* the capabilities provided by Category 1 technology providers, enabling many more users to view and collaboratively work with product and plant information; they extend PLM solutions to additional areas of a business and its extended enterprise. These are focused-application providers targeted at solving problems within specific sub-segments of the cPDM market, and they include a broad collection of companies focused on many different problems.

Category 4 providers supply solutions for *defining manufacturing process plans* and the analysis and simulation of production lines, including machinery and ergonomics.

Categories 5 through 11 are the applications and tools used to *create and modify* the intellectual property associated with an enterprise's products. Tools providers (e.g., Altair, Ansys, Autodesk, Bentley Systems, Cadence, Dassault Systèmes, IBM, PTC, Siemens, Synopsys, and many others) provide the functional design and analysis applications used by designers, engineers, and analysts to create the complete product definition.

Even though CIMdata segments these companies into a common high-level category for convenience in understanding the overall dynamics of the market, there are many different market niches these companies address that are often not competitive with each other. For example, companies like Bentley Systems and Nemetschek focus on the AEC market, and companies like Cadence and Synopsys focus on EDA.

PLM Market Analysis

This section describes how CIMdata measures the PLM market and then presents a summary of the market analysis for calendar year 2020.

Measuring the PLM Market

CIMdata uses several research methods to gather data for our annual PLM Market Analysis Report series. Approximately 550 companies currently receive a survey in the form of a Microsoft Excel workbook attached to an email. Multiple email reminders are used to increase the response rate. CIMdata's research team interviews approximately 30 of the world's largest PLM solution providers (by revenue) either in person, or more often, by phone. Since many of these companies cannot directly share detailed market figures, multiple interviews are often conducted with each company to gather insights and determine suitable revenue estimates. In addition, separate research is conducted in both China and Japan to discover more detailed information about those markets. Some data is publicly available and is used directly, and other market research information is used for cross-checking, such as information from the Electronic System Design Alliance (ESD Alliance), which collects and reports global EDA data quarterly. Collecting data for our global CAM MAR is a separate process involving over 60 other computer-aided manufacturing-focused companies. As a result of these combined steps, over 900 companies are "touched" during the data collection process. In addition, the revenues of many other players in the PLM economy are estimated using public and private information.

CIMdata strives to ensure that our research and estimation process is as accurate as possible. Each year CIMdata solicits more companies and some choose to participate. Each CIMdata PLM MAR publication includes a brief summary of the solution providers that have been added, the segments in which they compete, and how much revenue their addition increases the revenue estimate for each segment. To simplify reporting, the estimates do not include pro forma calculations with and without these new firms. CIMdata hopes that by summarizing their revenue contribution readers will be able to understand how these additions influence the results in any given year.

Solution providers report data either in their local currency or in US dollars. For the purposes of our global estimate, all currencies are converted to US dollars using the average exchange rate for the calendar year. All estimates are net of royalties to eliminate double counting revenues. The royalty paid by a reseller is deducted from their end-user revenue estimate and included within the direct revenues of the appropriate technology provider's estimate. All results presented are CIMdata's estimates of revenues and investments.

The Effect of Exchange Rates

Annual revenue estimates for players in the PLM economy can be denominated in a variety of currencies. For simplicity, as mentioned above, CIMdata converts all revenues into US dollars using the average annual exchange rate for that currency. In most years, this has a negligible impact on the market numbers. This was mostly the case for 2020. Table 3 shows the average exchange rates for currencies used during the MAR data collection.

Table 3: Average Exchange Rates for Currencies Used in the MAR

Currency	2019	2020	YoY Change
Euro to US Dollar	1.13895	1.11980	1.68%
Pound to US Dollar	1.28205	1.28700	-0.39%
Japanese Yen to US Dollar	0.00937	0.00891	4.96%
Swiss Franc to US Dollar	1.06496	1.01500	4.69%
Chinese Yuan to US Dollar	0.14491	0.14800	-2.13%
Korean Won to US Dollar	0.00085	0.00088	-4.32%
Swedish Krona to US Dollar	0.10858	0.10575	2.60%
Brazilian Real to US Dollar	0.18000	0.25354	-40.86%
Indian Rupee to US Dollar	0.01350	0.01420	-5.22%
Australian Dollar to US Dollar	0.68776	0.69490	-1.04%
Norwegian Krone to US Dollar	0.10624	0.11364	-6.97%
Russian Ruble to US Dollar	0.01387	0.01545	-11.38%

As Table 3 makes clear, the main currencies in which CIMdata receives data mostly held their own against the US dollar in 2020. In particular, companies who earn most of their revenue in Euros and Japanese Yen gained from a strong currency in 2020 when their revenues were converted to US dollars. The Chinese Yuan RMB saw a slight decline against the US dollar. No systematic pro forma analysis is included.

Update on Mergers and Acquisitions (M&A)

Each calendar year there are a number of mergers and acquisitions (M&A) in the PLM economy and 2020 was not an exception. By CIMdata's count there were 102 acquisitions of note during the year, down only slightly over 2019.

The PLM market leaders continued adding technology and capabilities, and 2020 brought other noteworthy moves in the segment.

- **Autodesk** acquired CAMplete and added them to their CAM portfolio. Additionally, they continued their construction offerings build-out by acquiring Pype for cloud-based construction project management; and Spacemaker, a cloud provider of generative design and AI solutions to help architects, urban designers, and real estate developers make more informed early-stage design decisions.
- **Cimatron**, a formerly independent CAM provider acquired in 2015 by 3D Systems, an additive manufacturing leader, was spun out to Battery Ventures, the same investment firm that bulked up Vero Software before cashing out by selling it to Hexagon.
- **Dassault Systèmes** bought two small companies: Proxem, who offers customer experience analysis solutions and AI-powered semantic processing software and services; and NuoDB, who brings a cloud-native distributed SQL database to the Dassault Systèmes portfolio.

- **Hexagon AB** was very active adding ten companies, including Romax Technology, a provider of Computer Aided Engineering (CAE) software for electromechanical drivetrain design and simulation; CAEfatigue Limited, a provider of mechanical fatigue simulation solutions; DP Technology, a leading independent CAM solution provider; and MECADAT A, a German VISI CAD/CAM software reseller.
- **Infor** was acquired by Koch Industries, buying the rest of the company for \$13 billion after investing \$2 billion in 2016.
- **PTC** acquired Arena Solutions, an early cloud PLM solution that adds to PTC's SaaS/cloud offering.
- **OpenText** added Xmedius, a provider of secure information exchange and unified communication solutions.
- **Sandvik**, a Swedish multinational engineering company, acquired CGTech, a company known for VERICUT, a leading machining simulation and optimization solution.
- **Siemens** added three companies: Avatar Integrated Systems for place and route software for integrated circuit (IC) design; UltraSoC for silicon lifecycle management; and Culgi for computational chemistry software with a focus on multiscale simulations in the process industries.

Simulation and Analysis (S&A) providers continued to acquire more physics to build out their multiphysics capabilities:

- **Altair Engineering** made five acquisitions, including newFASANT, a specialist in technology for computational and high-frequency electromagnetics; S&WISE Co. Ltd., a Seoul-based leading provider of polyurethane foaming simulation; Univa for HPC management capabilities; Ellexus for I/O analysis tools; and M-Base Engineering + software GmbH, an international supplier of material information with a focus on plastics.
- **Ansys** added two companies: Lumerical, a provider of photonic design and simulation tools; and Analytical Graphics, Inc. (AGI) in Q1, 2021, a provider of mission-driven simulation, modeling, testing, and analysis software for aerospace, defense, and intelligence applications.
- **Tech Soft 3D** made two simulation-related acquisitions. Ceetron, who offers 3D visualization technology for the CAE community; and Visual Kinematics, a maker of DevTools, a suite of component software development kits (SDKs) for CAE applications.

In the EDA segment:

- **Cadence Design Systems, Inc.** acquired Integrand, a specialist in 5G RF communications; and NUMECA International in Q1, 2021, a provider of CFD software.
- **Synopsys** made five acquisitions, including some IP assets of INVECA; Tinfoil Security for testing solutions; Qualtera for semiconductor

analytics; Moortec, a specialist in in-chip monitoring technology; and LIGHT TEC, which brings optical measurement capabilities.

Acquisitions in the AEC market included:

- **AspenTech** acquired Camo Analytics AS, a Norwegian provider of industrial analytics solutions; and OptiPlant, early plant layout solutions.
- **AVEVA** acquired MESEnter, a provider of production accounting software; and OSIssoft, the maker of Visual Kinematics DevTools, a suite of component software development kits (SDKs) for computer-aided engineering (CAE) applications
- **Bentley Systems** added NoteVault, a provider of voice-based construction management technology; PCSG, an expert in advising built-environment owners on going digital; and advancing BIM, GIS and infrastructure digital twins, and GroupBC, a UK-based SaaS provider.
- **Hexagon AB** added Blast Movement Technology, which provides solutions to manage open pit mines; Geopraevent AG, a provider of natural hazard monitoring and alarm systems; Alas Ing SA, a distributor of Hexagon PPM solutions; COWT's mapping business, which includes airborne surveying and spatial data processing; Tactiaware for LiDAR-based 3D surveillance software; and MDE Network, SRL, an Argentinian provider of solutions for operations management and optimization
- **Honeywell** bought Sparta Systems, a leading independent quality management system (QMS) provider.
- **Nemetschek** acquired DEXMA, a provider of SaaS AI/ML solutions for energy data management.
- **Rockwell Automation** acquired Kalypso, a systems integrator with a strong client base in life sciences, consumer products, and industrial high-tech; and Fiix Inc., a company offering an AI-enabled computerized maintenance management system (CMMS).

Many systems integrators continue to add expertise and geographical coverage:

- **Accenture** continued its buying spree with 18 acquisitions, including VanBerlo, a Dutch product innovation consultancy; ESR Labs, a Munich-based specialist in automotive embedded software; Callisto Integration, a Canadian IT services company; and PLM Systems, a Turin-based PLM services specialist.
- **Addnode** acquired Netpublicator, a SaaS provider of digital document and meeting management solutions; and Scanscot Technology, a Nordics-based simulation specialist.
- **Atos** bought three companies; Maven Wave, providing digital transformation consulting services; ALIA Consulting, an SAP-focused consultancy; and Motiv, a Netherlands-based provider of managed security services.

- **Capgemini** added three, including Advectas, a Scandinavian consultancy focused on BI and data science; and WhiteSky Labs, an independent MuleSoft consultancy.
- **Deloitte** bought DNM for their cloud services business.
- **HCL** acquired two companies: DWS Limited, an Australian consultancy; and Cisco SON Technology, a provider of self-optimizing network (SON) technology.
- **Infosys** added three, including Kaleidoscope Innovation, a product design consultancy.
- **Inspriage** bought Vertical Edge Consulting, an Oracle-focused consultancy.
- **Tech Mahindra** added two Australian consultancies.
- **Wipro** acquired three companies, include Eximus Design, focused on the semiconductor industry; and IVIA Servicos de Informatica, a Brazilian IT services company.

One reason that CIMdata tracks M&A activity in the PLM Economy is that acquisitions can distort the market results by adding significant revenue not previously counted in our analysis. Reviewing the actions in 2020, we can adequately compensate for these changes without affecting the overall results. The results of specific firms may change as a result, and those affected are noted in this report.

CIMdata's MAR reports are intended to focus on the calendar year of the analysis year presented. Because of the nature of financial reporting and market research, the reports take time to develop and publish. Very often, events happen between the new year and the publication date that CIMdata feels are important to note where applicable to trends or other information in the report. In those cases we will judiciously include such relevant information.

Measuring PLM Market Growth

PLM is a dynamic market, with new functionality continually added to the portfolio of leading providers, either through acquisition or by organic development. One question raised about this analysis is how growth is accounted for in CIMdata's market measurement. In some cases, two players already measured will combine, which, in most cases, has no effect on PLM market growth. In some cases, however, companies tracked by CIMdata will make acquisitions of companies not tracked by CIMdata. This could cause the appearance of growth if their revenues were not previously modeled as part of the CIMdata analysis.

There were no changes in CIMdata's sample that caused material changes in the analysis results in calendar year 2020. In most cases, these acquisitions are small tuck-ins, bringing specialized technologies and small revenues. While these numbers may affect the reporting of a specific company in 2020 and going forward, in a \$53.5 billion market they are relatively small.

Forecast Assumptions

Our forecasting process leverages a wide range of sources, including:

- CIMdata's 30+ year experience conducting PLM-related market research and our extensive contacts across the PLM Economy.
- The previous years' results and next year's guidance from the public companies in the PLM Economy, which represents over 30% of the total PLM market.
- Global economic growth estimates from organizations like the International Monetary Fund (IMF), World Bank, IHS, and the Economist Intelligence Unit (EIU).
- Global IT market forecasts from well-known analysts like Gartner, Forrester, and IDC.
- Insights from CIMdata's global consulting activities with software and services providers and industrial companies.

For this challenging year we drew on all of these sources and more.

CIMdata believes that the underlying fundamentals driving PLM investment remain strong, and are different from the last major market disruption, the Great Recession. This time the PLM market is different. More revenue comes from subscriptions vs. perpetual licenses that can provide a floor in segments where they are more common, i.e., MCAD-DF, S&A, and AEC. More software is bought online, with "contactless" delivery to use a term popular in this crisis. There is also more collaboration done using the Web than before.

Besides impacts on the market segments, there are some societal and technology drivers that were not as important in the Great Recession. The push toward autonomous vehicles and electrification requires more use of digital tools. Telecoms are moving to 5G, creating waves of investment. Manufacturing is getting smarter and more connected, and increasingly relies on new materials and manufacturing technologies, to make the Industry 4.0 vision a reality. Products are getting smarter and more connected across almost all industries, creating a need for systems thinking and analysis, with more electronics and software to animate these products and the digital transformation many companies are pursuing to take advantage of them.

These factors helped inform our forecasts for the next few years. While vaccination is increasing in the West and China, many countries are only just starting that process. CIMdata expects PLM spend to return to pre-COVID levels but market perturbations will remain a fact of life for the next couple of years.

Our five-year forecast is based on the following assumptions for each segment, all of course subject, in the near-term, to the impacts of the COVID-19 pandemic:

- *MCAD Multi-Discipline (MCAD-MD)*: The two leading MCAD-MD competitors, Dassault Systèmes CATIA V6 and NX from Siemens are seeing sluggish growth. At the same time, offerings from the MCAD-DF segment, Dassault Systèmes SOLIDWORKS and its competitors have grown more strongly. At one time companies would reach a limit with

those MCAD-DF packages and want to move up to MCAD-MD. That is becoming a rare occurrence. At the high-end, CIMdata has lowered its expectations for overall growth for this segment because the tops of most supply chains in the industries needing MCAD-MD capabilities have a chosen solution, which means that Siemens and Dassault Systèmes will battle for the same customers. PTC should see some growth in both MCAD segments from their shift to subscription.

- *MCAD Design Focused (MCAD-DF)*: In the MCAD-DF segment, there is still a lot of 2D being used in the developed world that can be converted to 3D, as illustrated by Autodesk's Platform revenues. Globalization and rapidly developing domestic markets are also leading industrial companies in emerging economies to adopt 3D solutions. The introduction of cloud-based solutions, like Onshape, now part of PTC, have the potential to disrupt the market over the next few years. SOLIDWORKS has continued to impress, but users are responding negatively to the reduced focus on traditional SOLIDWORKS from parent Dassault Systèmes. The biggest impact on growth in MCAD-DF will come from Autodesk, with the move to subscription potentially driving double-digit growth in the years to come. CIMdata's forecasts for MCAD-DF have been adjusted upward to accommodate this shift.
- *Non-Bundled CAM*: This segment has seen its share of mergers and acquisitions, with many of the leaders gobbled up or merged, as in the case of Vero Software, now part of Hexagon. 2020 saw two CAM deals. CIMdata has tracked this space for decades and, with the exception of bad recessions; growth has been in the 5 to 7% range. In the last few years there has been a small shift upwards, perhaps due to the increasing complexity of machining operations and the move toward Industry 4.0. This may see a pause due to both COVID-19 and decrease in machine tool consumption over the last two years.
- *cPDM*: There are several indications that cPDM growth will continue. Large companies in early adopting industries like automotive and aerospace still have aging implementations that need to be updated or replaced. Companies in all industries are also working to broaden and deepen their cPDM implementations. As companies move up the value chain, the complexity of their products almost demands the use of cPDM solutions to manage their work processes and intellectual property. Finally, solutions like Aras Innovator, Autodesk Fusion Lifecycle, and Upchain are opening up new delivery and licensing models, like open source and cloud, and promoting PLM to a much broader range of industrial companies than ever before. PTC moved to a subscription model, which will impact this segment going forward, raising their revenues slightly over historical norms, and expanded their SaaS business by acquiring Arena Solutions in 2020. All of the major providers see cloud as an opportunity, which could affect their results in the short term. Another major impact on CIMdata's reporting in this segment is the inclusion of Medidata in Dassault Systèmes' cPDM revenues. The application and the markets it serves fit into CIMdata's definition.

Medidata added over \$700 million to Dassault Systèmes cPDM revenues in 2020, and is slated for strong growth in the coming years.

- *S&A*: This segment has been the star of the PLM market for the last several years. There is little indication that S&A growth will cease. In fact, growth should accelerate a bit over the forecast horizon. The growth rates at some of the larger S&A solution providers will eventually slow, partly because their revenues are so high at present.
- *Digital Manufacturing*: Digital manufacturing struggled in 2020, with both Siemens and Dassault Systèmes down. This makes sense as many factories were impacted by the pandemic. We expect this segment to see continued growth, in part as a response to Industry 4.0. Significant opportunities do exist as more companies move up the value chain in industries like automotive and aerospace, particularly in emerging markets. Growth is anticipated for companies offering automotive and aerospace products for domestic, and hopefully global, consumption. Companies in these emerging markets often emulate established firms, and digital manufacturing has been shown to provide significant benefits. In addition, both Siemens and Dassault Systèmes, the market leaders, are integrating more manufacturing capabilities into their portfolios, which means cross selling opportunities and more ways to create new capabilities by combining their various offerings.
- *SI/Reseller/VAR*: This market has suffered since the global recession but saw solid growth overall in 2019 just in time to be impacted by COVID-19. The face-to-face nature of most SI work flies in the face of a world where six-foot (or two-meter) personal separation is the new normal, but overall SIs adapted better than even they (and their customers) expected. There were already changes afoot in this segment before the pandemic. Companies are looking for different types of services to support PLM strategies than in the recent past. In addition, the move to cloud-based solutions will also change the dynamics in this segment, with less call for customization. On the flip side, cloud solutions will require different types of integration and implementation skills. For these reasons, we expect growth to moderate in the short and medium term even after the pandemic wanes.
- *Other Tools*: Primarily consisting of software and systems development tools like application lifecycle management (ALM), DevOps, software configuration management, systems engineering, etc. Developing smart, connected products drives adoption of software and systems engineering tools. CIMdata also includes IoT platform revenues in this category, another potentially high growth application.
- *EDA*: The “smart” in “smart, connected” originates in electronic design automation tools for printed circuit boards, chips, and wiring. That same product trend is driving growth in this segment as well. This segment has been affected by economic conditions in the past but excelled during the pandemic, with the two market leaders upping their guidance during the

year when others were struggling. CIMdata expects solid growth in this segment over the next several years.

- *AEC*: Of all of the segments, AEC can be the most affected by changes in the economy or, more specifically, commodity prices. If oil prices are down, oil companies will slow plant construction plans, which can slow software purchases. However, growth in the AEC segment will remain strong given the dominant position of Autodesk in this segment. CIMdata expects Autodesk to grow in the double-digits for the forecast horizon and with others in AEC also delivering strong results, like Nemetschek. This segment will also suffer in the short term but the long-term prospects are bright.

Of course, any such gains are subject to fluctuations in the global economy. Early in 2020, according to the IMF, the prospects for global growth were bright and darkened as the global pandemic gripped the world, strangling most economies. CIMdata's forecast assumes that the global economy will return to growth in 2021, off an easy comparison with a dismal 2020, and the forecasts for the out years (2023 through 2025) have been adjusted to reflect that growth. The governments of many emerging countries, like India and China, see the importance of developing competent global competitors that can help develop their domestic economies, and are helping their domestic companies invest in PLM-enabling solutions.

Simulation and Analysis Segment of the PLM Market

Trends Impacting the S&A Market

Overview

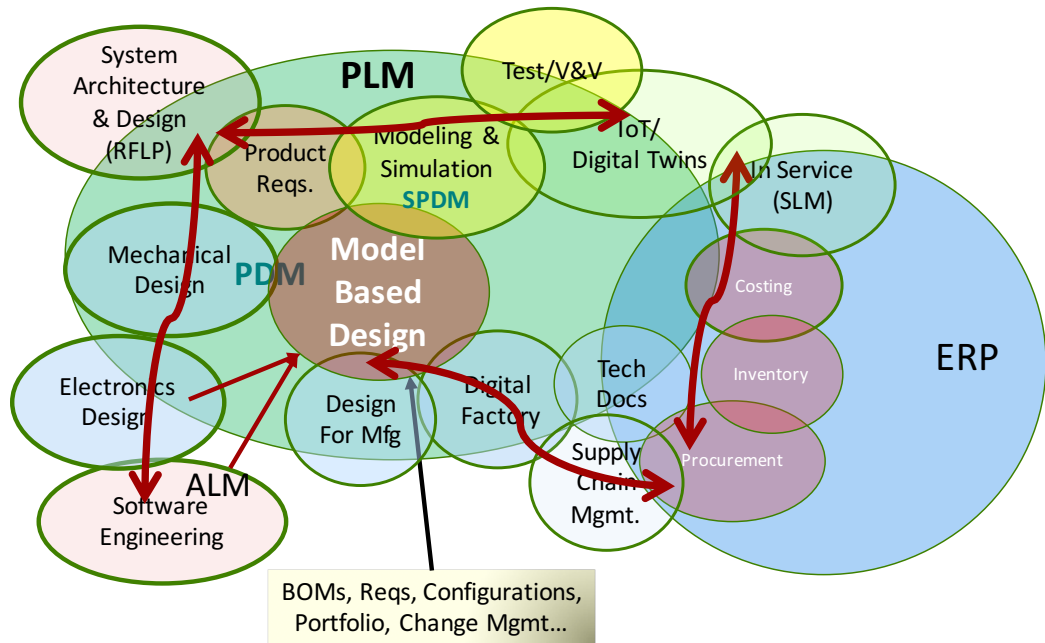
Significant global product development trends are making multi-domain, multi-physics, and multiscale systems-level virtual prototyping and performance simulation indispensable to enable a transformation to digital systems development for complex cyber-physical systems. These global industry trends include:

- Smart, connected products enabled by the Internet of Things (IoT) and Industry 4.0, including autonomous vehicles and systems.
- Electrification and light-weighting of vehicles and mobility systems.
- Artificial intelligence (AI)/machine learning (ML)/deep learning (DL) enabled by very large-scale data analytics.
- Mass customization using formalized product line engineering approaches with embedded software features being a key new product differentiator for end-user functionality across all industries.
- Custom engineered materials from micro to macro scale.
- New manufacturing methods that are designed to meet specific customer requirements (e.g., additive manufacturing combined with subtractive manufacturing).
- New generative design and generative engineering processes that leverage design, simulation, and manufacturing technologies to create

optimized product definitions at both the component/sub-systems and systems architecture levels.

- Design for sustainability, resource efficiency, and regulatory compliance.
- Products as a Service, i.e., the ongoing utility business model where the consumer pays for the benefits and use of a product owned by the manufacturer or other third-party service organization and that may be upgraded and/or re-configured multiple times throughout its lifecycle.
- The growing impact of new technologies such as augmented reality (AR), virtual reality (VR), and artificial intelligence/machine learning in product development, manufacturing, and operations support.
- The digitalization of all enterprise functions (see Figure 4) including the “Platformization” of product development driven by industry M&A consolidation, emerging open standards for engineering data and model interoperability, and new Cloud/SaaS (Software as a Service) delivery models.
- Rapid movement toward the digital thread/digital twin paradigm to connect product data and information throughout all domains and ecosystems, throughout the lifecycle, to enable product innovation, quality, sustainability, and profitability.

Figure 4:
PLM: Connecting the
Model-Based Domains
Enables the Lifecycle
Digital Thread



These global business trends now place systems modeling and simulation squarely on the critical path for the development of today’s complex cyber-physical systems and their associated manufacturing processes. Virtual prototyping has become an indispensable element in developing a true Model-Based Systems Engineering (MBSE) process and will play a key role in the transformation to the interconnected world of the Industrial Internet of Things (IIoT). Companies that adapt their product development platforms and related processes to take advantage of model-based

approaches which leverage virtual prototyping and simulation as a strategic element of the product development process will not only survive but will thrive. The application of physics-based “digital twins” in the rapidly emerging IoT and Industry 4.0 domains to enable real time, digitally connected in-service maintenance, repair, and operations (MRO) will be transformational in the way that future products are conceived, designed, manufactured, and continuously sustained over the lifecycle of complex and interconnected cyber-physical systems. Companies that lag in the adoption of such new concepts will fall behind and may ultimately face extinction.

There are a wide range of solution and service providers that support adoption, implementation, and use of behavior modeling and simulation technologies. The following segmentation list covers the majority of the major S&A disciplines within the electro-mechanical systems domain. However, not all segments listed here are included in the S&A market numbers in this report. For example, emerging capabilities for requirements management and systems architecture definition are captured today within the “Other Tools” category revenues as tracked by CIMdata. Physics-based S&A tools that exist within the AEC and EDA/Electronics market segments are also not explicitly tracked in this report but are becoming an ever-increasing element of those PLM market segments.

Segmenting the S&A Market

CIMdata has routinely gathered data on the S&A market as part of its PLM Market Analysis Report process. While our market definition was broad, in practice most of our contacts were focused within the mechanical computer-aided design (MCAD) and computer-aided engineering (CAE) firms. CIMdata gathers S&A revenue and information in other PLM segments, but this has not been a primary focus to date of this report.

With the formation of CIMdata’s Simulation-Driven Systems Development Knowledge Council and consulting practice in 2015, created by merging our separately focused Simulation & Analysis and Systems Engineering practices, CIMdata expanded its definition and coverage into the broader realm of the systems modeling and simulation market including technologies that impact the area of MBSE. This report reflects the reality that many of the PLM, mechanical CAD, and CAE firms we have traditionally tracked are expanding into new domains within the S&A sector as well as into adjacent domains such as MBSE, EDA/ECAD, data analytics/AI, and IoT. At the same time, several of the major EDA solution providers are now offering S&A technologies that cross over into the traditional mechanical engineering disciplines (thermal, flow, durability, materials characterization, etc.) and compete with tools from the legacy MCAD and CAE providers.

This broader S&A market view encompasses many different capabilities, most of which are focused on specific physics performance areas as listed in Table 4.

Table 4: S&A Application Domains

Focus on Specific Physics Performance Areas
2D/3D structures, strength, stiffness, and vibration; linear and nonlinear
Structural fatigue, durability, and failure prediction
Materials characterization, materials development, and materials data libraries—both empirical-based as well as engineered-to-purpose
Laminate composites and advanced materials analysis
CFD (computational fluid dynamics) and thermal/flow analysis
Thermal and heat transfer analysis—conduction, convection, and radiation
Multi-body dynamics and mechanisms—both rigid and flexible bodies
Impact, crash, and safety (explicit nonlinear analysis)
Electromagnetic Interference (EMI)
Optics
Acoustics and vibro-acoustics
Integrated multi-physics (vertical solutions by application disciplines)
3D topology and geometry optimization
High-performance 3D results visualization
Predictive analytics for large volume simulation results as well as empirical data from field operations and controlled tests
Process integration and orchestration, and automation across multiple simulation domains and tools (often referred to as process integration and design optimization, PIDO)
System dynamic simulation (0D/1D mechatronics systems with controls)
System synthesis
Multi-disciplinary design optimization, design of experiments (DOE) and robust design (MDAO)
Uncertainty quantification (UQ)
General math-based calculations (e.g., Matlab, Mathcad, Maple, Mathematica)
Physical testing and empirical data analysis (model validation, loads, etc.)
Manufacturing process simulations such as injection molding, metal forming, casting, etc.
Chemical formulations and reaction
Embedded software and controls simulation and quality validation
Vertical applications by industry (e.g., vehicle NVH, engine performance, combustion, powertrain, gear system analysis and design, etc.)
Cross-domain modeling and simulation (M&S) data interoperability tools
Simulation process and data management (SPDM)
Engineering consulting services

Systems engineering capabilities used in conjunction with S&A capabilities for implementing model-based systems engineering (MBSE) include:

- Requirements definition, allocation, and traceability (the “R” of RFLP)
- Systems architecture definition across engineering domains to meet the system design requirement (FLP for systems engineering)

All of the market leaders provide solutions across many of these application areas, but there are also specialists that often have best-of-breed solutions in a particular physics domain. Consulting services can also be quite different in the S&A segment

from the other PLM segments, with much more focus in the consulting mix on contract engineering services to support actual product development programs.

Because of the extreme interest in the S&A segment by the financial community over the last decade, CIMdata has worked with many private equity and venture capital firms looking to invest in the segment. One common question is the relative growth rates and revenues from the largest software application areas listed above. In part, through our work with financial organizations, CIMdata has developed estimates of revenues at the applications level for a select set of S&A segments through calendar year 2020. CIMdata consolidated the S&A application segments listed above into the 14 segments listed below:

- 3D Modeling/Meshing/Results Visualization, Analysis Platforms: e.g., Ansys Workbench, Altair HyperWorks, Autodesk Simulation 360, SIMULIA Abaqus Pre/Post & Dassault Systèmes 3DEXPERIENCE, BetaCAE ANSA & META, COMSOL Multi-Physics, ESI VPS, FEMAP, MSC Patran & Apex, Siemens Simcenter 3D.
- Linear Statics FEA Structural Analysis: 2D/3D strength, stiffness, durability, e.g., Altair Inspire, Ansys Mechanical, Autodesk Simulation 360, Abaqus/Standard, Beta CAE EPILYSIS, COMSOL Multiphysics, ESI VPS, MSC Nastran, Siemens Simcenter Nastran, etc.
- Structural Dynamics FEA, Acoustics & Vibro-Acoustics Analysis Solvers: e.g., Altair OptiStruct, Ansys Mechanical & LS-DYNA, ABAQUS Standard, Beta CAE Epilyis, COMSOL Multiphysics, ESI VA One, MSC Nastran, Siemens Nastran.
- Implicit Non-Linear FEA Structural Analysis Solvers: e.g., Altair RADIOSS, Ansys Mechanical and LS-DYNA, Abaqus/Standard, COMSOL Multiphysics, ESI VPS, MSC Nastran, Siemens Nastran, etc.
- Explicit Non-Linear FEA Structural Analysis Solvers: impact, crash, safety, etc. E.g., Altair RADIOSS, Ansys/LS-DYNA and AutoDyn, ABAQUS Explicit, ESI VPS/Pam-Crash and Pam-Stamp, MSC Dytran, etc.
- Multi-Body Dynamics/Motion: Mechanisms with rigid and flexible bodies, e.g., Altair Inspire & MotionSolve, Ansys Motion, COMSOL Multiphysics, MSC ADAMS, Siemens Simcenter NX Motion, Recurdyne, SIMULIA Simpack.
- General Purpose Math-Based Calculations: excludes Microsoft Excel) (e.g., MathWorks MATLAB, PTC Mathcad, Maplesoft Maple, Mathematica.
- 0D-1D Systems Modeling and Simulation including controls & Co-Simulation: e.g., Altair Activate, Ansys SCADE, Dassault Systèmes CATIA SE, ESI Simulation X, MathWorks Simulink/Simscape, MSC Easy5, Maplesoft MapleSim, Modelon Impact & FMI, Siemens Simcenter Amesim.

- CFD, Thermal & Flow/Thermal Multi-Physics: e.g., Altair Acusolve, Ansys FLUENT and Lumerical, COMSOL Multi-Physics, Dassault Systèmes SIMULIA PowerFLOW, ESI ACE+ Suite, MSC Cradle, Siemens Simcenter STAR CCM+ and Flowtherm.
- Electro-Magnetics Interference Analysis:—from low to high frequency ranges, e.g., Altair FEKO, Ansys HFSS & PHAROS, COMSOL Electromagnetics, Dassault Systèmes SIMULIA CST Studio Suite, Siemens Simcenter Electromagnetics Suite.
- Simulation Process and Data Management (SPDM): includes SDM + process orchestration and automation across multiple simulation domains and tools, e.g., Altair SimData Manager, Ansys Minerva, Aras SDM, BetaCAE SPDRM, Dassault Systèmes SIMULIA/3DEXPERIENCE, ESTECO VOLTA, Jotne IT EDM/openSimDM, MSC SimManager, Siemens Teamcenter for Simulation & Simcenter SysDM, etc.
- Design Optimization & 3D Topology Optimization, Design of Experiments (DoE), Multi-Disciplinary Analysis and Optimization, Robust Design: e.g., Altair OptiStruct, Ansys optiSlang, COMSOL Multiphysics, Dassault Systèmes SIMULIA Tosca and iSight, Simcenter, ESTECO modeFrontier, Phoenix Integration ModelCenter Explore, Siemens Simcenter HEEDS, VanderPlatts R&D Genesis.
- Materials & Manufacturing Process Data: materials characterization and material data libraries including laminates, plastics, and additive materials, e.g., Altair Material Data Center, Ansys Granta, COMSOL Multiphysics Material Library, MSC Material Center, SENVOL, Siemens Simcenter 3D.
- Other Niche Physics & Miscellaneous Apps: Optics, Fatigue/Failure Analysis, Test Data Acquisition and Analytics, Test/Analysis Correlation, Mission Analysis, Vertical Apps, UQ, data interfaces, chemical reactions, etc.

Note that systems engineering capabilities used in conjunction with S&A capabilities for implementing model-based systems engineering (MBSE) can include:

- Voice of the Customer (VoC) and Quality Function Deployment (QFD)
- Requirements definition, allocation, and management for lifecycle traceability (the “R” of RFLP)
- Systems architecture definition across engineering domains to meet the system design requirement (the “FLP” of traditional systems engineering)
- Failure Mode and Effects Analysis (FMEA)
- System Verification and Validation (V&V)—Functional, Logical and Physical

These capabilities are not explicitly included in the S&A market revenues tracked within the CIMdata S&A Market Analysis Report with the exception of the physics-based tools used in physics-based V&V. Any revenues associated with these other systems engineering application areas are lumped within the *Other Applications* category of the overall PLM market revenues as reported by CIMdata.

If you are interested in more in depth reporting of this set of systems engineering applications, we would welcome your inquiries, suggestions, and support in working to quantify the overall MBSE market revenues and growth metrics.

The S&A application segment market estimates are discussed more fully in the S&A Market—Results and Forecast section of this report and in Figure 38.

Technology Trends in the S&A Market

Overview

Virtual prototyping and systems simulation employing both lower fidelity 0D/1D and higher fidelity 2D/3D modeling and simulation approaches have moved well beyond use as a design screening tool or an alternative to minimize physical testing and validation cycles. Today's simulation technologies in areas such as mechanical (e.g., structural analysis, thermal analysis, thermo-fluid, and computational fluid dynamics), electrical and electronics (power characteristics, electromagnetics analysis, signal integrity, etc.), and embedded software and controls enable engineers to quickly and cost-effectively investigate “what-if” scenarios, explore innovative new design alternatives, and gain deeper insights into how a product can deliver its intended customer value throughout its lifecycle, including recycling, repurposing, remanufacturing, etc.

The phenomenon popularly known as Moore's Law has resulted in the doubling of technical computing capability every eighteen months for over five decades. One astounding result is that we can now compute in one second what would have taken over 1,500 years when the Apollo moon program was being engineered. Improvements in computer software and mathematical algorithms have added further orders of magnitude, and all this comes at a rapidly declining cost, at least for computing hardware. Although simulation engineers will always clamor for more, computing has become increasingly fast and vanishingly cheap in less than a lifetime.

During this timeframe, physics-based simulation and analysis has delivered business results more quickly, at lower costs, and with higher fidelity (i.e., resolution and accuracy), while supporting more comprehensive and realistic physics-based behavior predictions. This major trend allows simulation to be used earlier in the engineering design and development process than was the case even a decade ago. We are now truly in the era of simulation-driven engineering—an era where simulation can help synthesize and define the optimal system, subsystem, and component designs, rather than simply evaluate and validate a single design option during and after the detailed design phase of product development. More importantly, we are now able to evaluate complex cross-domain systems at higher levels of fidelity and even mixed fidelity, not just as 3D components and subsystems.

The key to simulation's utility is response time to the engineering team making design decisions. In the early 1980s, designs were on paper and finite element models were built by hand or digitized from 2D drawings, node point by node point. It took months to analyze even simple components. In most cases, simulation was too slow to impact the design process—it was more often used for forensic analysis of parts that failed in service. With the advent of 3D CAD, improved software for meshing, and faster computers, simulation was able to evaluate completed designs to assist in product validation, albeit often still after the product design was frozen. But engineers were then able to examine alternative designs and, by the turn of the 21st century, simulation was supporting automated design validation of components. While simulation must still be applied to the essential task of final product validation, it is now, by necessity, moving upstream into the earliest stages of product design as well as into manufacturing process and systems design.

As such, a major transformation is underway towards model-based or model-driven processes in engineering product development and manufacturing for today's complex systems and cyber-physical products consisting of integrated mechanical, electronics, embedded software, and controls components.

Global market leaders across many industries are rapidly expanding their strategic use of virtual prototyping and simulation into the cyber-physical systems realm to deal with rapidly changing global market trends and end-customer requirements for the latest features and functions.

Traditional multi-physics-based mechanical S&A platforms are being extended and integrated to work with other engineering domains such as electronics, controls, optics, biology, chemistry, and software, with all of the intellectual property linked back to requirements.

In CIMdata's view, systems engineering has been slow to deliver on its vision of MBSE and broad use of the SysML standard, which have been more than two decades in the making. However, the pace of adoption is quickening and there is optimism that numerous integrations between PLM and S&A platforms along with the SysML 2.0 standard due for release in 2021 will be catalysts to enable growth.

Openness, web-based architectures, AI/machine learning, cloud/SaaS software delivery models, and engineering data interoperability standards such as XML, FMI/FMU, and OSLC are playing an increasingly important role in enabling S&A to be a core strategic component of future product development platforms that will enable product innovation in the model-based enterprise.

The growing trend toward product innovation platforms, (i.e., integrated business process and data platforms) by the large PLM solution providers and largest S&A focused solution providers is leading to significant consolidation of smaller companies and vertical niche technologies as the larger companies acquire the smaller companies to fill out their product innovation platforms.

While there is now some debate within the industry on how long Moore's law will persist, it is important to note that Moore's Law is not yet dead. In ten years, it is likely that computers will be a hundred times faster and cost less than half as much

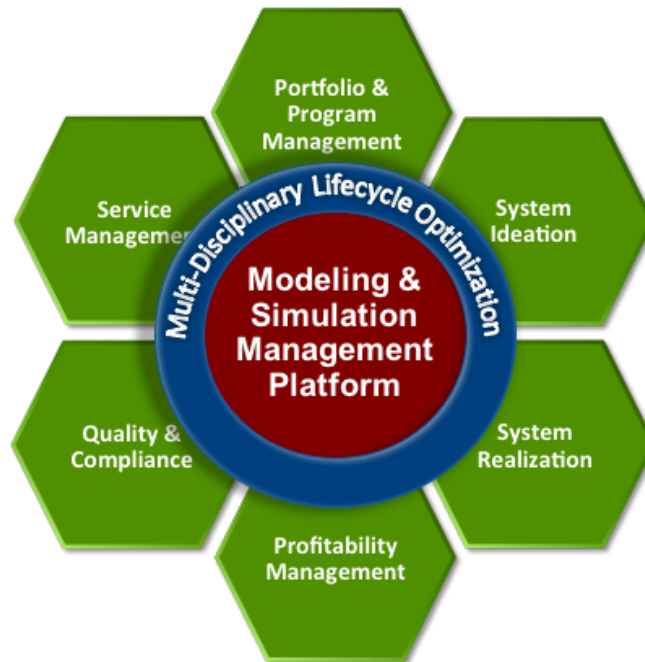
as they do now. The physical resources (e.g., prototypes and people) will probably double in cost in that same time. It is simply imperative that companies figure out how to effectively leverage simulation earlier and earlier in their product and manufacturing system development processes.

PLM Integration and Product Innovation Platforms

As noted, over the past several decades simulation's importance has continuously increased because it can be done faster, with more detail and fidelity, and earlier in the development process, usually at much lower cost than creating multiple physical prototypes. But now simulation processes and data must also integrate across multiple physics disciplines, as well as across the domains of mechanical, electrical, software, and controls, as well as biological and chemical design and development, from concept through life.

To achieve maximum business impact, modeling and simulation capabilities must be an integral element of enterprise product innovation platforms (see Figure 5), providing nimble access throughout the product life cycle, from concept through life, to the currently valid product development requirements, architectural design data, process workflows, materials, test, and other related product verification and validation information, as well as in-field or operational data. Also, simulation results, which are predictions of product and manufacturing performance, must be made available to a wider audience in an easily searchable, accessible, reusable, and consumable manner using engineering applications working on engineering desktops, mobile devices, via web browsers, and the cloud. Product innovation platforms that integrate S&A solutions with the traditional enterprise IT functionality contained in PLM, ERP, and other enterprise platforms that support cross domain activities such as requirements management, product line engineering, design configuration, revision management, workflow management, multi-BOM management, etc., will be the future of model-centric product development processes.

Figure 5:
CIMdata's Modeling &
Simulation Platform is at
the Core of the Product
Innovation Platform



In CIMdata's view, the S&A industry is continuing to move towards comprehensive and interoperable platform solutions that embody capabilities beyond just the traditional S&A domain of mechanical 3D CAD and CAE. These include:

- Robust geometry creation and editing capability (2D and 3D CAD)
- Simulation data management (both 2D/3D and 0D/1D)
- Process automation and knowledge capture augmented by AI/ML
- Role-based user interfaces and results visualization augmented by AI/ML
- Analytics and AI/ML applied to both simulation results and empirical data obtained from prototype testing, as well as in-service operations
- Multi-domain (mechanical, electronics, controls, software, chemical, etc.)
- Multi-physics (structural, thermal, flow, durability, vibration, noise, etc.)
- Multi-scale (large scale systems down to nano-, micro-, and molecular levels)
- Materials characterization (composites, customized materials based on the capabilities of new additive manufacturing processes, etc.)
- Process orchestration & robust design (stochastics, design of experiments), system simulation (0D, 1D, networks), and dynamic co-simulation to link the mechanical, electrical, controls, and software elements of models
- Physics-based digital twins leveraging S&A technologies beyond product design into manufacturing and in-service operations

- MBSE linking descriptive system modeling tools such as SysML/UML with performance requirements as well as the executable behavior modeling tools of the S&A domain

Solution providers in other domains such as EDA/ECAD and AEC (architecture, engineering, and construction) have also been making acquisitions or striking alliances for traditional mechanical domain S&A capabilities. Most of the major EDA companies are now providing targeted S&A capabilities for integrated flow and thermal analysis in electronics systems. Many EDA companies have acquired these S&A capabilities from the traditional mechanical engineering S&A market to integrate with their ECAD suite of design analysis capabilities. A prominent example is Mentor Graphics acquiring Flomerics to provide an integrated electronic design and packaging solution that addresses the issue of greater heat dissipation required in today's densely packed chips and electronics assemblies. Mentor Graphics was subsequently acquired by Siemens Digital Industries Software, marking the first major merger across the traditional silos of MCAD/CAE and EDA/ECAD.

Cadence Design Systems, another EDA software market leader, acquired AWR Corporation from National Instruments at the end of 2019. AWR is an industry leader in high-frequency RF EDA software technology used in applications for 5G equipment systems design. Cadence continues to invest in developing its Clarity3D solver for Electromagnetics (EM) simulation and also acquired NUMECA International in Q1, 2021. The addition of NUMECA's technologies and talent supports the Cadence® Intelligent System Design™ strategy and broadens its system analysis portfolio with computational fluid dynamics (CFD) solutions. These products will contribute to Cadence's system analysis solutions for integrated circuits (ICs), electronic subsystems, and full system designs.

Synopsys, another EDA software market leader, provides human body modeling and material analysis capabilities in their Simpleware portfolio. The Simpleware software offers 3D image data visualization and analysis and model generation solutions for moving from scans to 3D models. Simpleware accurately processes images, obtains measurements and statistics, and exports high-quality models to design, simulation, and 3D printing applications. Synopsys also provides solid optics design and analysis (CODE V) and illumination design (LightTools) software solutions. Japan-based EDA software company Zuken acquired Vitech during 2019 to provide a broader scope of multi-domain MBSE capabilities.

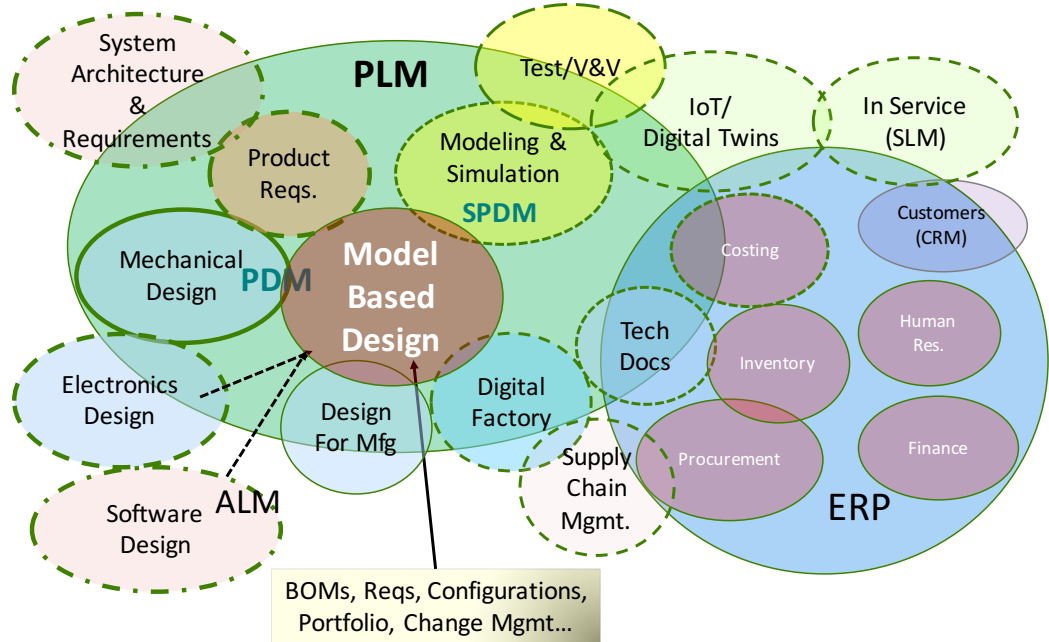
In the domain of electronics systems test and evaluation, companies such as National Instruments (LabView) and KeySight Technologies (PathWave) are also providing software-related solutions that augment traditional physics-based simulation and analysis applications. Brüel & Kjær is a Danish multinational engineering and electronics company headquartered in Nærum, near Copenhagen. It is a leading manufacturer and supplier of sound and vibration measurement equipment, systems, and solutions including specialized software for test data acquisition, acoustics analysis, and sound quality engineering. Brüel & Kjær is a subsidiary of Spectris.

These cross-industry developments are driven by the systems design needs of specific customers in the industries that the solution providers serve such as automotive, aerospace, high tech electronics, industrial machinery, and medical equipment.

Even as solution providers broaden and round out the S&A capabilities of their offerings, the overriding trend desired by industrial users is clearly toward openness and interoperability. The idea of one provider offering a universal solution across all the required engineering domains, or that a solution provider will be able to lock its customers into a single, proprietary set of solutions, is functionally obsolete and will no longer be tolerated by industrial customers of PLM and S&A solutions. A major driver for openness is for customers to integrate their proprietary systems, data, and capabilities, not to integrate competitive vendor offerings. While many end users want to leverage integrated S&A platforms because of potential process efficiencies, the reality is that the vast majority of industrial customers have a heterogeneous engineering environment consisting of multiple commercial CAD and S&A tools (often the result of acquisitions) as well as numerous custom in-house tools including the widespread use of Microsoft Excel. These complex S&A environments drive the ongoing need for data and model interoperability standards.

Even given these requirements, many of today's virtual performance engineering environments lack the domain scope necessary to deal with complex cyber-physical systems as well as interconnect models and data across digital platforms operating in multiple domains. These environments are typically loosely connected or even totally disconnected from the enterprise PLM workflow processes and IT infrastructure necessary to realize maximum top- and bottom-line business impact. This is aggravated when virtual performance simulation and physical test-based validation information domains are not connected to each other and with the enterprise product development platform (i.e., the development-focused elements of an enterprise's product innovation platform), thus becoming information and knowledge silos (see Figure 6). This lack of integration is not adequate to meet industry's business challenges going forward. There is a critical need for open and standards-based product innovation platforms that connect systems requirements, product data, engineering best practice processes, and enterprise knowledge across functional domains within organizations and their ecosystems, including customers.

Figure 6:
Engineering Domains
and Models are Loosely
Connected Today
Across the Enterprise
Product Development
Process



Tomorrow’s systems modeling, simulation, and related physical testing and validation processes, as well as associated performance engineering capabilities, must be at the core of the infrastructure for enterprise product engineering platforms. Placing these systems at the core enables innovative product and process ideation and design, allows rapid prediction and validation of system performance versus customer and regulatory requirements, and fosters high confidence in business decision-making in a highly dynamic and collaborative global product development environment.

Increasing R&D investments in the S&A domain are being fueled by the growing need to employ the tools and methodologies more effectively in virtual design and prototyping and model-based processes. This supports systems development of more innovative products, improves design quality, speeds time to market, and reduces the overall costs of products and systems. Making S&A offerings easier to use can help make non-expert engineers and managers more effective and enable the “democratization” of S&A, which remains an elusive, yet high value goal to unleash more benefits from S&A technology adoption throughout the enterprise. A number of new tools are emerging in this space to address not only the ease of using simulation technologies by a broader range of engineers but also providing more rapid and near real-time feedback on alternative design concepts. Several prominent examples are SimSolid from Altair Engineering and Discovery Live from Ansys.

Improvements in multiple areas of physics-based performance analysis and systems behavioral modeling continue to provide higher accuracy prediction of product performance early in the conceptual stages of the product development lifecycle as well as for product verification and validation before release to manufacturing. Performance modeling tools and solver algorithms continue to be refined and extended in domain scope, dimensional fidelity, and scale, to deal with extremely large model sizes, co-simulation of dynamic system models, and analysis of products

at the nanoscale, including analyzing materials on the microscopic and molecular levels. Corresponding increases in computing power available to engineers on the desktop leveraging GPUs, HPC clusters, software hosted on the cloud, and cloud-based services (SaaS) make it both feasible and cost-effective to build and exercise analysis models at ever-increasing levels of fidelity.

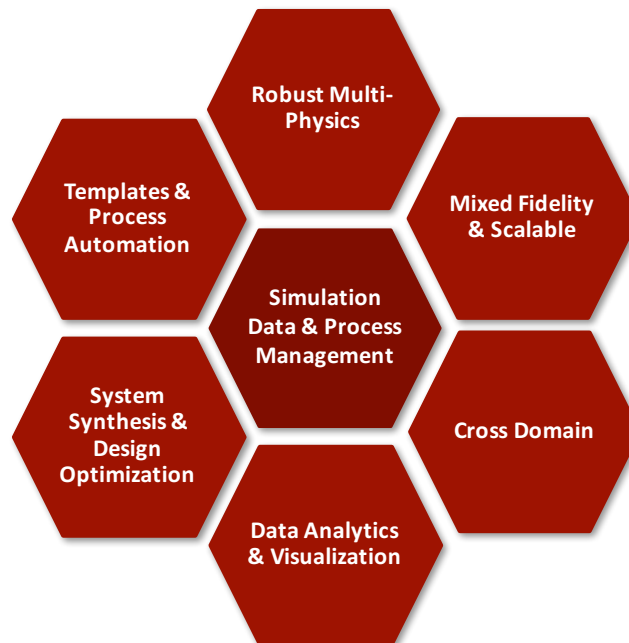
Over the past several years S&A solution providers have focused on addressing key aspects of systems simulation and analysis that can greatly increase the value that simulation provides to the overall enterprise. Specifically, CIMdata is seeing a focus on providing:

- Solutions to enable modeling and simulation of complex dynamic systems earlier in the conceptual design process, including cyber-physical systems that cut across the engineering domains of mechanical, electronics, controls, and embedded software. This includes the rapidly emerging area of co-simulation for hardware-, software-, and model-in-the-loop (HiL/SiL/Mil) simulations employing open modeling languages like Modelica and new model interoperability standards for system level co-simulation such as FMI/FMU and System Structure and Parameterization (SSP).
- Automation tools and related engineering consulting services to capture simulation best practices and standard processes that can be repetitively used and improved throughout the enterprise. Simulation is starting to be democratized to support a broader user base and audience of “consumers” of S&A results using purpose-built web-based applications. For example, 3D interactive visualization can be effectively and safely used by engineers who are not experts in the underlying S&A tools that perform the engineering calculations. In some cases, these web apps have been extended to non-engineers, such as product sales people in configure-to-order or design-to-order business applications.
- Solutions to better manage performance modeling and simulation and analysis processes and integrate these processes and the data created from them (i.e., S&A models, results, reports, and metadata) more effectively into the broader enterprise’s overall PLM strategy and technologies. Data analytics, AI, and machine learning are expected to play an ever-increasing role in this area.
- Solutions for data interoperability and collaboration including new methods for integrating physics-based S&A tools with emerging systems engineering tools, based on architecture description languages such as SysML and Capella, that can capture and track the overall system requirements in conjunction with the system-level functional, logical, and physical architectures (i.e., classical RFLP). The emerging ISO/STEP standard for Modeling and Simulation in the context of Systems Engineering Collaboration (MoSSEC) now formally designated as AP243 is expected to play a significant role in this area in the near future.

These new capabilities address the key business challenges of developing complex cyber-physical systems are raising the visibility of S&A to the “C level” of companies of all sizes. Industrial companies are focusing more attention on S&A as a core and strategic element of delivering innovative new products, as well as improving product development efficiency. Engineering organizations are increasingly focusing on better ways to capture corporate knowledge about business processes and engineering best practices to improve the efficiency and business impact of S&A.

In response, the leading S&A platform solution providers are increasingly focusing on satisfying these S&A market needs and delivering business value to their customers through significant R&D investments and by acquiring small- to medium-sized providers of niche world class technologies and/or vertical solutions. The S&A space has actively consolidated over the past 15 to 20 years and we do not expect any slowdown in M&A activity for the foreseeable future, although the list of available companies of significant market share continues to dwindle. This is because many leading solution providers, including Altair Engineering, Ansys, Autodesk, BETA CAE, COMSOL, Dassault Systèmes/SIMULIA, ESI Group, Hexagon/MSC Software, and Siemens Digital Industries Software are increasingly focused on providing these comprehensive modeling and simulation platforms (see Figure 7) that support an integrated, process-centric, and data-managed user experience across the S&A applications highlighted in the previous section. This niche technology consolidation and the integration of data and processes across multiple domains also enables the platform solution providers to deliver more complete S&A solutions for users in targeted vertical market segments (e.g., aerospace, defense, vehicle/automotive, high tech electronics, medical equipment, consumer products, process and energy, etc.).

Figure 7:
Key Elements of the
Systems Modeling &
Simulation Platform



Ansys achieved its S&A market-leading position over the past 15 years in significant part due to numerous acquisitions, several quite large in size, such as Fluent, Ansoft,

and most recently, Livermore Software Technology Corporation (LSTC). Altair, Autodesk, Siemens, and Dassault Systèmes all have expanded their S&A technology portfolios via aggressive acquisition initiatives. In particular, Siemens has made several major acquisitions, including LMS and CD-adapco, which vaulted their S&A market share into the number three position, trailing only Ansys and MathWorks. Interestingly enough, the one notable exception among the S&A market leaders not pursuing an integrated innovation platform and S&A solution consolidation through acquisitions strategy is MathWorks. While they do make some smaller technology acquisitions, their number two market position is based primarily on organic growth of their widely-used flagship MATLAB product and the Simulink/Simscape suite of systems modeling tools. But more recently, MathWorks has begun to acquire and develop some niche technologies in the 2D/3D simulation and analysis domain and has adopted a more standards-based, open platform mindset in working with other S&A and PLM solution providers.

Other small- to medium-sized S&A providers focus on providing best-in-class capabilities within one or more of the S&A niche segments. These include BETA CAE Systems, Analytical Graphics (acquired by Ansys in 2020), Modelon, Cybernet Systems (Maplesoft/Noesis Solutions), Phoenix Integration (acquired by Ansys in May 2021), VCollab, Gamma Technologies, Romax Technology (acquired by Hexagon in early 2020), ESTECO, nCode, EASA, AutoForm, ThermoAnalytics, SimScale, OnScale, NLign Analytics, Coreform, nTopology, AVL, Ricardo, and InterCAX. These smaller providers continue to develop innovative and game-changing S&A technologies that often become too tempting to resist for the larger S&A platform firms.

Also emerging and growing rapidly over the past decade is the domain of chemical/biological and molecular level modeling and simulation software for use in the drug/pharmaceutical, biotechnology, agrochemical, cosmetics, and food and beverage industries. A number of privately owned, as well as publicly-traded companies, such as Simulations Plus (SLP-NASDAQ) are active in this segment. While outside of the mechanical S&A domains that CIMdata has traditionally tracked in this report, we expect that these application areas for molecular/atomic-based modeling and simulation will be increasingly important in dealing with the COVID-19 pandemic and the development of new drug therapies. This will make such firms likely of more interest as acquisition candidates by the major players in the traditional PLM and ERP software industry. In fact, Dassault Systèmes acquired Accelrys in 2014 and has made that technology the core of its BIOVIA offerings for biological, chemical, and materials modeling and simulation.

All of these focus areas offer excellent potential for continued revenue growth within the S&A solution market, and their implementation by industry will continue to provide significant bottom line benefits to companies over the coming years. The ongoing market growth and the corresponding increase in R&D spending by the solution providers will significantly improve S&A's value to the overall product development process within the evolving model-based enterprise paradigm.

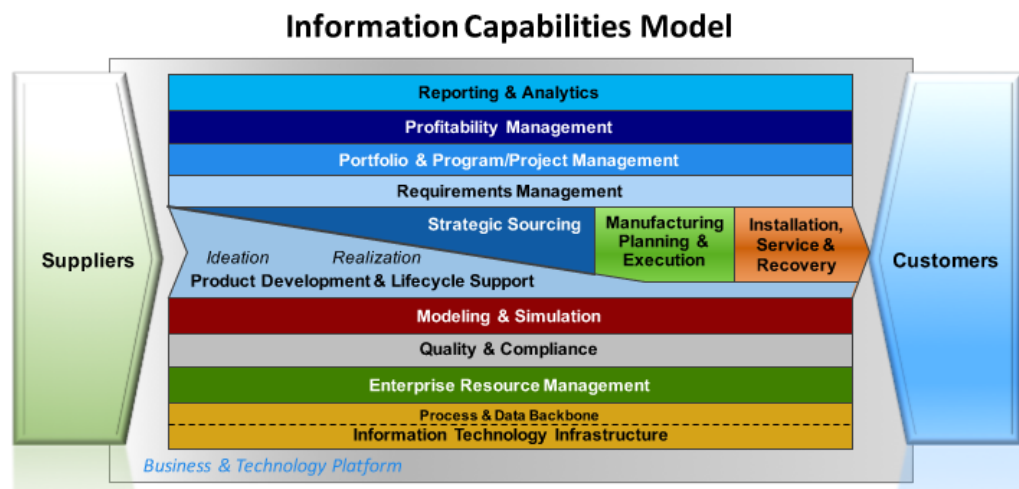
Digitalization and PLM

Over the last several years, the IT world has dramatically changed due to major technology advancements in social media, mobile connectivity, analytics for big data, and cloud computing (often abbreviated as SMAC), and most recently by the Internet of Things (IoT) and Industry 4.0 initiatives. The next big thing on the horizon seems to be enterprise digitalization, which leverages solutions addressing the SMAC and IoT trends to help companies fundamentally transform their businesses.

Digitalization is a pervasive and disruptive force in today's world, both socially and economically. Digitalization is defined by the Gartner Group as “the use of digital technologies to change a business model and provide new revenue and value-producing opportunities; it is the process of moving to a digital business.” Notable examples of successful businesses that have employed digitalization to create significant new business models and enterprise value while disrupting traditional business models are Amazon, Uber, Lyft, and Airbnb. According to a recent IDC study, digital transformation (DX) will spur global direct investment of over \$6.8 trillion from 2020 to 2023.¹

As such, modern business organizations are leveraging digital and model-based technologies in functional disciplines related to product ideation, realization, and sustainment across the virtual enterprise, including supply chain partners and even end users of their products. Digitalization will be the force that brings together the virtual world with the physical world. Digital enterprises will need to embrace information capabilities as an architecture (Figure 8). The enterprise architecture is defined in terms of capabilities that are defined and directed by an organization's Business Platform. In this context, capabilities are processes and technologies (i.e., functional capabilities) that are used to perform a business function.

Figure 8:
Key Capability Elements
of CIMdata's Enterprise
Application Architecture
(EAA) Model



Engineering and product development face similar challenges as companies place an ever-increasing value on innovative new products and services to remain competitive even as the use of software and electronics in today's cyber-physical systems

¹ IDC Reveals 2021 Worldwide Digital Transformation Predictions. IDC. Oct. 2020. <https://www.idc.com/getdoc.jsp?containerId=prUS46967420>

increases exponentially. Embedded software and computing technologies add significant value and complexity to the products and systems that consumers demand. New manufacturing processes such as 3D printing, additive manufacturing, and associated new materials are leading not only to a major revolution on the factory floor and in product design, as well as where and how products are used and maintained over their lifecycle. The IIoT promises to revolutionize the way companies and governments do product development and sustainment in the near future. Bottom line—all of these factors are driving the need to adopt a systems-oriented and model-based approach to PLM.

Digital Thread and Digital Twin

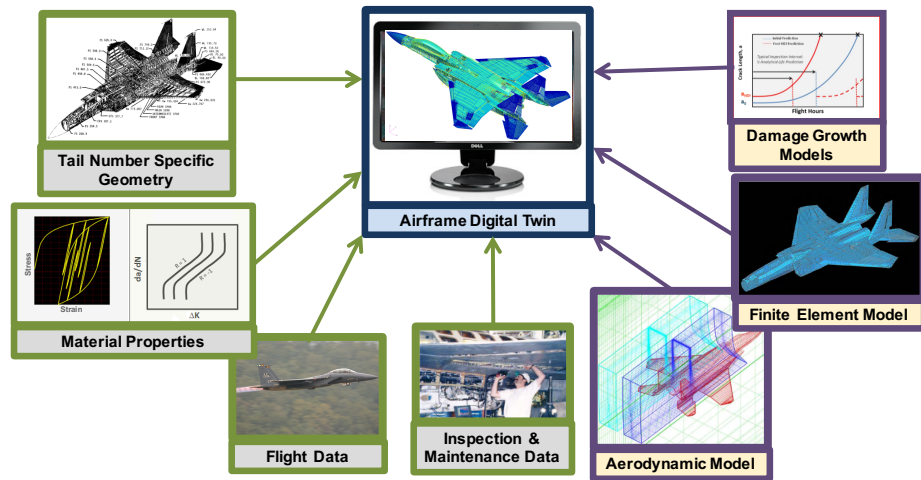
In the world of large-scale systems with extremely long in-service lifecycles such as in aerospace and defense, shipbuilding, nuclear power, etc., the concept of the “digital thread” has gained increasing mind share within the systems engineering community. The fundamental idea is that as all of the various disciplines within an enterprise move from paper-based processes to digital and model-based approaches, there needs to be a way to connect or “thread together” the relevant digital data and information required to make informed decisions throughout the enterprise over the entire product lifecycle including design, development, manufacturing, operations, and sustainment. CIMdata defines the digital thread as the communication framework that allows a connected data flow and integrated view of an asset’s data (i.e., its digital twin) throughout its lifecycle across traditionally siloed functional disciplines and domains. Another widely quoted definition for the digital thread and the interconnected concept of the digital twin comes courtesy of the US Air Force and Department of Defense (DoD):

- Digital thread is the creation and use of cross-domain common digital surrogates of a system to allow dynamic, real-time assessment of a system’s current and future capabilities to inform decisions throughout the entire lifecycle.
- A digital surrogate (i.e., the digital twin) is a physics-based description of a system resulting from the generation, management, and application of data, models, and information from authoritative sources across the system’s lifecycle.

The concept and terminology of the digital twin is relatively new but is in reality a logical extension of the digital prototype terminology widely used in the electronics design and mechanical CAE industry since the early 1990s. There is currently a great deal of market interest (and associated marketing hype) around the business opportunities associated with the use of digital twins. Not surprisingly, the definition of the digital twins’ scope and related business value can vary widely based on the industry application segment and the role of the digital twin stakeholder such as IT solution providers, end product and service creators, end product users and consumers, etc. CIMdata prefers the digital twin definition put forth and promoted by the USAF/DoD because it is based on a virtual representation of the system which can be used to mirror and predict the physical behavior of the as-configured and as-used product in addition to other performance characteristics such as cost, quality, reliability, customer satisfaction, etc. See Figure 9.

In other words, this is not just a digital 3D description of the physical product and its real-world operations data reflecting its current “in service” environment; it is also an executable virtual model that can be continuously updated and used to make real world decisions about the system as it is being operated by the end user. The physical sensor data being obtained from the system in real time (e.g., pressures, stresses, vibration, fluid flows, temperatures, power consumption, etc.) can be used in conjunction with advanced data analytics and realistic physics simulation models to monitor, predict, and potentially improve or change the real-time behavior of the system in use (supporting maintenance, repair and operations) as well as in-service product upgrades and next generation product design enhancements.

Figure 9:
Digital Twins Integrate
Data with Engineering
Models



Courtesy of Air Force Research Laboratory

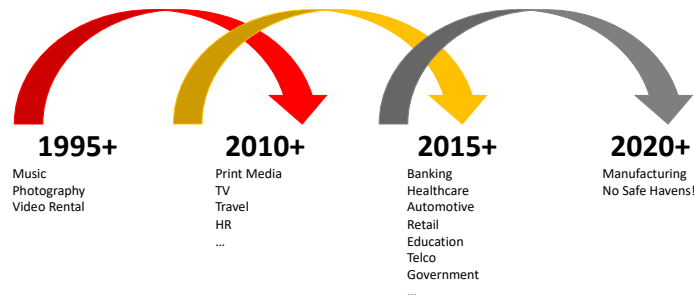
The business and engineering implications for this are indeed large. High value and mission critical systems such as jet engines, power turbines, petrochemical exploration rigs, military drones, etc., can provide continuous real-world performance data on their status—24x7x52. Potential product failures can be predicted by the digital twin simulation model and prevented before they occur. Key system performance parameters can be adjusted and optimized based on the digital twin’s prediction to better reflect its real-world operating conditions and duty cycles, which are often very particular to each instance of the physical system. For example, an industrial pump operating in a desert region will see far different conditions than the exact same pump operating in the Arctic region. Their digital twins can reflect and account for those as-operated conditions as well as any ad-hoc physical configuration changes made in the field by operations personnel. In contrast to the digital prototype that typically reflects the static view of the as-designed or as-built product, the digital twin reflects the dynamic, as-operated condition.

Depending on the application use case for the digital twin, different platforms will be called upon to provide data—for example, MES, MRO, and ERP systems used for manufacturing operations and quality assurance. These enterprise business systems contain operational and cost data that is key to maintaining, repairing, and efficiently operating today’s complex systems. The IIoT-enabled digital twin, when connected into these other enterprise data platforms (PDM/ERP/MES/MRO)

provides required advanced data analytics, enables continuous feedback of real world information on how the product is actually being used by a specific customer or a class of customers (e.g., in the US vs. in China or in Brazil), and how a specific product or even a family of products are performing (or not performing) versus the design requirements and specifications of the customer or owner. This more in-depth knowledge of product behavior can be applied by product development and applications engineers to the design of in-service product fixes, continuous system performance upgrades, or in the design of next generation products and systems. Typical engineering assumptions used as inputs to digital performance models such as system operating conditions, design load cases, factors of safety, and product life can be refined.

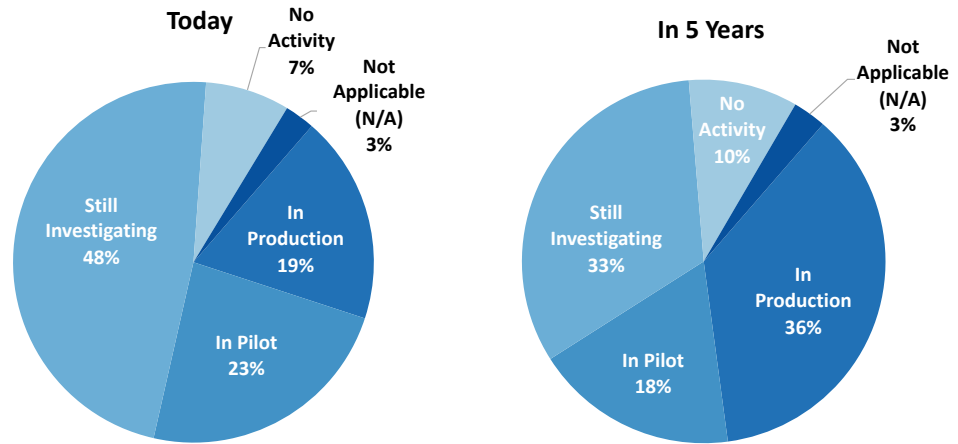
Driven by the Industry 4.0 vision, the IIoT, and key enabling IT technologies such as big data, analytics, AI/ML and deep learning, AR/VR, and cloud/edge computing, the world is rapidly moving towards megabillions of interconnected smart products, cyber physical production systems, and physical infrastructures. A number of studies conducted by leading IT research organizations have highlighted that the manufacturing industry is still relatively immature in achieving a fully digital enterprise business model from product ideation through creation and operations. This is often referred to as the Third Wave of Digital Transformation and is shown in Figure 10.

Figure 10:
Waves of Digital
Transformation



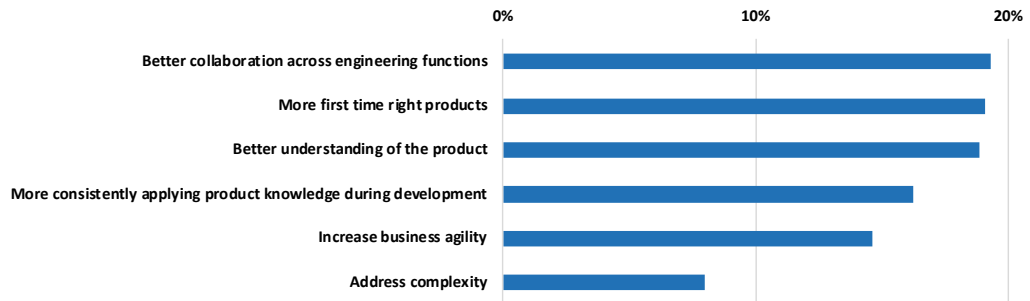
During 2019 and 2020, CIMdata conducted market research activities focused on evaluating the state of digital transformation initiatives in manufacturing companies. The survey included questions related to the use of digital twins and what value adopters sought. The audience polled was predominantly involved in product design, performance simulation and analysis, and manufacturing engineering so the results should be viewed accordingly. With respect to the adoption of digital twin technology, 48% were investigating today, only 19% are in production, and 23% are involved in pilot evaluations. These percentages are expected to shift significantly within the next 5 years as shown in Figure 12.

Figure 11:
Digital Twin Adoption
Plans



The business benefits that the organizations participating in this survey expect to receive from the use of physics-based digital twins are not surprisingly focused more on the activities conducted during product design and development versus manufacturing and in-service operations where much of the current focus is for the use of digital twins that are dominantly “data-driven twins” leveraging IoT platforms and big data analytics but not typically connected to simulation models of the “as used” physical asset. See Figure 13.²

Figure 13:
Business Benefits
Expected from Digital
Twins



Typically, there are several enterprise data platforms involved to realize all the benefits of having a digital twin. The underlying Product Innovation Platform must enable bringing the threads of all the other enterprise platforms together to ensure that data and information are consistent, up to date and not duplicated. Emerging standards for vendor-neutral collaboration, model exchange, and co-simulation are vital to any business to ensure an agile and efficient approach for enabling the required digital thread and connecting its digital twins.

As such, it is clear that the enterprise-wide digital thread can only be enabled and supported by a robust digital systems architecture (i.e., one encompassing both the digital system prototype and the multiple digital twin artifacts) and will require a MBSE process that ultimately spans the entire product lifecycle. Many leading PLM solution providers want to be the preferred platform for achieving the digital thread vision. The leaders in PLM (and its various segments, e.g., MCAD, EDA, and S&A and even ERP, and MES) are actively investing today in building and providing some

² CIMdata Digitalization Research 2019 and 2020

level of IoT-enabled digital twin capability. Some are enabling data-driven twins only, while others also offer physics-driven twins combined with empirical data analytics. There are also a number of smaller providers of virtual prototyping and digital twin capabilities that fill vertical niches. Some are supplementing their digital twin offering with AR/VR hardware to enable human in the loop operations monitoring and training systems for mission critical assets in the construction, mining, heavy equipment, alternative energy, oil and gas production, marine, and shipping industries. Examples of these pioneering small companies are:

- Mevea Oy, Finland
- Akselos SA, Lausanne, Switzerland and Brookline, MA
- CM Labs Simulations, Montreal, Canada

Model-Based Systems Engineering

MBSE is a major industry initiative focused on moving away from a document-centric process for developing products to one that is based on digital information and models that better represent all aspects of a system's design. The International Council on Systems Engineering (INCOSE) defines MBSE as: "The formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later lifecycle phases."

Why do engineers want to use digital systems models versus documents? For the same reason that mechanical and electrical design over the past three decades has moved away from 2D paper drawings to 3D digital CAD representations created and managed within PDM systems. Documents tend to be much more static and can often become out-of-date even before they are published or formally shared with other people. Version management and data pedigree and traceability are extremely difficult if not impossible to create and maintain with paper records. Digital information is not static in nature and is much easier to continuously update, version, validate, trace, manage, and collaborate with across today's multi-domain and globally distributed product development teams.

The conceptual systems engineering process is often referred to in industry as defining the "RFLP" aspects of the system architecture design: Requirements, Functional, Logical, and Physical facets of the system. A key enabler in successfully implementing MBSE is integrating digital performance modeling and simulation (historically referred to as CAE or analysis) with the traditional systems engineering activities of requirements definition and allocation, systems architecture design encompassing the function, logical, and physical dimensions of the conceptual design as well as verification and validation of the system design. Trade studies conducted for evaluating and comparing conceptual design alternatives are a routine aspect of the systems engineering process. By leveraging today's advanced systems analysis and design optimization technologies in the design trade-offs process, systems engineers can identify the most promising design concept that best meets all of the cross-domain system requirements of today's complex cyber-physical systems

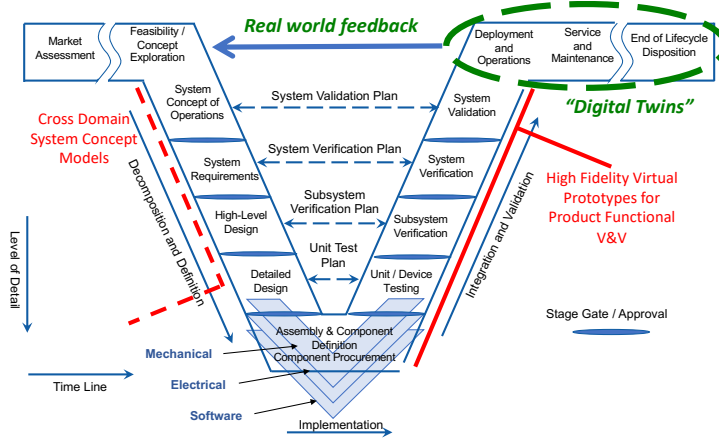
Companies have always faced intense competitive pressure to develop products better, faster, and cheaper. Digital modeling and simulation used in place of or in conjunction with physical testing and validation is a key enabler in accomplishing this business goal today, and this emphasis is expected to continue increasing substantially. As already noted, due to the exponential advances in computing resources, faster response (turnaround) times for more complex and larger scale simulations enable them to be used earlier and more often in the product development process to make conceptual design tradeoff decisions and optimize the functional performance of designs to meet stakeholder requirements at the systems level across multiple domains (mechanical, electrical/electronics, embedded software, controls, chemical formulations, cost, material specifications, etc.).

Traditionally, simulation has been used to assess the performance of pre-released designs and physical prototypes, validating them against a defined set of requirements. However, these requirements and the associated designs often change during the course of the product development process, not to mention over the entire product lifecycle when the products are in use by customers. To support this reality, verification and validation functions have become well established at many companies and simulation has been increasingly used earlier in the product development process, ahead of the commitment to detailed design and prototype hardware and manufacturing. However, using cross domain systems simulation up front involves a different set of engineering processes and issues than when simulation is only used as a final verification of a design at a subsystem or component level, or in only a single domain. CIMdata sees the adoption of MBSE strategies as a way to formalize this usage of simulation early and throughout the design process, and most importantly, to foster collaboration across domains to enable true concurrent engineering.

The Systems Engineering Vee is often used to depict the product development process, as shown in Figure 14. For mechanical product design, the base of the Vee is usually where detailed design (3D MCAD, EDA, and software) of individual design components occurs. The right side of the Vee is where validation and integration of the components into subsystems and systems is accomplished, ending with verification and validation of the final product design. The left side of the Vee represents the process of understanding system-level engineering requirements in the context of the Voice of the Customer (VOC) and then specifying in increasing detail (decomposing and allocating) the functional requirements for the systems, subsystems, and components.

The left side of the Vee also encompasses ideation, design synthesis, concept selection, and the definition of the overall system architecture. Here decisions are made that trade off competing system level requirements such as cost, weight, durability, performance, range, power, emissions, fuel economy, etc. Engineering on the left side of the Vee clearly is a systems engineering challenge.

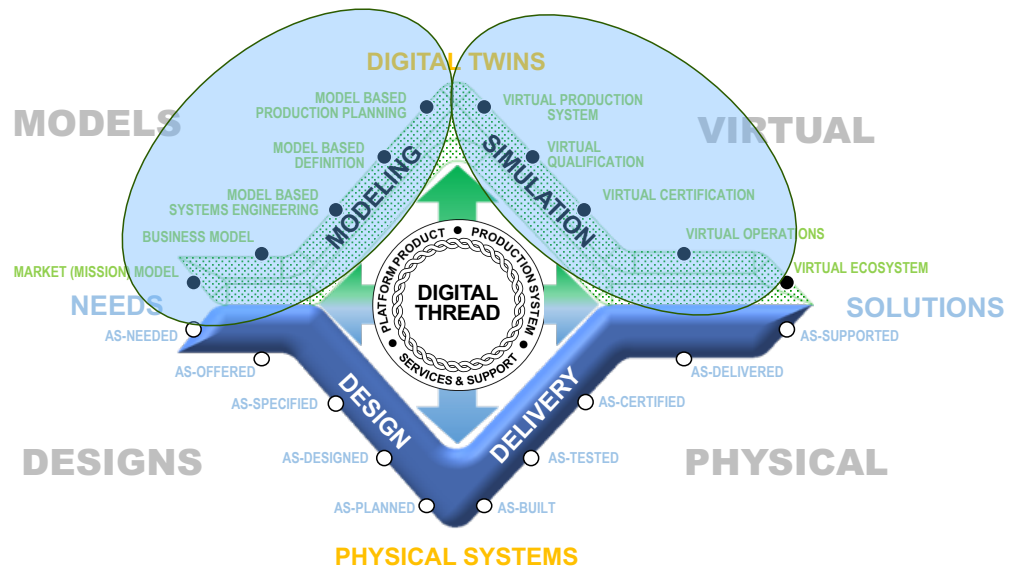
Figure 14:
Digitalization Enables
Model-Based Systems
Engineering Across the
Entire Lifecycle



Adapted from: US Federal Highway Administration: "Systems Engineering for Intelligent Transportation Systems" <http://ops.fhwa.dot.gov/publications/seitsguide>

An alternative view of the systems engineering Vee developed and promoted within industry is the Boeing "Diamond" (see Figure 15). This representation is broadly referenced within the industry as it better represents the in-synch and parallel lifecycles of the physical design process with the virtual design process. It also better communicates visually the modern concepts of the digital thread and the digital twin.

Figure 15:
The Boeing Diamond



Copyright © 2018 Boeing. All rights reserved. Used with permission.

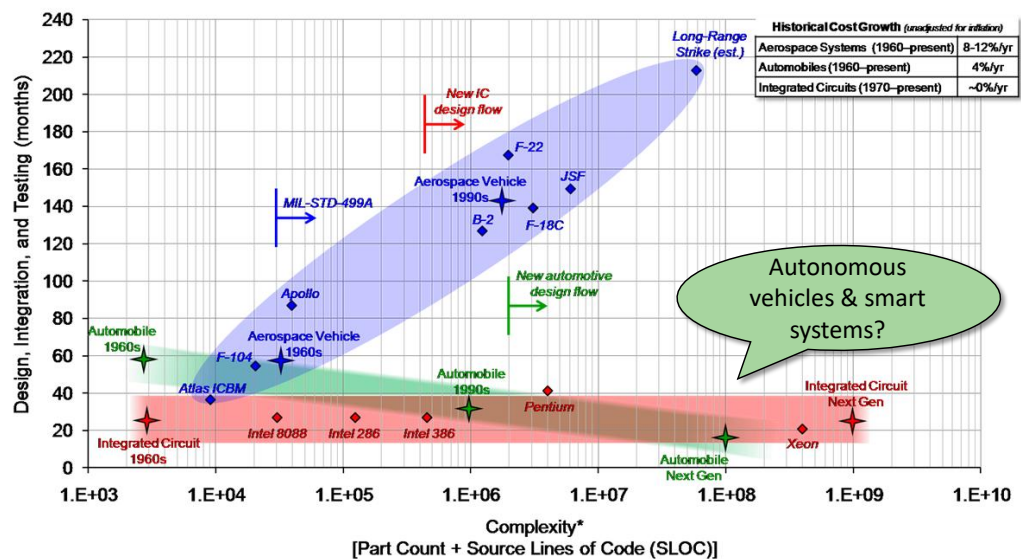
By necessity, simulation on the left side of the Vee requires a multi-domain, multi-physics, and multi-scale M&S capability within the integrated data and process framework of model-based systems engineering. As modeling and simulation are implemented up front for balancing performance to meet or exceed requirements, simulation must simultaneously comprehend performance requirements for many different physics phenomena, as well as for other related disciplines (e.g., controls, electronics, and software). For example, the design of a space optical device (e.g., telescope) demands coupling the structural, thermal, and optics analyses. In-vehicle

active sensors that regulate ride and handling control systems must also simulate the entire suspension as a flexible multi-body assembly.

Thus, system complexity today is caused not only by an increase in the number of physical components and assemblies in a product but also by the exponential growth of electronics, sensors, embedded software, and controls features in cyber-physical systems. The rapid growth of electronics and embedded software in almost all products is now a game changer in terms of delivering customer value and satisfaction in meeting the customer’s perceived utility of the product versus competitive alternatives. In addition, the IoT and Industry 4.0 are expanding the requirements for products to connect with one another (i.e., to become smart, connected products). Businesses need to adjust rapidly to this increasing cyber-physical product complexity to stay competitive and survive.

Some industries have already adapted to this business challenge while others are still in the process of dealing with change, as suggested in Figure 16. For example, the integrated circuit and chip design industry has continuously applied the latest digital systems design technologies over the past several decades to help significantly decrease costs and time-to-market. The automotive industry managed to drastically reduce physical prototyping costs and average time-to-market over the past two decades but now faces major new challenges from the rapid move to exponentially increasing software content, electrification, and autonomous control systems. The established aerospace and defense industry, a pioneer in the use of advanced systems design methodologies in the mechanical engineering domain, is nonetheless facing major challenges in designing, deploying, and maintaining the highly complex cyber-physical systems and “systems of systems” required by their customers today.

Figure 16:
Complexity Issues Cut
Across Industries



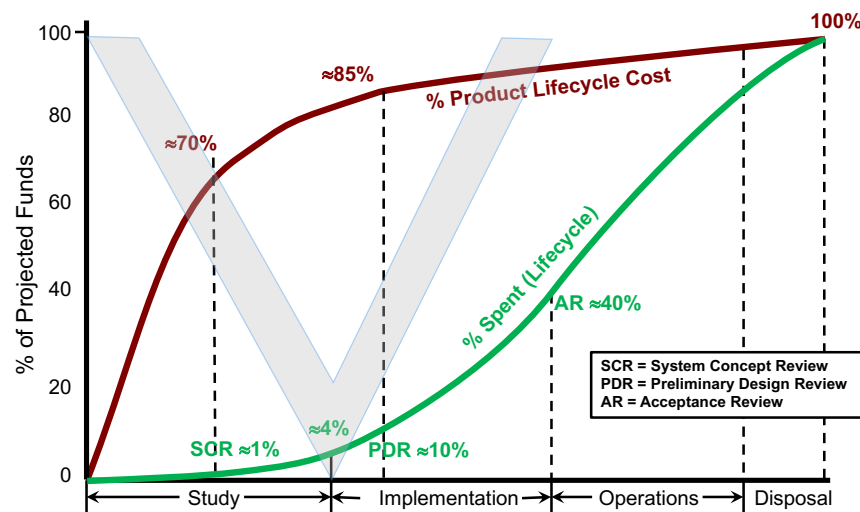
Source: DARPA Adaptive Vehicle Make Program, 2008

As an example, tomorrow’s autonomous vehicles will be highly complex cyber-physical systems that require systems-level engineering to advance to the next level of maturity. The vehicles are supported by hundreds of onboard sensors and

computers, all connected and controlled by on-board wireless networks and hundreds of millions of lines of embedded computer software code. In the world of the IoT, these on-board systems will continuously interact with other external systems in real-time to meet requirements for driving performance, collision avoidance, passenger comfort and safety, pedestrian safety, etc. While automotive and commercial aerospace are often seen as being at the forefront of applying model-based systems engineering methods and technologies, many other market leaders in heavy equipment and vehicles, manufacturing equipment, medical devices, consumer products, consumer package goods, and process and power are actively exploring and beginning to leverage MBSE strategies and are piloting implementation initiatives.

As suggested in Figure 17, the driving forces to adopt MBSE and M&S early in a project are program cost and product lifecycle costs. Studies over four decades have shown that the vast majority of total product lifecycle costs are determined by very early decisions in the product development process. Engineering on the left side of the Vee typically consumes less than 5% of a program's cost but determines more than 80% of the product lifecycle cost. The implications are tremendous.

Figure 17:
The Majority of Lifecycle
Costs are Committed
Early in the Product
Development Process



Adapted from: Forsberg, Kevin, Hal Mooz, and Howard Cotterman.
Visualizing Project Management. John Wiley & Sons. Hoboken, NJ. 2005.

As companies drive to up-front systems level modeling and simulation to improve early product decisions, they are driving toward ever higher fidelity multi-physics and multi-domain simulations to achieve true model-based systems engineering.

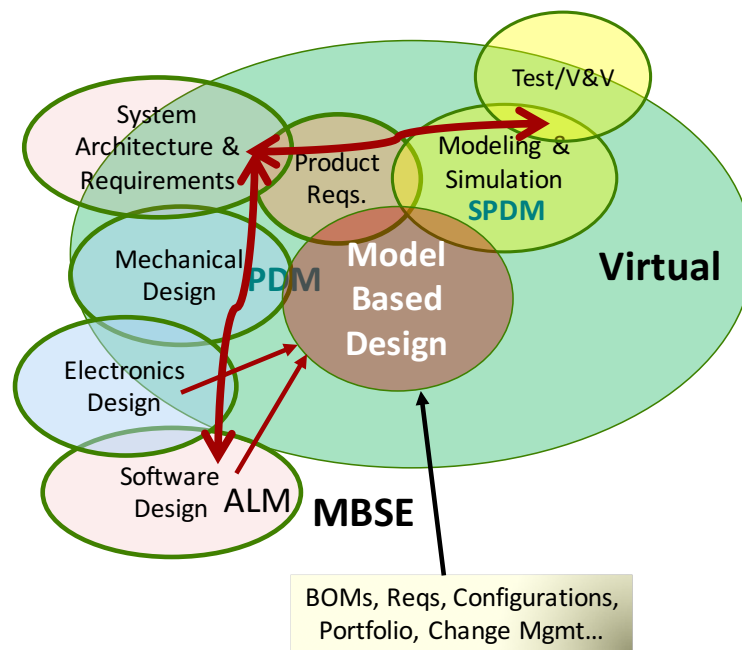
The use of systems engineering practices has been well established for software development and electrical system design for some time, much more so than for mechanical system design. Software development processes and tools have become quite mature over the past 15 years. Systems architecture modeling tools such as Unified Modeling Language (UML) and Architecture Analysis & Design Language (AADL) have been widely applied in the software and electronics domains but were largely absent from the mechanical aspects of system designs until very recently. With the development and application of the SysML language standard, used

predominantly in aerospace, defense, and space systems applications to date, we are now seeing formal systems modeling tools employed to support the mechanical systems design aspects across many other industries.

As noted previously, today’s products are no longer simply mechanical systems. A modern automobile contains hundreds of microprocessors, more than a hundred million lines of computer code, and several operating systems, with thousands of software parameters. As such, systems engineering is a critical enabler for the concurrent design of mechanical, electrical, and control systems and the implementation of concurrent engineering techniques for verification and validation of these complex systems via MiL/HiL/SiL techniques. With the growing use of virtual and augmented reality, we are also now faced with virtually modeling the “human-in-the-loop.”

Increasing product complexity and interdependence across these domains is now driving systems engineering to holistically account for all of these engineering disciplines, including mechanical, electrical, embedded software, control systems, and other physics-driven domains, such as materials engineering and optics design as well as key non-physics design aspects such as cost. The physics-driven domains will become increasingly important as intelligent sensors become the virtual eyes of systems interacting with other systems in the IoT and Industry 4.0 landscape of the future. Conceptual design of modern cyber-physical systems cuts across many design information domains that need to be connected. See Figure 18.

Figure 18:
MBSE Links
Requirements with the
Model-Based Design
and Engineering
Domains



A model is a digital description of one or more aspects of a product. In this regard, a digital prototype virtually represents selected aspects of a product’s or manufacturing system’s functional performance. Such models are created for mechanical, electrical, software, and control system behavior for products. Models from one domain can often be used as surrogates in another domain to enable

concurrent engineering. For example, a control system can be developed before the actual electronic or mechanical hardware is available and then used in a system level co-simulation when the hardware model becomes available. This is the basis for the evolving paradigm of MBSE.

A serious concern here is quality assurance of the control system software deployed with the product, particularly when safety issues are involved. There have been several serious and widely publicized product failures in the automotive and aerospace industries over the past several years. These failures were attributed to a shortfall in the systems engineering process, especially as it relates to the role of electronics and embedded software and their associated digital validation models used for safety certification. As a result, safety-related standards such as ISO 26262 in automotive and DO-178C in aerospace/defense are becoming increasingly important in the development of cyber-physical systems.

Several solution providers have taken the lead on addressing this industry issue. Ansys has pioneered certification of their SCADE/Simplorer system simulation capabilities for use in the nuclear and automotive industries, while MathWorks introduced tools to enable a more rigorous implementation of systems engineering, including systems level requirements management and failure mode analysis within their MATLAB/Simulink suite. INCOSE has published an MBSE roadmap that now extends beyond 2025. The move to MBSE is not a fad or short-term trend. It is also not intended to replace traditional systems engineering best practices or totally eliminate the need for documents, presentations, and other materials as a means of communication and collaboration. But in CIMdata's view, MBSE will indeed be a required foundational element for product development in the future, especially for designing, building, and continuously maintaining complex cyber-physical systems.

To quote Mr. David Long, recent past President of INCOSE and current CEO of Vitech Corporation, a supplier of MBSE technology and services that is now part of Zuken, "Model-Based Systems Engineering is the future of Systems Engineering and is in fact Systems Engineering. They are conceptually one and the same."

There are a number of technology and business drivers for the move to implementing a systems engineering process throughout the lifecycle. This includes going beyond implementing MBSE for up-front engineering but also for detailed design and validation, manufacturing, and in-service operations. Among these drivers are:

- *Focus on Systems, not on Components:* The component design capabilities of most companies have improved remarkably over the past few decades, to the extent that component design is no longer much of an issue. The focus is now on overall performance in the context of systems or subsystems. Why? Because customers buy products and systems that meet their needs and are reliable. Consumers really don't care what specific components are inside the system to make that value a reality.
- *Optimization and Robust Design:* Robust design is a probabilistic method for design optimization. It seeks to maximize design performance and simultaneously minimize the sensitivity of performance with respect to

variation in manufacturing and customer use, among other factors. Robust design and associated optimization techniques help users explore the design space by assessing hundreds, or even thousands, of design alternatives. Robust design is critical to support effective trade studies that define and optimize the key system design factors such as functional performance, cost, reliability, etc., early in the concept stage when the design can still change without large cost and time penalties.

- *Regulation and Compliance:* European organizations, and the global automotive industry in particular, have led the way in developing regulations and standards related to safety, fuel and energy conservation, and other performance concerns. CIMdata expects to see even more focus on standards dealing with the certification of embedded software systems such as ISO 26262, an international standard for functional safety of electrical and electronic systems in production automobiles defined by the ISO in 2011.

The US DoD also requires digital system models to be used in many new acquisition programs to facilitate collaboration and improve communication between DoD and its suppliers. SysML is one such descriptive and graphical system modeling language that essentially replaces the use of document-centric methods traditionally used for systems engineering. SysML derives from UML, a modeling language that has been widely used for decades within the software development domain.

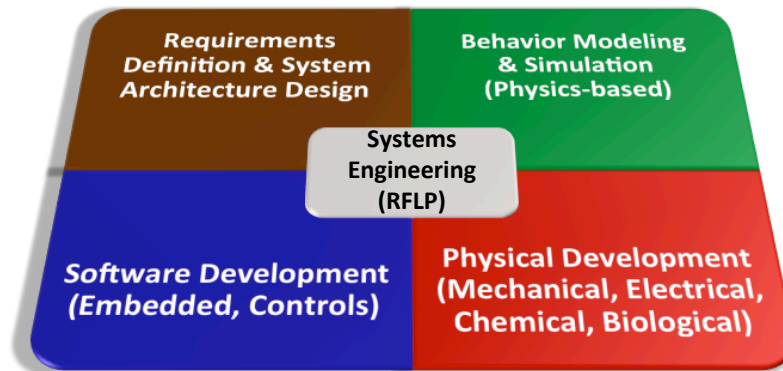
Systems engineering methods are also an implied requirement in highly-regulated industries, such as medical devices, pharmaceuticals, utilities and power, and commercial aerospace, where companies must thoroughly document their development processes and the pedigree of product-related data in addition to meeting specific regulatory requirements. In fact, recent CIMdata industrial consulting has focused on helping companies in many other industries, besides aerospace and defense, to adopt systems engineering principles to foster product innovation, reduce future recalls, enhance design traceability, and facilitate regulatory compliance.

Companies are looking to their product development solution providers for the right offerings to support today's more complex systems requirements and integrate engineering data and processes across the current domain silos in mechanical, electrical and electronics, controls, embedded software, optics, biological, and chemical engineering. Ideally these domains would be tightly integrated, but looser connections can work in the short term. This is important not only to support work with tools from multiple solution providers within and across the various engineering domains but also to accommodate customer-developed proprietary technology and in-house software tools. End users want the flexibility to leverage whatever technology best meets their requirements vs. total cost of ownership over time.

This is indeed a tall order and no single PLM solution provider can provide an integrated product innovation platform that covers all the required breadth and depth at any time in the near future (see the systems engineering Vee in Figure 14). Therefore, the product development solutions of the platform providers, as well as the niche tools in each of these domains, must be open and standards-based by

design to meet the industry needs. PLM, S&A, and MBSE solution providers seeking to offer multi-domain MBSE capabilities now originate from different engineering domains and expertise as shown in Figure 19. As noted, the boundaries between these traditional domain silos are becoming increasingly blurred due to industry M&A activities.

Figure 19:
Engineering Domains
are Supported by Many
Overlapping MBSE
Solutions



Physics-Based System Simulation and Co-Simulation

Many disciplines use tools for simulating system performance based on lower fidelity 0D, 1D, or mixed fidelity representations of the product design. These tools help bridge the analysis gap between the physical and virtual aspects of a system and are typically used prior to the design being fully conceptualized from a 2D or 3D perspective. MATLAB/Simulink is a ubiquitous and widely used modeling and calculation tool in the systems realm, as is Microsoft Excel, but there are many other commercially available software tools. Examples include Dymola from Dassault Systèmes, AMESim from Siemens, Simplorer from Ansys, MapleSim from Maplesoft, SimulationX from ESI Group, GT-Suite from Gamma Technologies, OPTIMICA from Modelon, and Wolfram System Modeler.

Electronic Design Automation (EDA) tools also offer systems-level simulation capabilities that focus primarily on the electronics and software performance aspects of a design. However, even those suites are beginning to move across the boundaries into the mechanical and physics-based domains such as integrated thermal and flow analysis capabilities. Examples of commercial tool suites in this domain include SABER and Simpleware from Synopsys, Design Gateway from Zuken, Clarity 3D Solver from Cadence Design Systems, and Vista and Flotherm from Siemens.

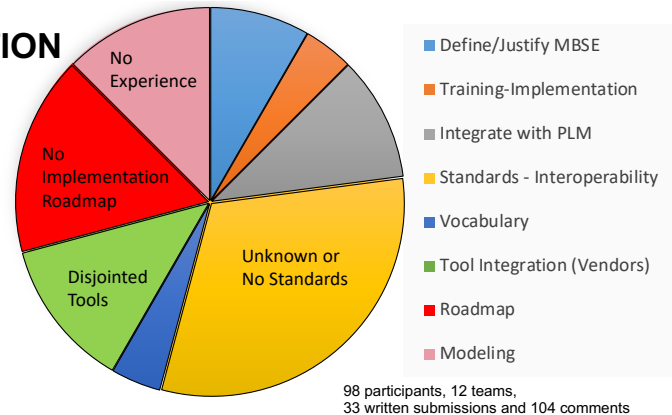
Data and Model Interoperability Standards

According to a number of industry standard organizations, the lack of widely accepted and mature standards for digital model interoperability has been identified as a major barrier to implementing effective MBSE processes. One such group of aerospace and defense companies that meets annually is the Global Product Data Interoperability Summit (GPDIS). A subset of the attendees conduct a one-day MBSE Workshop each year to learn about developments and best practices in the area of MBSE and to identify challenges for the industry. A survey of the MBSE user

attendees is conducted each year and the results of the 2018 workshop survey identifying standards as a major gap are highlighted in Figure 20.

Figure 20:
Implementation Issues
in MBSE

IMPLEMENTATION ISSUES



Courtesy of GPDIS

For this reason, there is a strong drive towards the definition and adoption of industry standards to enable common languages, data interoperability, and model co-simulation across the multiple engineering domains and the hundreds of S&A tools used in industry today. Heterogeneous software environments are a reality that is not going to go away any time soon (perhaps ever) despite the best efforts of the major solution providers to provide integrated S&A platforms that address all the functional needs of industry. Standards bodies such as ISO/STEP, PDES Inc., the Object Modeling Group (OMG), OASIS Consortium, and the Modelica Association are actively engaged in collaborative projects involving members from both the end user and solution provider communities.

Within the physics-based behavior modeling realm, the Modelica modeling language and the Functional Mock-up Interface (FMI) standard for co-simulation of dynamic systems have gained widespread acceptance and adoption within many industry segments over the past decade. Modelica was developed as a common computer language for modeling components and systems and enables open-source collaboration of component models. The FMI and associated Functional Mock-up Unit (FMU) definition is a specification that enables data interchange during co-simulation. FMI/FMU has seen strong end user demand and rapid industrial adoption. While not technically authored by a traditional data standards group such as ISO/STEP or OMG, FMI has quickly become a de facto standard in the automotive industry as well as other industries. The joint System Modeling and Simulation Working Group between NAFEMS and INCOSE is promoting its widespread use across all industries. This type of tool independent cross-domain modeling and simulation capability is essential for achieving MBSE and lifecycle design collaboration. It provides the means to share subsystem models to create simulations reflecting the entire system. For example, system simulations can help optimize thermal performance and fuel economy for vehicles and support development of control systems. With cross-domain capabilities, it is no longer necessary to model the entire vehicle system and all its subsystems and components in a single systems modeling and simulation application such as MATLAB/Simulink,

Simcenter AmeSim, or MapleSim. Subsystems and components modeling in other software tools such as 3D FEA can be shared as FMUs for use in systems level simulation tools.

The Modelica Association has recently developed an extension to the FMI specification called System Structure and Parameterization (SSP) to support components for virtual system design. In many applications there is the need to design, simulate, and execute a network of components (simulation models, software, hardware etc.). To be able to do this independent of tools used and seamlessly, this Modelica Association SSP specification:

- Defines a standardized way to store and apply parameters to components.
- Defines a standardized format for the connection structure for a network of components.
- Assures that the developed standard and any associated APIs should be usable in all stages of the systems development process (architecture definition, integration, simulation, test in MiL, SiL, HiL).

The new Modelica Association standards for SSP and the Distributed Co-simulation Protocol (DCP) build upon the FMI/FMU concepts to enable co-simulation of complex cyber-physical systems while using a heterogeneous set of modeling and simulation tools.³ SSP is already gaining widespread acceptance within automotive and vehicle industry OEMs as a foundation for enabling digital MBSE processes that support system architecture design integrated with behavior optimization and validation.

Other current notable standards that support MBSE modeling and simulation interoperability are:

- SysML is a general-purpose modeling language designed for cross domain systems engineering applications. It supports the specification, analysis, design, verification, and validations of systems and systems of systems across a broad range of industries. SysML was originally developed by an open source specification project and includes an open source license for distribution and use.⁴
- Open Services for Lifecycle Collaboration (OSLC) is a methodology for linking data across disparate enterprise authoring and data archiving systems based on W3C Linked Data web standards such as HTTP/URIs and RDF/XML.
- Requirements Interface Format (ReqIF) is an XML file format that can be used to exchange requirements, along with their associated metadata, between software tools from different vendors.

³ For more information on Modelica Association activities see <https://www.modelica.org/>

⁴ SysML is defined as an extension of a subset of the Unified Modeling Language (UML) using UML's profile mechanism.

- Object Process Methodology (OPM) is a conceptual modeling language and methodology for capturing knowledge and designing systems, specified as ISO/PAS 19450.

Unfortunately, standards for exchange of requirements and system architectures (commonly referred to as RFLP—the requirements, functional, logical, and physical aspects of systems design) are widely recognized as a major gap in fulfilling the promised business benefits of MBSE and the digital thread. Systems architecture modeling languages such as UML/SysML, MARTE, and AADL continue to evolve to meet the needs of targeted segments of the systems engineering community but progress has been much slower than desired limiting industry adoption. For example, it has been over 13 years since the original OMG SysML v1.0 standard was released. While there have been incremental updates on a regular basis (v1.6 is the latest version), the formal approval and release of the SysML v2.0 specification to industry still remains 1- to 2-years away.

Interoperability of SysML models across the various solution provider authoring environments is currently very poor. As this report goes to press, it is still not clear if the SysML 2.0 standard will adequately address this heterogeneous tool interoperability issue. In fact, the expectation in industry is that it likely may not. As a result, some smaller vendors are emerging who attempt to fill the gap; a similar situation to MCAD 3D model interoperability in the 1990s. Also, there are a number of open source tools used to enable systems architecture modeling emerging as a complement to or even as an alternative to the SysML-centric authoring tools. Prominent examples include Capella, based on the Arcadia methodology, and Papyrus. Both are open source tools available from the PolarSys/Eclipse Foundation. The Arcadia methodology and framework was originally developed by engineers at Thales Aerospace from 2005 to 2010. Thales still provides significant resources for ongoing software development and support for Arcadia/Capella, which is also supported by the Eclipse Foundation as well as commercial companies such as OBEO.⁵ While not an international standard per se, Capella usage by systems engineers is growing rapidly, especially in the European aerospace and defense community.

Another important initiative is the Open Model-Based Engineering Environment (OpenMBEE), initially developed by NASA's Jet Propulsion Laboratory (JPL), that is now supported by a volunteer community of companies including JPL. OpenMBEE is an open source community designed to create an integrated environment for engineering that is driven around models and capabilities that support model-based approaches. Such open environments are designed to serve multiple modeling languages as well as a variety of techniques for model checking, simulation, document generation, etc. In addition, OpenMBEE GitHub has a variety

⁵ For more information on these industry groups and open source systems modeling tools see:
<https://www.eclipse.org/>
<https://www.polarsys.org/>
<https://projects.eclipse.org/projects/polarsys.capella>
<https://www.obeo.fr/en/products>

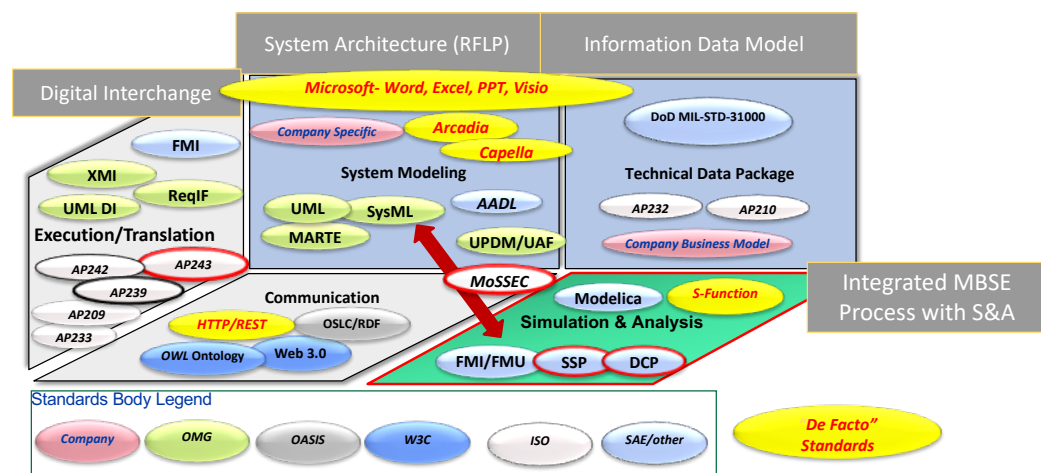
of open source projects supporting this pursuit as well as contributed open source models.⁶

An emerging initiative still in the process of becoming a formally released ISO standard is Modeling and Simulation in a Systems Engineering Context (MoSSEC). MoSSEC is designed to enable the sharing and exchange of modeling and simulation information in a collaborative systems engineering context. It includes support for traceability to both PLM/PDM and system engineering solutions where the system design data is typically created and managed. This new standard, emerging from the ISO/STEP standards community, is targeted at capturing and bringing together the key process metadata (i.e., the who, what, when, where, why, and how) associated with performing MBSE. This proposed standard is an extension of the existing STEP AP239/AP242 data architecture. The MoSSEC standard is now under industry review with formal release of AP 243 expected during 2021.

In addition to the formal industry group standards cited above, it should be noted that there is still widespread use of other tools and data formats that have become de facto standards for enabling systems design collaboration. The most obvious example is the Microsoft Office suite. Word, Excel, PowerPoint, Visio, and Project are used extensively in the engineering domain across all industries. Many early systems engineering efforts are still performed primarily in these tools with the information exchanged via the ubiquitous Microsoft file formats (e.g., .xls, .doc, .ppt, .vsd). Visual data standards such as 3DPDF and JT are also widely used in engineering communities to share design information digitally and to support collaborate, but while digital in nature, these are not really model-based methods.

Viewed from a product development process perspective, there is a need for data and model interoperability standards that can connect the key system design information across engineering domains as well as across the lifecycle. Figure 21 captures a high-level view of what are currently seen as some of the key standards for data and model interoperability needed to enable conceptual systems design and development.

Figure 21:
MBSE Emerging
Standards Landscape

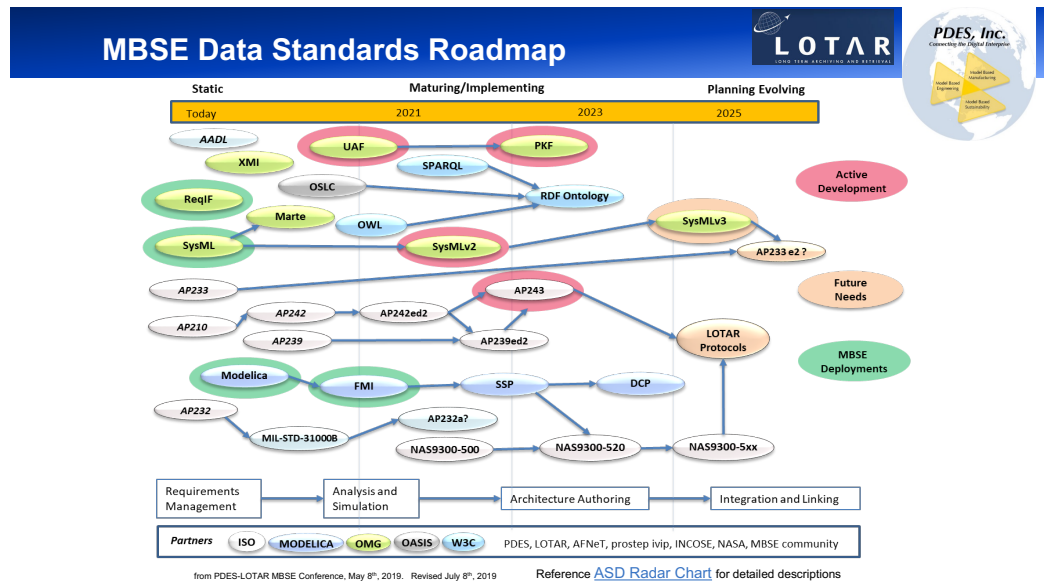


⁶ For more information on OpenMBEE see: <http://www.openmbee.org/>

Adapted from: Chown, Bill. Mentor Graphics. MBSE Roundtable. Global Product Data Interoperability Summit. 2015.

Industry groups such as the LOTAR Initiative (Long Term Archiving and Retrieval) and PDES Inc. (Product Data Exchange Specification), AFNet, ASD-STAN (Standardization), prostep ivip, and the CIMdata Aerospace & Defense PLM Action Group (ADPAG) continue to collaborate on defining an MBSE data interoperability standards roadmap for the industry to agree upon and adopt. The latest version of that roadmap can be seen in Figure 22.

Figure 22:
MBSE Emerging
Standards Landscape



Simulation Process & Data Management

End user interest in Simulation Process and Data Management (SPDM) has grown substantially over the past decade. As we move toward digitalization and look to realize the business benefits of model-based systems engineering processes working with PLM, and the digital thread and the digital twins functioning with other enterprise platforms such as ERP, MES, and MRO within the construct of Industry 4.0, companies will need to better manage simulation models, results, and related design information; improve collaboration and reuse; and better integrate simulation activities into the PLM environment. Doing this supports a wider audience of product development engineers, engineering managers, product line managers, and others in the extended organization and supply chain who can benefit from access to the S&A information to make informed decisions. Companies are realizing huge gains by developing and automating selected processes that leverage their managed S&A data and processes. Analysis processes can be reduced from months to days or even hours. For example, automotive crash, safety, and NVH analysis can be drastically shortened by automatically generating large and complex 3D finite-element (FE) models for 3D body-in-white structures on HPC facilities in overnight processes. Similarly, the structural certification of large aerospace systems such as commercial aircraft require an extensive level of 3D computer modeling to ensure that the certification test aircraft meets or exceeds the aircraft performance requirements as well as the FAA safety specifications. So, despite the significant cost

of implementing an enterprise level SPDM system, the business case and the return on investment to implement SPDM have been compelling.

Even so, the effective adoption of SPDM by industry has been relatively slow over the past 20+ years, especially outside of the major automotive and aerospace OEMs. The real adoption rate within mainstream product development activities has been extremely disappointing from a business impact perspective. Industry estimates are that fewer than 10% of all simulation and analysis specialists worldwide use some form of commercial simulation data management technology to manage and archive their S&A models and to collaborate with other simulation specialists as well as other design disciplines within their organizations. Unfortunately, the most common form of SPDM in practice today is still the use of personal hard disk storage on the S&A engineer's desktop or perhaps a shared drive used in common with other members of their immediate organization. Naming and versioning of simulation models and results is haphazard at best and totally inconsistent in the worst cases. Contextual metadata (e.g., the who, what, when, where, why, and how) about the simulation model is typically incomplete or even non-existent. Standards for what metadata is required and its format are lacking in consistency and robustness. All of this makes the traceability and pedigree of simulation models and results extremely difficult if not impossible to accomplish and can lead to a lack of confidence in the accuracy of the simulation results vs. physical test data obtained from in-lab and prototype testing as well as from product in service data.

Another adoption issue is that current commercial SPDM technology was developed primarily for deployment in the 3D modeling and simulation area (e.g., FEA, CFD) so it lacks effective support for models and information generated from 0D/1D systems modeling which is critical to implementing an MBSE approach beginning early in the conceptual design of today's cyber-physical products.

A notable exception to the statement above is the Simcenter SysDM capability available from Siemens, obtained via the LMS acquisition. Its model and metadata management capabilities for 0D/1D system analysis are now being enhanced and integrated to work in concert with the Teamcenter platform as part of the Teamcenter for Simulation capabilities. MathWorks also provides a basic level of systems model management capability but is limited to data developed while working within their platform.

However, all of the major S&A solution providers are now recognizing the need to manage systems level simulation data and we expect to see significant progress in this area over the next several years. Of note is the acquisition of Comet Solutions by Aras Corporation in late 2018. Aras has now released an initial SPDM offering built on the Aras Innovator platform with a flexible and multi-fidelity data model leveraging the integration of the Comet abstract modeling approach. The first commercial SPDM solution from Aras released during Q4, 2020 in conjunction with the new System Architecture application.

It is also interesting to note that the Aras Innovator platform is the basis for the Ansys Minerva SPDM offering announced in late 2019 and commercially released during 2020. Ansys is building its SPDM applications on top of the Aras Innovator

platform and delivers that core capability to all of its SPDM customers. Given the market leadership and scale of Ansys, this could lead to much broader adoption of SPDM within the Ansys customer base, as well as the industry as a whole.

Simulation, Analysis & Validation Governance

In CIMdata's opinion, the problem of adoption is not simply one of technology. SPDM adoption plans must also address: 1) people (organization/culture/training) and 2) process (S&A best practices, synchronization with physical verification and validation, an implementation maturity model roadmap, and associated governance plan) as two other essential elements. People, culture, and organization factors are often the most challenging aspects of successful SPDM adoptions, not the technology requirements. In response, CIMdata has adapted and applied a proven maturity model methodology for SA&V implementation to help companies with their overall modeling and simulation governance strategies and the development of detailed implementation roadmaps, including SPDM and its integration with PLM.

A simulation, analysis and validation governance vision, strategy, and plan should be the first step on the path to implementing a SPDM system. Why is this the case? The increasing reliance on virtual prototyping and simulation to support product development decisions underscores the need for a governance framework to capture and manage systems modeling, simulation and analysis data, knowledge, and best practices as a strategic capability that can be used to validate and optimize design decisions throughout the entire product lifecycle. The validation aspect includes not only those activities performed in the virtual realm but also their connection with physical test data and empirical-based product knowledge that can complement and improve the accuracy of and confidence in virtual simulation activities.

Governance is about managing, within an overall enterprise product innovation framework, the core engineering approaches to product development. Amid the explosive growth of computer-aided engineering and model-based systems engineering, a product innovation framework embraces and supports model-driven product development throughout the lifecycle. SA&V governance is a corporate strategy to manage specific lifecycle processes, solutions, and technologies regardless of how and where they are used in the enterprise.

Fundamentally speaking, governance is a structured way to ensure technical competence around SA&V and to continuously improve its level of maturity across the organization. The focus includes capturing and re-using best practices, standardized work processes, embedding quality assurance within FMEA activities (leveraging both simulation and test), integration of product development with manufacturing, and now, with IoT and Industry 4.0, collaboration across the extended enterprise over the full product lifecycle.

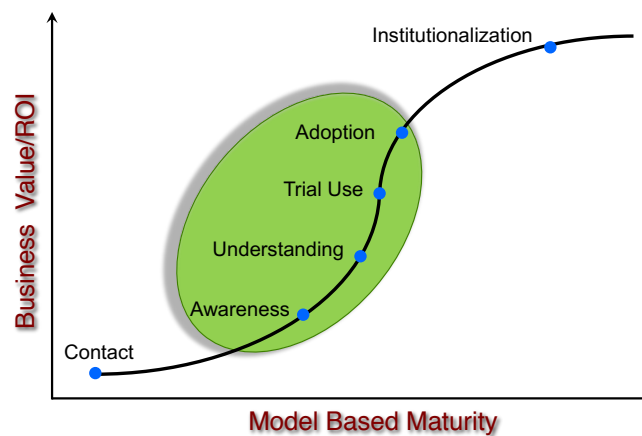
In practice, this means governance is a strategy to impose coherence and consistency through standards, both ad-hoc and formal, across all the "silos of expertise" in engineering and product development. Lest coherence and consistency bog down in rules, a Governance Council is put in place to foster flexibility and innovation within the enterprise. Council members are typically S&A experts, managers, and leaders with both practical hands-on and digital product development experience as well as

interpersonal persuasion skills and authority within the organization to push improvements through to conclusion.

SA&V Governance is a strategy that extends across all levels of the organization, which should establish:

- Support for SA&V across design, simulation, and testing functions and awareness of its value at the highest levels of corporate management.
- Understanding of the role of SA&V, as well as strategies to democratize SA&V by making simulation results and information available to a much wider audience of people in product development roles.
- A cultural environment in which to develop and nurture SA&V as a strategic competence.
- Integration of SA&V as an integral component of a company's product development strategy, IT infrastructure and other lifecycle product development processes such as digital twins.
- A rigorous focus on SA&V quality, including documented standard work processes and the verification and validation of SA&V as fit for purpose for every case in which it is applied.

Figure 23:
Business Value Comes
with Adoption Maturity



The use of well-established organizational process improvement techniques such as Six Sigma and CMMI-based maturity models fit well within the context of supporting a formal SA&V governance structure. As illustrated in Figure 23 business value comes with adoption maturity—to achieve value takes time, management and general commitment, and cultural change management.

Cloud Computing and Software as a Service (SaaS)

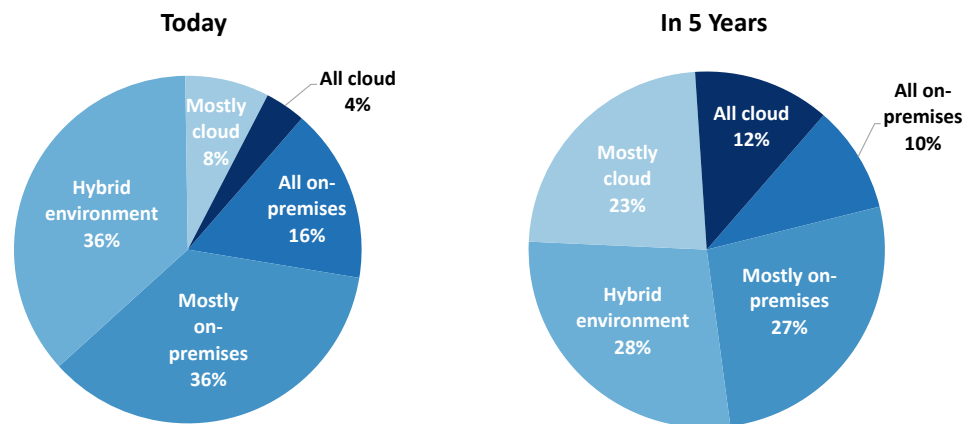
The widespread adoption of simulation stands to benefit significantly from cloud computing and SaaS business models in a number of ways. Simulation providers as well as third-party IT providers are now making S&A applications available in the cloud with a variable, “as used” price, as is common for SaaS pricing for other types of application software. This may ultimately reduce the burden on end user companies to provide the infrastructure and IT integration skills to deploy simulation inside their organizations. Cloud deployments also offer a solution for peak or

“burst” HPC requirements even in large organizations that have significant in-house S&A capacity and access to niche S&A application software that is needed only intermittently, such as on a project-specific basis.

Significant issues like cost, software licensing, data transfer, and security must be addressed, but the trend towards cloud computing is unmistakable. Altair, Ansys, and other S&A companies have their own enterprise-scale cloud offerings, while they and other PLM leaders such as Siemens and Dassault Systèmes SIMULIA have also partnered with cloud resource providers such as UberCloud, Rescale, TotalCAE, Penguin Computing, and Amazon, and Microsoft to make an ever growing range of simulation capabilities available on the cloud.

In a market research survey conducted by CIMdata in co-operation with Altair during the first half of 2020, CIMdata queried the S&A industry’s view of the cloud’s role for performing simulation and analytics. CIMdata asked respondents: “How aggressively has your company embraced moving data analytics and simulation activities to the cloud today? Where will you be in five years?” Figure 24 summarizes the results, which suggest an increase in cloud-based solution adoption.

Figure 24
Moving S&A to the
Cloud



The biggest impact of the cloud and SaaS is likely to be in the democratization of simulation. Web-enabled apps will provide mobile 24x7 access from any device while also reducing software licensing cost, security, and installation concerns. In this way, simulation tools can be made available economically to a much wider audience, especially for small- to mid-size companies. There are also some relatively new start-up providers of simulation applications that have been built from the ground up to be web-centric and cloud enabled. One example of such a company is SimScale GmbH. Founded in 2012 and with offices in Munich, Boston, and New York City, venture capital-backed SimScale claims to be the world’s first production-ready SaaS application for engineering simulation. SimScale provides instant access to CFD and FEA capabilities using a cloud-based application accessible to any designer or engineer in the world through an easy-to-use Web browser interface.

SimScale is growing at well above the overall S&A market rate and received a Series C funding round of €27 million in 2019. While their current annual revenues are not publicly available, SimScale claims to have over 70 employees and over 150,000

industrial users of their technology. The SimScale software portfolio can be purchased at 3 different levels of access and scalable price points—single user, teams of up to 5 users, and enterprise-wide licenses.

OnScale (<https://onscale.com/>), another relative newcomer to the S&A market, provides a cloud-based platform for simulation and analysis using a SaaS business model. OnScale's computer-aided engineering tools are based on proprietary multi-physics solvers that were developed and validated over 30 years by one of the largest engineering consulting firms in the world for DARPA, the U.S. Department of Defense (DOD), and large commercial customers. OnScale and its R&D team were spun out of Thornton Tomasetti in 2017.

OnScale's CAE solvers were architected for highly parallel mainframe computers to handle very large engineering simulation problems and are a perfect fit for modern cloud-based, high-performance computing. OnScale claims to provide highly accurate simulation results up to 100x faster than legacy CAE offerings. Current OnScale solutions are targeted to address the simulation needs of semiconductor and MEMS, 5G mobile, next-gen biomedical, and autonomous vehicle markets.

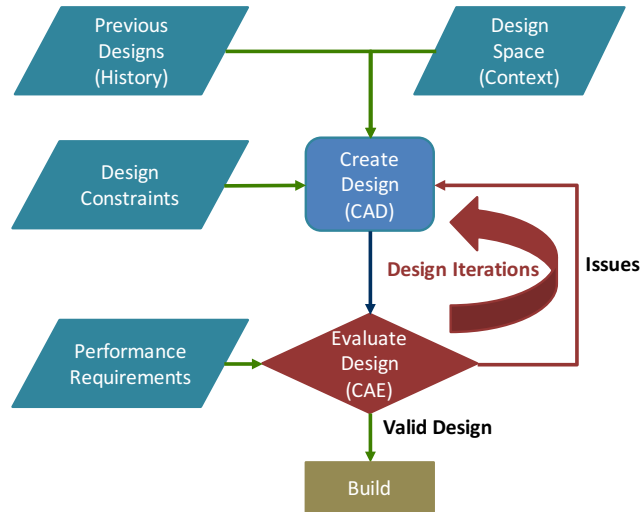
In concert with the movement to product innovation platforms, it is likely that in the not too distant future, the cloud and web-based standards will become the common IT infrastructure. This shift will make it practical for all PLM and S&A solution providers as well as end users of all sizes to have ready, affordable access to the required functionality for enabling model-based systems engineering and the digital thread.

Generative Design and Generative Engineering

The concepts of Generative Design (GenDes) and Generative Engineering (GenEng) are rapidly gaining the attention of industry, as well as all of the major MCAD and S&A solution providers. GenDes proposes to use algorithmic methods to develop designs (geometry and material selection) based on requirements and constraints. It often leverages topology optimization in concert with additive manufacturing techniques to effect or develop a new product design process. Generative designs are often, but not always, based on simulations of the structural physics. Examples include topology and shape optimization, parametric rule-based CAD, and optimized truss design using a catalog of available beams. Autodesk has applied a GenDes approach to architecture, engineering, and construction (AEC) use cases and their 2020 acquisition of Spacemaker greatly expands their capabilities with cloud-based AI/GenDes technology designed to help architects, urban designers, and real estate developers make more informed early-stage design decisions faster.

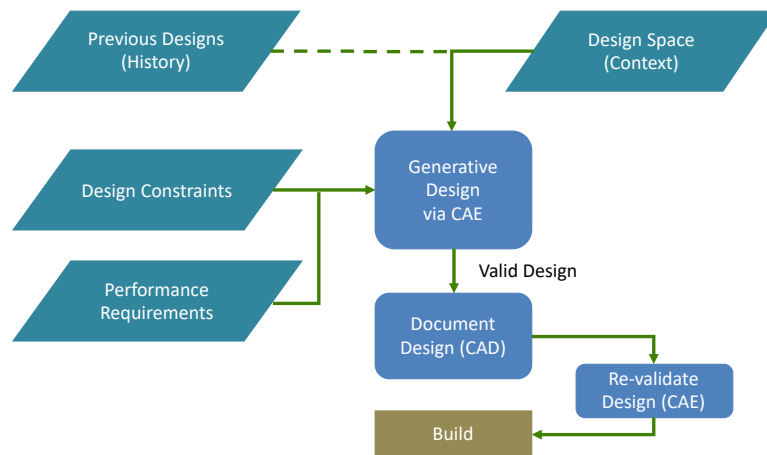
Traditional development processes generate CAD based largely on experience and previous designs as shown in Figure 25. Then, when the design is complete, simulations or tests are used to evaluate the design's performance against its requirements.

Figure 25:
Component Design
Process



Generative design uses the requirements and constraints up front to create the design (see Figure 24), with simulation, optimization and validation being done continuously throughout the design activity.

Figure 26:
Generative Design
Process



Note that GenDes depends much less on previous designs and experience than does the traditional design process. GenDes turns the traditional process of design, build, and evaluate on its head; in the GenDes vision, all possible designs need to meet the requirements.

Topology optimization is an important tool for GenDes. Shape optimization was developed during the 1980s and topology optimization a decade later. These techniques typically optimize geometry to meet strength, stiffness, or other physics-based requirements while minimizing weight.

The complexity of geometry optimization tools is still an issue that adversely impacts their adoption. In addition, optimized shapes are very often difficult to realize as CAD geometry and may be difficult to manufacture using conventional means such as casting, stamping, or machining. Software providers have mitigated these issues by considering manufacturing constraints in the optimization software.

The advent of additive manufacturing is thought to be a solution, particularly for the organic shapes generated by topology optimization. Indeed, there have been notable successes. Companies such as GE Aviation (formerly GE Aircraft Engines) and MOOG, Inc. continue to devote substantial resources to researching and applying additive manufacturing capabilities for key structural parts such as turbine blades, fuel injectors, and rocket control valves.

However, additive manufacturing has constraints. Material properties are often not homogeneous and may be impacted by the part's orientation during manufacturing. On the other hand, it is now possible to use multiple materials when making a single part and to make parts that are not easily made by other manufacturing processes. Clearly, additive manufacturing capabilities and material properties need to be included in the overall part geometry optimization process.

Realizing the results of topology and shape optimization using CAD models is still difficult. Frequently, it is preferable that additive manufactured parts not be solid but rather composed of lattice or honeycomb structures. Conventional CAD systems are often ineffective for defining such structures, either to create the starting geometry for an optimization or to contain the optimization results. Some have suggested going from optimization to additive manufacturing without using CAD tools. Yet, the fact remains that CAD is often required to document the final design and support the generation of other product information such as manuals and regulatory reports.

The end-to-end process for generating and manufacturing parts using topology optimization remains very difficult. It is clear there are unmet technology requirements to improve design and optimization for additive manufacturing. A recent CIMdata analysis points out the deficiencies in optimization, CAD, CAE, and additive manufacturing tools that are being investigated by government, academia, and solution providers. Several S&A providers are already working intently on solving this end-to-end process problem.

Numerous solution providers have made strides in better integrating geometry optimization in design tools. Some examples are:

- Altair has incorporated lattice structures into its design optimization tools (OptiStruct, solidThinking, and Inspire).
- Siemens provides generative design capabilities integrated in the NX electro-mechanical design platform based on the Convergent Modeling™ technology that allows designers to seamlessly work with and model with faceted geometry.
- Dassault Systèmes SIMULIA (Tosca Structure) has demonstrated results for lattice and tubular structures.
- Autodesk provides generative design capabilities packaged for both the discrete Manufacturing and Architecture, Engineering & Construction (AEC) industries. Their 2020 Spacemaker acquisition brings added capabilities.

- PTC acquired **Frustum** and now offers the Creo Generative Design Extension (GDX). Onshape, their 2019 acquisition, will also be able to access GDX technology in the cloud..
- Simpleware Ltd. (part of Synopsys) can generate lattice structures for additive manufacturing parts, but this is not related to optimizing the shape itself for weight or strength.
- Several relatively small start-ups, such as nTopology Inc., with a focus on the design for additive manufacturing aspects are emerging in this space. See <https://ntopology.com/> for more information.
- Universities and government research organizations such as Sandia National Labs are also actively developing promising new technologies in this area.

Optimization is now embedded in many 3D CAD systems. This is a welcome development but does raise some concerns. The first is that CAD is too often focused on component design, so the optimization does not comprehend the part in the context of its system, for example, a link in a flexible mechanism. Another is that the structural solvers used tend to be linear. One can argue that since optimization leads one closer to design limits, the analysis should be non-linear, and robust design techniques should be used.

To address these limitations, GenEng is seen as the next level up from typically component-centric GenDes encompassing more of a systems thinking approach and design philosophy. Siemens has been a leading proponent of GenEng and defines it as: “Generative Engineering expands upon key elements of the Generative Design concept to encompass an overall systems-level view of product design where computer-augmented robust design/design exploration and design synthesis technologies combined with other AI-based methodologies such as machine learning/deep learning methods are utilized to identify optimal system architectural design alternatives needed to meet complex cross-domain functional requirements.” Thus, a GenEng approach supports innovative design, development, and manufacturing of increasingly complex cyber-physical systems requiring cross-domain synthesis and optimization (e.g., mechanical, electrical/electronics, embedded software, and controls) to meet the ever expanding competitive and regulatory requirements being driven by the adoption of Industry 4.0 technologies, “green” sustainability initiatives, the Circular Economy, and radically new business models such as “products as a service” enabled by the Internet of Things.

These GenDes and GenEng approaches can support a much more thorough exploration of the feasible design space than humans (unaided by computers) can hope to accomplish in a reasonable amount of time. As computer speed continues to improve an order of magnitude every five years, the fact that many optimization and AI/ML algorithms rely on brute force heuristics becomes much less relevant. The addition of tools along the spectrum from data mining to analytics to artificial intelligence to machine learning offers immense promise for this technology.

Fundamentally, simulation is becoming better, faster, cheaper, and ever easier to use. All of the capabilities we have outlined above allow users to do more simulations and

perform them much more rapidly. They also make using simulation early in the product and manufacturing development processes more effective in influencing fundamental design decisions. But who will conduct performance simulation in the future? That is still a major question and challenge for the PLM industry as a whole that leads into our next topic.

The Democratization of Simulation

A significant issue with simulation at the vast majority of companies, especially larger organizations, is that S&A is generally the province of elite groups of domain experts, many holding PhDs or master's degrees in engineering with highly specialized training and expertise. Many market forecasters estimate that fewer than 10% of all engineers involved in product development currently make regular use of S&A capabilities outside of what is considered to be the most widely used analysis tool in industry, Microsoft Excel. Many within the industry believe that for simulation to be effective it must be pervasive within all sizes of companies and accessible to a much larger audience of engineering users. In other words, simulation and analysis must be "democratized" for use by non-specialist engineers and occasional users of analysis capabilities as well as by advanced analysis specialists.

The underlying issue is complexity of the simulation and analysis techniques and tools. Many of the technologies are difficult to use and may require years of hands-on experience to develop the appropriate expertise and confidence to make product engineering decisions based on simulations. In addition, simulation involves multiple applications and typically a heterogeneous IT environment, including interfaces to CAD information and high-performance computing (HPC) resources. Smaller companies cannot afford to develop deep simulation expertise in particular, and they often do not have the resources to integrate simulation into their engineering environment.

It must be emphasized that democratization is about reducing the hurdle for the usage of the tools and making them more widely available to support informed and valid engineering decisions. The objective is not for these tools to be used by those who do not understand the strengths and limitations of the tool and the fundamental engineering issues. The goal is to leverage the in-depth knowledge of S&A experts in specific domains to advance the effective use of the technologies within the natural flow of the design and development process. The user environment can be simplified, but the underlying capability of the S&A tools and algorithms and the engineering competence of the users will continue to be required.

Though some companies have had success, early attempts at democratization have generally failed or only been partially successful. Although pioneered as far back as the mid-1980s, the idea of simulation capabilities embedded inside the CAD environment really took hold about twenty years ago. The idea was to provide a simplified simulation capability for linear structural analysis of single components. However, these simplified tools often did not have the needed capability, and many CAD users (designers) did not have the required engineering expertise. These factors, and others, limited the effectiveness of this CAD embedded approach.

In recent years the situation has changed dramatically. Most 3D CAD products now have highly capable, geometry-associative simulation suites that support linear and nonlinear structural, kinematics, fluid flow, and thermal capabilities and can also handle multi-component assemblies. In addition, easy-to-use CAD tools capable of direct modeling, are being integrated into simulation environments. Now 3D geometry can be brought fully into the simulation process, starting with the early conceptual design stage.

But democratization has multiple dimensions. It is not simply the merging of the CAD and CAE environments. Some applications involve “always on” simulation to provide guidance to a designer. Examples include designing molded parts, where the designer has continuous feedback on the cost and manufacturability of the part, and the design of ductwork or manifolds, where the designer receives feedback on pressure drop as duct sizes are changed. Leading solution providers offer design guidance to arrive at better first-time-valid designs. However, as noted previously, the embedded simulation tools are not a substitute for S&A expertise and the essential processes required for final design validation prior to product release to manufacturing.

Some companies have seen dramatic improvements—reducing design time from months to days—by using complete design combined with analysis applications for particular devices and components. Requirements are specified with a simple spreadsheet-like tool. The rest of the process is automated, including parametric CAD and structural simulations, resulting in a completed design, which includes cost and manufacturability assessments.

Web-deployable simulation process integration and automation software has emerged that enables domain experts to capture standard simulation processes and best practices in reusable templates. Greatly simplified web interfaces can then be created to enable non-expert users such as design engineers, systems engineers, sales engineers, engineering managers, and others to safely run these standard process simulations and generate pre-defined analysis reports.

EASA is an example of one such web-based vertical application builder for a wide variety of S&A applications. Most of the major S&A solution providers are also building similar low code “democratization” capabilities into their platforms, often linked into their core analysis tools for simulation process automation and design optimization (see the previous section).

More recently, the dimension of time has become recognized as perhaps an undervalued dimension of democratization. For decades, the industry has talked about how simulation should be faster and easier to use, but users and solution providers have focused primarily on the accuracy of simulation results. Is that really the right question?

Suppose we said that simulation should be instantaneous, as long as we understand the software tools’ limitations? We can now compute in one second what would have taken the Apollo program engineers 1,400 years to do. In five years, computers will be at least 10 times faster, and cheaper than they are today. In ten years, they will be 100 times faster, and cheaper still. In 1980, a Cray-1 supercomputer cost \$40 million.

Today, a Raspberry Pi, has about 20 times the capability of that Cray-1 and costs about \$30. So, what if we prioritize response time first, and let the compute technology mature to eventually bring us the high levels of accuracy required for the purposes of final design validation performed by the analysis experts?

Rather than demand precise accuracy at the conceptual design stage, we can now get “good enough” answers to A vs. B vs. C design questions, just as long as the feedback is extremely quick and visually easy to understand by the average design engineer. Several tools supporting integrated geometry have recently been introduced, such as Ansys Discovery Live, PTC Creo Simulation Live (embedding Ansys technology in Creo), and Altair’s SimSolid. These focus on providing highly interactive feedback of 3D simulations that can guide design trade-off analyses essentially in real time by leveraging the advanced algorithms and computing power available today on the engineering desktop including leveraging graphics processing units (GPUs).

Coreform is an emerging, venture backed company that is pioneering a new isogeometric analysis (IGA) approach to FEA based on commercializing innovative technology for rapid meshing and analysis of complex 3D shapes. Coreform has a partnership with Sandia National Laboratories to license, sell, and support the CUBIT meshing technology developed over several decades within that DOE facility. See <https://coreform.com/> for more details on their version of the CUBIT meshing tool and the IGA solver for isogeometric analysis.

In accordance with Moore’s Law, computing has become infinitely fast and vanishingly inexpensive. And it will continue to become more so. So, the democratization of simulation can also be accomplished by giving engineers the best available simulation results as fast as possible to make better design decisions early and often throughout the entire product development lifecycle.

The expanded potential of simulation and analysis also enables support for a wider range of tradeoffs, including using advanced optimization, design of experiments, and stochastic design techniques for design trade studies, one of the guiding tenets of systems engineering. Tools in this domain include HyperStudy from Altair, Isight from Dassault Systèmes SIMULIA, ModelCenter from Phoenix Integration (acquired by Ansys in 2021), modeFRONTIER and VOLTA by ESTECO, optiSlang by Dynardo (now part of Ansys), Dakota from Sandia National Laboratories, Optimus from Noesis Solutions (Cybernet Systems), and Simcenter HEEDS from Siemens.

The ever-increasing computing power available to engineers will also be a key factor in increasing the use of multi-disciplinary analysis and optimization (MDAO) tools. By their very nature, these tools typically perform thousands of simulation workflow iterations to provide conceptual design guidance. The ability to get the simulation results in minutes or hours vs. days or weeks dramatically increases the impact on making better design decisions.

Solution Providers Respond to the Demand

Simulation solution providers continue to deliver more capable and better-integrated software. Increasingly, providers are offering suites of software that comprise 3D

multi-physics capabilities which include capabilities for model building, results visualization, and analysis in a single user environment, combined with functionality for robust design and optimization. These next generation suites also offer capabilities for simulation process automation and simulation data management. More recently, the leading S&A solution providers have started offering 0D/1D dynamic systems modeling capabilities, primarily through acquisitions.

Advanced data analytics and AI/ML/deep learning capabilities are also becoming a core component of S&A platforms to deal with the large volume of performance data being generated both from product performance simulations, as well as from real world operational data captured by as many as thousands of sensors embedded into today's smart systems. These technologies also hold great promise to enable engineers to deal with the exploding complexity of cyber-physical systems design. Numerous R&D efforts are underway by the leading solution providers to leverage AI/ML/deep learning with PLM, S&A, and MBSE processes.

A number of targeted application areas exist to augment human decision making (now often referred to as augmented intelligence) and to further democratize the usage of S&A and MBSE tools including:

- Interactive and guided application task specific user interfaces (UI).
- Understand requirements interdependencies across domains (software, hardware, control systems) and cross-domain interactions between logical, functional, and physical aspects of systems.
- Automated and guided exploration of the feasible systems design space based on the model-based system architecture diagrams and parameters leveraging physics-based Multi-Disciplinary Analysis and Optimization (MDAO) capabilities.
- Automated and guided Uncertainty Quantification (UQ) for system level risk analysis beginning early in the systems conceptual design process to evaluate system robustness and design risks.

Virtual model linkages with immersive AR/VR capabilities for engineers to “visually experience” the system design. As an example of this trend, Altair Engineering acquired the data analytics and visualization company Datawatch in December 2018. Datawatch's legacy installed base was dominantly in the financial services and capital markets but the Datawatch technology is now integrated with the Altair S&A platform for model-based engineering. It has been rebranded as KnowledgeWorks to bring artificial intelligence and data analytics directly into play for up-front simulation and analysis activities.

Mr. Jim Scapa, Altair's Founder, Chairman, and Chief Executive Officer, stated: “Bringing Datawatch into Altair should result in a powerful offering consistent with our vision to transform product design and decision making by applying simulation, data science and optimization throughout product lifecycles. We see a convergence of simulation with the application of machine learning technology to live and

historical sensor data as essential to creating better products, marketing them efficiently, and optimizing their in-service performance.”⁷

To reinforce this point, Gartner recently cited both Altair and MathWorks in their Magic Quadrant for Data Science and Machine Learning Platforms dated March 2021.⁸ MathWorks is positioned in the Leaders quadrant.

Comprehensive S&A Platforms

Most of the top 10 solution providers in the S&A market segment would be considered S&A platform providers that provide a combination of capabilities and solutions. These include comprehensive multi-domain, multi-physics, multi-scale, and design optimization solutions as well as web-based collaboration and SPDM capabilities.

Not surprisingly, seven of the top ten leading S&A solution providers fall into this “comprehensive S&A platform provider” category:

- Ansys
- Siemens
- Dassault Systèmes/SIMULIA
- Altair Engineering
- Hexagon/MSC Software
- ESI Group
- COMSOL

Greece-based BETA CAE Systems is a privately-owned but rapidly emerging S&A platform company. While not yet offering the scope and breadth of applications to be considered an S&A platform comparable to the top seven market leaders, BETA CAE continues to aggressively expand their S&A solutions portfolio. Even though they do not publicly disclose their financial data, CIMdata has again included BETA CAE on our revenue leaders chart with total revenues estimated at \$100 million in 2020.

Others listed in the S&A leaders list do not currently have a comprehensive S&A platform and product portfolio, but instead provide more focused S&A solutions in one or more vertical segments:

- MathWorks—provides general purpose mathematics-based modeling via Matlab and 0D/1D systems simulation in the Simulink/Simscape suite. One could easily argue that MathWorks should be considered an S&A platform. MathWorks market share is quite substantial with revenues approaching \$1B/year. However, they are still not seen as a comprehensive S&A platform provider of the same scale and portfolio breadth as the industry leaders of Ansys, Altair, Dassault Systèmes, or

⁷ <https://investor.altair.com/news-releases/news-release-details/altair-announces-agreement-acquire-datawatch>

⁸ <https://www.gartner.com/en/documents/3998753/magic-quadrant-for-data-science-and-machine-learning-pla>

Siemens. However, MathWorks shows signs of expanding its product scope to have a broader S&A portfolio including basic 3D thermal and structural analysis capabilities. It will be interesting to see how far down this path MathWorks is willing to go in incorporating new capabilities for 3D multi-physics analysis and SPDM.

- Cybernet Systems—primarily an IT and CAE services company headquartered in Japan that sells and supports many commercial engineering and CAE software tools, including Maplesoft and Noesis (which are both owned by Cybernet Systems).
- ISI-Dentsu—Primarily an IT services and value-added reseller of leading CAE solutions in Japan and other sections of Asia/Pacific, ISI-Dentsu also offers some internally developed and supported software products.
- Simulations Plus—develops absorption, distribution, metabolism, excretion, and toxicity modeling and simulation software for the pharmaceutical and biotechnology, industrial chemicals, cosmetics, food ingredients, and herbicide industries. This modeling and simulation domain is outside of the traditional mechanical physics-based S&A space tracked and measured by CIMdata but the major CAE and PLM companies are more closely tracking and investing in this area.

S&A providers are constantly improving their physics to address new problems. For example, explosion damage to a military vehicle includes high-speed flow (blast waves), multi-phase flow (dirt and gravel), as well as large structural deformations. It can be argued that co-simulation with computational fluid dynamics (CFD) and a structures application do not correctly couple the physics for this problem. Consequently, a multi-physics capability working within a single application or platform is often required.

In addition to the push for expanded 3D multi-physics capabilities, solution providers are extending the scope of their physics-based applications by adding 0D/1D systems simulation tools and moving into new domains outside of the traditional mechanical realm. In the past several years, multiple providers have acquired solutions in the electronics, electromagnetics, chemical reactions, human and biological modeling, and embedded software engineering and controls domains.

Another recent focus is on materials engineering. The widespread adoption of structural composites has changed the manufacturing landscape over the past several decades. “Materials” no longer means just building a properties database. Today’s materials are engineered in conjunction with 3D component design and incorporate new manufacturing processes such as additive manufacturing that can directly impact the nature of the materials to be used and even the final “as manufactured” material properties. As such, both organic and inorganic materials are now being engineered at the atomic and molecular levels to be “fit for purpose.”

S&A providers acquired or struck alliances with companies that have strong expertise in composite materials. Some examples are FiberSim (acquired by Siemens), Evolutionary Engineering (acquired by Ansys), Multiscale Design Systems and

Componeering (acquired by Altair), e-Xstream Digimat (acquired by MSC Software) and Firehole Composites and Magestic Systems (acquired by Autodesk). These capabilities are now essential foundation components in any comprehensive behavior modeling and simulation suite.

There are also smaller niche companies who focus on developing and distributing standard engineering material properties in software libraries. Two such examples are Granta Design (acquired by Ansys during 2019, now Ansys Granta) and DatapointLabs. These companies provide both materials testing services and material libraries as a software toolkit that is embedded into the simulation modeling platforms of a number of the larger S&A solution providers.

Small companies are also emerging, particularly from university research departments, to address the emerging need for physical properties characterization of advanced materials resulting from the new additive manufacturing processes. One such company is Senvol, who provides the comprehensive Senvol Database™, the first database of industrial additive manufacturing materials and machines. Senvol actually partners with Ansys Granta to make the Senvol AMdata database available within Granta's software tools: Ansys Granta MI™ and CES Selector™. Another small company providing niche technology and services in this segment is Endurica LLC. Endurica focuses on optimizing the durability characteristics of elastomeric materials used in 3D printing processes.

Smaller but Key Emerging Players in MBSE

Of course, many more companies perform vital roles in the S&A market and may not be individually cited because the focus is on the revenue leaders. As we have seen in the S&A market over the last few years, firms of all sizes have great new ideas, and larger firms often assimilate niche firms to extend their solution coverage. In fact, there are many smaller modeling, simulation, and MBSE companies whose relevance is out of proportion to their current size. The simulation landscape, in particular, includes many smaller companies and technologies whose contributions are important and growing rapidly.

Data Interoperability and Physics-Based Co-Simulation for MBSE

One such smaller company is Modelon, a fast-growing Sweden-based company in the rapidly evolving area of systems modeling and simulation to facilitate MBSE. Modelon provides engineering consulting services and software technology based on the Modelica and FMI open standards. These standards enable interoperability of Modelica-based simulation components generated using the rapidly maturing FMI/FMU standard. This model interoperability and co-simulation technology is evolving as a key enabler for the cross-domain systems modeling and simulation required for today's complex mechatronic and cyber-physical systems. Over 100 software solution providers currently support the FMI standard across many different industry segments and the number continues to grow.

Based on their expertise gained in real world consulting projects, Modelon has extended open source systems modeling capabilities by creating standard reusable libraries of physical components based on the Modelica language. These libraries can

be used in a wide range of applications in automotive/transportation, heavy vehicles, aircraft, engine/powertrain, HVAC, and power/energy generation..

Modelon is also now providing their own dynamic system solver capability called OPTIMICA Studio. Other leading S&A solution providers such as Ansys, Dassault Systèmes, Siemens, ESI, Maplesoft, and Ricardo are adopting Modelon's technology to embed in their system dynamic modeling solutions.

Other relatively small US-based companies focusing on MBSE data interoperability include Phoenix Integration, Intercax LLC of Atlanta, GA and Koneksys of San Francisco, CA. Intercax's technology and domain expertise originated from research at Georgia Tech and is now embedded in commercial software offerings that enable SysML-driven modeling and simulation of complex systems, including integration with CAD, CAE, and PLM tools. This is essentially middleware that connects the systems engineering domain with the traditional mechanical hardware design and behavior simulation domains. Koneksys provides software and consulting services focusing on the use W3C web-based collaboration standards such as OSCL and RDF for linking data and information across currently disconnected MBSE data authoring languages and tools such as SysML, Modelica, Eclipse, Matlab/Simulink, and enterprise data management platforms such as PLM and ALM.

Emerging technology companies in the MBSE data interoperability domain include SodusWillert (provider of the SE Collab and MDWorkbench platforms) and Obeo (provider of a number of commercial tools such as Obeo SmartEA, Obeo Designer, Team for Capella, and others which are based on open source technologies). Both companies are headquartered in France. Ingrano Solutions of Germany provides the ModelBus Tool Integration Framework as well as several other MBSE- and ALM-related model integration and collaboration tools.

In addition to Phoenix Integration's ModelcenterMBSE capabilities, another promising example of working towards "democratization of MBSE" is MapleMBSE product from Maplesoft (Cybernet Systems). This tool provides an intuitive, Excel spreadsheet-based GUI for entering detailed system design definitions used in SysML authoring tools (e.g., structures, behaviors, requirements, parametric constraints) and then integrates that spreadsheet information behind the Excel-based UI with the system architecture defined in standard MBSE platforms (e.g., IBM Rhapsody and Dassault Systèmes MagicDraw) for trade studies and rapid impact analysis of design changes. This novel approach does not require an engineer to use or to understand systems design tools based on the relatively complex SysML architectural modeling language.

Multi-Disciplinary Analysis & Optimization

Tools that enable process improvements (supporting best practices automation and tool integration) and organizational capabilities (collaboration and best practice reuse) will continue to have a major and even disruptive effect on how work gets done at industrial companies. U.S.-based Phoenix Integration (now part of Ansys) and ESTECO, based in Italy, are both relatively small companies in this area sometimes called process integration and design optimization (PIDO) or multi-disciplinary analysis and optimization (MDAO). Another small but well established player in the

structural design optimization market segment is Vanderplatts R&D based in Colorado Springs, Co.

ESTECO's business is strongest in the automotive and vehicle industry, particularly in Europe, while Dynardo's customer base is more diversified across the automotive, industrial machinery, and oil and gas market segments. Phoenix Integration's customer base is overwhelmingly in the aerospace and defense segment and with government organizations in the U.S. market such as the DOD and NASA/JPL.

However, in addition to the classical MDAO and process automation capabilities all three companies provide a basic capability for "work-in-process" simulation data and process management integrated with their MDAO suites. This is a very nice feature for those companies using MDAO solutions who do not require an enterprise-level SPDM solution.

ESTECO's Volta is a web-based second generation SPDM solution based on a service-oriented architecture that can actually be deployed independent of ESTECO's core ModeFrontier MDAO suite. It provides capabilities for simulation data management; distributed compute execution including for HPC, and optimization-driven design and simulation data analytics. As such, it could actually be viewed as either a workgroup level or enterprise SPDM platform.

Phoenix Integration has also developed new capabilities (ModelCenterMBSE) for linking parametric as well as non-parametric systems model information generated in SysML tools such as IBM Rational Rhapsody, Dassault Systèmes MagicDraw Cameo Systems Modeler, PTC's Windchill Integrity Modeler, and Vitech Genesys with physics-based multi-disciplinary analysis processes developed in Phoenix ModelCenter to perform systems trade studies and design optimization early in the design lifecycle. See Figure 27. This essentially bridges the gap between traditional systems engineering "graph-based" descriptive system models and executable physics-based S&A models to enable design optimization and verification processes within an MBSE framework—a major step forward in integrating systems engineering with the rest of the product development process.

Figure 27:
A Collaborative Effort to
Integrate Systems
Engineering Data &
Processes with S&A
Tools

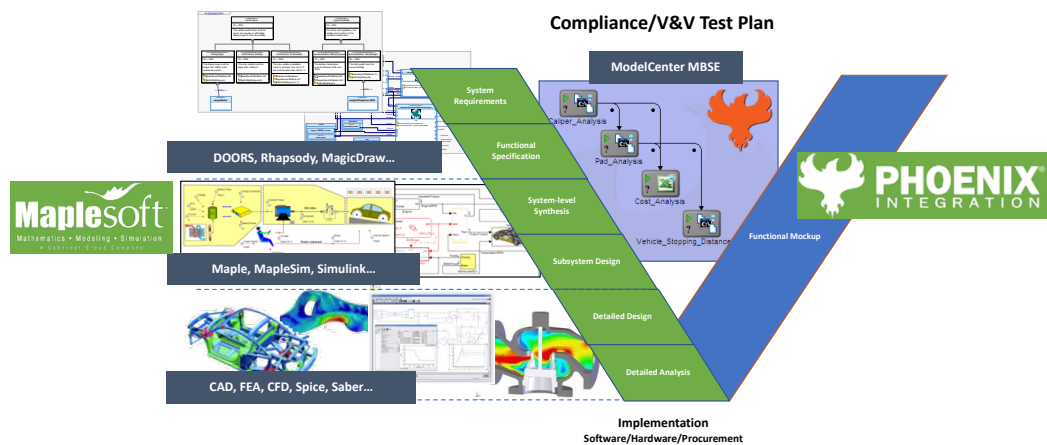


Image courtesy of Phoenix Integration and Maplesoft

Engine/Powertrain & Transmission/Driveline Systems

Another important specialty area in S&A is engine / powertrain and transmission / driveline systems simulation. Powertrain systems are critically important for addressing fuel economy and noise, vibration, and harshness (NVH) concerns. They present a significant challenge in terms of multi-discipline integration of mechanical, thermal, electrical, software, and controls—a systems of systems problem. There is growing recognition that state-based simulations such as MATLAB/Simulink are not adequate for this application. Time-based simulations (that do performance calculations in real time) are essential. Players in this space include Simcenter AMESim (from Siemens) but also smaller S&A software companies such as Gamma Technologies, SIMPACK (now part of Dassault Systèmes SIMULIA), and Romax (acquired by Hexagon in early 2020). Large powertrain engineering development and consulting organizations such as AVL, FEV, Ricardo, and Magna Styer have also developed and sell niche software applications for powertrain design and analysis applications. This is a relatively small percentage of their overall business, but these applications do have a considerable user base in the automotive and heavy vehicle industries. In addition, both end users and universities have developed a host of proprietary applications in this domain, a relatively underserved segment.

High-Performance 3D Results Visualization, Analytics, and Reporting

A key enabler to the productivity of S&A experts as well as to simulation democratization is the ability to rapidly process extremely large amounts of 3D analysis results and distribute that critical information for review in an easy to use and collaborative, graphical manner via the web. Visual Collaboration Technologies (VCollab) of Troy, Michigan, provides a suite of lightweight 3D visualization solutions for product performance analysis results and real time web-based collaboration. Standard analysis reports can be automatically generated using customized templates.

Much as the common 3D PDF format has made it easy to share and distribute documents and 3D models originating from many different sources, the **VCollab** CAX technology allows expert CAE engineers to process, organize, share, and collaborate in real time with design engineers, engineering managers, and even non-engineers. This is accomplished using highly compressed, yet interactive 3D CAE models and performance analysis results generated from a wide range of CAD and CAE tools. The VCollab suite also enables the exchange of product design and analysis data in many industry standard formats such as 3D PDF, JT, and VRML and within the Microsoft Office suite of tools for reporting and documentation. VCollab CAX is becoming a common, unifying language for web-based visualization and engineering collaboration for 3D physics-based performance simulation and analysis.

VCollab sells their CAX-based visualization solutions through both sales channel partners as well as embedded within the solution suites of larger software S&A solution providers, such as MSC Software. VCollab currently provides integrations with the following commercial SDPM, MDAO, and PLM software solutions:

- Ansys Engineering Knowledge Manager (EKM) and Ansys Minerva
- Dassault Systèmes SIMULIA

- Simulation Lifecycle Management (SLM)
- Dynardo optiSLang (now part of Ansys)
- JOTNE EDM OpenSimDM
- MSC Software SimManager (now part of Hexagon)
- Noesis Optimus (part of Cybernet Systems)
- Phoenix Integration ModelCenter: PHX Analysis Library
- Siemens
- HEEDS (formerly CD-adapco)
- Teamcenter for Simulation

Another interesting company in the area of graph-based data visualization, analytics and reporting is Tom Sawyer Software. While Tom Sawyer has provided general purpose tools for a wide range of scientific applications, more recently the Tom Sawyer Perspectives software is being adopted in the realm of MBSE due to its interactive desktop and web-based capabilities for customization, filtering, analysis, visualization, and navigation of complex systems architecture diagrams authored in UML and SysML software and systems tools such as Dassault Systèmes MagicDraw and IBM Rational Rhapsody.

Advanced Materials Engineering

New products often rely on innovative new materials in addition to the traditional metals used in manufacturing, making material properties and materials engineering much more essential today. Two decades ago, specifying materials for simulation was simply a matter of having material properties “cards” to include in input decks for applications like NASTRAN. Now materials engineering is properly recognized as a distinct and increasingly important discipline. As previously noted, software applications from companies like DatapointLabs, Granta Design (now part of Ansys), and Senvol define and manage materials as a discipline while exposing needed data to activities for product design and simulation.

With the emphasis now on composites, simulation applications like EVEN from Ansys, OptiStruct from Altair, and Fibersim from Siemens are used to “design” materials in terms of laying down filament plies in the context of a particular component design. Nonlinear analysis tools like Abaqus and Ansys have been used to calculate micro scale structures to generate “equivalent” macro material properties for use in macro simulations. Topology optimization tools such as TOSCA (acquired by Dassault Systèmes/SIMULIA in 2013) can be used to create and analyze concept designs for additive manufacturing processes.

The widespread interest in and application of additive manufacturing is also creating a strong need for capabilities to represent the material properties of products that are being created using these advanced manufacturing processes. The previously mentioned Senvol is an emerging solution supplier in the additive manufacturing domain.

We expect there will continue to be small companies emerging from government R&D and academic research organizations that address the future materials characterization needs of the many different types of additive manufacturing processes, new advanced materials and chemical formulations, and molecular biological modeling for pharma/drugs and human body health care.

As mentioned previously, companies such as Simulations Plus and the former Accelrys (part of Dassault Systèmes BIOVIA) focus on material behaviors in terms of chemistry and non-continuum physics. Both organic and inorganic materials are now being engineered at the atomic and molecular levels to be “fit for purpose.”

Significant efforts are also being made to develop biologically realistic models of humans (rather than of mechanical dummies) for ergonomics and crash safety simulation. Virtual crash dummies are no longer just represented as lumped masses and inertias. The human structure can now actually be modeled in full 3D with the appropriate bone, organ, and tissue material characteristics needed to evaluate the actual damage to humans due to various crash impact angles and scenarios.

Engineering Consulting and Cloud Services

Engineering services are often critical in applying S&A solutions to product development. These services extend well beyond the training and implementation typical in other PLM segments. Many S&A software companies such as Altair Engineering earn significant revenues from engineering consulting services by providing on-site engineering personnel. There are also a relatively large number of small to medium size engineering analysis and test consulting services companies that provide specialized expertise in support of major industry programs, especially in the automotive, transportation, aerospace & defense, heavy industry and consumer/high-tech electronics industry segments. Several engineering services companies of significant size and impact in the North American market include ATA Engineering (San Diego, CA), CAElynx (Detroit, MI), ETA Engineering (Detroit, MI), Front End Analytics Solutions (Boston, MA), Maya Heat Transfer Technologies (HTT) (Montreal, Canada), and Quartus Engineering (San Diego, CA).

Several of these companies also develop, sell, and support their own custom S&A software applications in addition to working with one or more of the leading S&A software solution providers. Maya HHT is particularly unique in that regard. It is actually as much a software sales and development organization as it is an engineering services company. Maya has a long strategic relationship with Siemens (which started during the early 1990s with SDRC developing applications in I-deas) to develop, maintain and support commercial applications for Siemens that are now integrated into the Simcenter suite within the NX platform and other specialty tools such as test & analysis correlation and ECAD PCB translators.

In the European market, TECOSIM is one of the largest vendor-independent suppliers of CAE-related engineering services. In addition to their German HQ and several other German locations, TECOSIM also has significant engineering staff located in the United Kingdom, Romania, Japan, and India. ISI-Dentsu and IDA-Japan are the largest providers of CAE-related engineering services in the Japanese

market with ISI-Dentsu also being a developer of several custom S&A software applications widely used in their Japanese customer base.

Systems integrators such as Tata Technologies are another type of engineering services provider. They are one of several IT services companies that support CAE simulation tools training and S&A software application projects, not just IT issues. They provide a flexible source of S&A resources and product development expertise that their customers can use as needed.

In a similar vein, cloud computing and SaaS for S&A has the potential to greatly simplify access to S&A resources and to relieve companies of the burden and expense of integrating software and HPC capabilities into their own IT environment. In addition to the cloud and SaaS offerings of the major solution providers such as Ansys, Altair, Autodesk, Siemens, and ESI, several IT cloud services companies such as Rescale, UberCloud, TotalCAE, and Penguin Computing are focused on providing on-demand access to S&A applications via cloud and SaaS platforms. Some of the larger solution provider offerings are based on partnerships with these focused S&A Cloud providers.

Requirements and System Architecture Modeling

Another set of companies, whose revenues are counted by CIMdata in the Other Tools market segment outside of the S&A market revenues, provide systems architecture modeling solutions that enable the digital definition, documentation, traceability, and re-use of four key system design disciplines throughout the product lifecycle:

- Requirements definition, decomposition, and management
- Functional system architecture
- Logical system architecture
- Physical system architecture

Companies active in these areas are very focused on the upper left side of the engineering Vee and are working to replace document-centric and manual processes with digital systems design tools and processes that can be continuously updated, work across domains, be made repeatable and automated, and be traceable over time as the system design evolves and becomes a real product in service. Many of these companies provide systems engineering solutions that are based on the UML/SysML modeling languages or their derivatives.

The larger providers of PLM, application lifecycle management (ALM) for software engineering, and S&A solutions have entered the systems engineering segment through acquisitions. Several have historically focused on the software engineering realm (IBM's Rational/Rhapsody suite, PTC Integrity, Ansys SCADE/Simplorer) while others focus more on the electro-mechanical hardware domain (PLM providers such as Siemens and Dassault Systèmes) or the electronics hardware domain. This includes EDA providers such as Mentor Graphics (now part of Siemens), Cadence, Synopsys, and Zuken (who acquired **Vitech** in 2019). This convergence of systems

engineering solution providers coming from different domain perspectives was discussed earlier in the report and is illustrated in Figure 6.

However, there is another group of small- to medium-sized companies that hold promise to be key players in the systems engineering market space. They are likely to have a significant impact on the future of the PLM industry and the eventual achievement of integrated MBSE processes to achieve the business goals of the digital thread.

Several of these companies provide a comprehensive systems engineering platform that addresses the four discipline areas listed above, typically based on the ability to author digital system architecture models using the SysML or UML modeling languages as a core capability. Examples of these independent companies include Sparx Systems of Australia (Enterprise Architect), SPEC Innovations (Innoslate), and XLDyn.

There are also open source system architecture design codes available in this area based on the Arcadia method (e.g., Capella, Papyrus) and OPM, as well as open source collaboration environments for MBSE such as OpenMBEE, which originated from the efforts of NASA and Jet Propulsion Lab.

Further reinforcing the trend towards industry consolidation and platformization across the engineering domains, Dassault Systèmes acquired No Magic of Austin, TX during 2018 and Zuken of Japan announced its acquisition of Vitech Corporation in January of 2019.

Another fast-growing company is venture capital-backed **Jama Software** which has evolved from a niche solution provider in the system requirements capture and management domains. Bolstered by a venture capital investment of \$200M in June 2018, Jama is now pursuing an aggressive global growth strategy based on providing a more comprehensive next-generation product development platform for today's complex cyber-physical systems.

Some of the smaller niche companies in this SE segment such as The Reuse Company of Spain (www.reusecompany.com), and SBE Vision (www.sbevision.com), based in the US, focus primarily on efficient knowledge-based allocation and leveraging of functional performance requirements across targeted domains in the systems development lifecycle. The Reuse Company's V&V Studio software tool is designed to enable and manage verification, validation, and quality activities in accordance with the ISO 15228 process standard. SBE Vision software is based on an innovative "intelligent agents" approach that offers a new dimension for managing requirements across complex cyber-physical product and program organizations.

PHM Technology, based in Australia, provides a suite of systems engineering related software and services branded as MADe, which stands for "maintenance aware design." MADe is a model-based systems modeling technology based on the principles of failure mode and effects analysis (FMEA) to understand, predict, and optimize the functional safety requirements of a design based on key performance

parameters and the criticality of each failure mode (cause, mechanism, fault, symptoms, etc.). See www.phmtechnology.com for more information.

These are companies to watch as they are likely to grow significantly over the next several years, and they will likely be attractive acquisition candidates for the larger PLM and S&A solution providers.

Current CIMdata SDSD Consulting Practice Research

CIMdata's Simulation-Driven Systems Development (SDSD) Consulting Practice, which serves both industrial end users and software solution providers, focuses on helping the industry achieve tangible business benefits from the integration of systems modeling and simulation technologies, processes, and best practices within the complete product development lifecycle. The SDSD Consulting Practice intent is to observe, measure, and share best practices in how to apply virtual systems modeling and simulation more effectively in product and manufacturing systems design, development, validation, and ongoing sustainment. To achieve this goal, the SDSD Consulting Practice contributes to:

- The development of appropriate data and model interoperability standards for cross-domain systems modeling and simulation to enable MBSE and integrated simulation-driven digital engineering processes across the entire product lifecycle.
- Defining the characteristics of product development platforms that will facilitate the integration of simulation tools and data with the related education services and IT resources required to enable an enterprise digital thread and digital twin(s) environment.
- Evaluating, publishing, and promoting industry best practices for implementing model-based processes that leverage MBSE and S&A throughout the product lifecycle. This includes the development of systems engineering and modeling and simulation maturity models based on the CMMI process accounting for organization/people, process, and technology dimensions as well as ROI models used in planning and implementing MBSE and SPDM processes and technologies.
- Working with global manufacturing companies to implement industry best practices for simulation-driven model-based engineering approaches to the product design, development, manufacturing, and in-service support domains

On these and related topics, the SDSD Consulting Practice works in concert with leading industry organizations, such as NAFEMS, and the Simulation Data Management Working Group (SDMWG), INCOSE and the Systems Modeling & Simulation Working Group (SMSWG), the SMSThinkTank™, the Object Management Group (OMG), the Modelica Association, NIST, NDIA, prostep ivip and PDES, Inc. CIMdata is also actively involved in industry thought leadership organizations such as the Aerospace & Defense PLM Action Group⁹, as well as

⁹ <https://www.cimdata.com/en/aerospace-and-defense#>

industry events such as the Global Product Data Interoperability Summit,¹⁰ and the ASSESS Congress.¹¹

While technological enhancements and change are often essential to solve product development problems, CIMdata has long recognized that technology can often be the easiest part of developing and deploying any component of an enterprise PLM strategy, including systems engineering and simulation and analysis technologies. Implementing new processes and philosophies such as the digital thread, digital twin, and MBSE require cultural and organizational changes that impact people both in terms of their roles and the skills needed to make the new product development processes successful.

Research focus areas for the SDSD Consulting Practice are driven by customer interests and priorities. Current research topics include systems modeling and simulation platforms, data and model interoperability standards for systems modeling, simulation implementation maturity models, and governance best practices to enable MBSE, and best practices for implementing simulation data and process management (SPDM).

For more information about CIMdata's Simulation-Driven Systems Development consulting practice and its work on effectively using virtual prototyping and simulation in product and manufacturing development to provide innovative decision support over the entire product lifecycle from ideation to end-of-life disposition, please go to <https://www.cimdata.com/en/consulting/focused-consulting-practices>

S&A Market—Results and Forecast

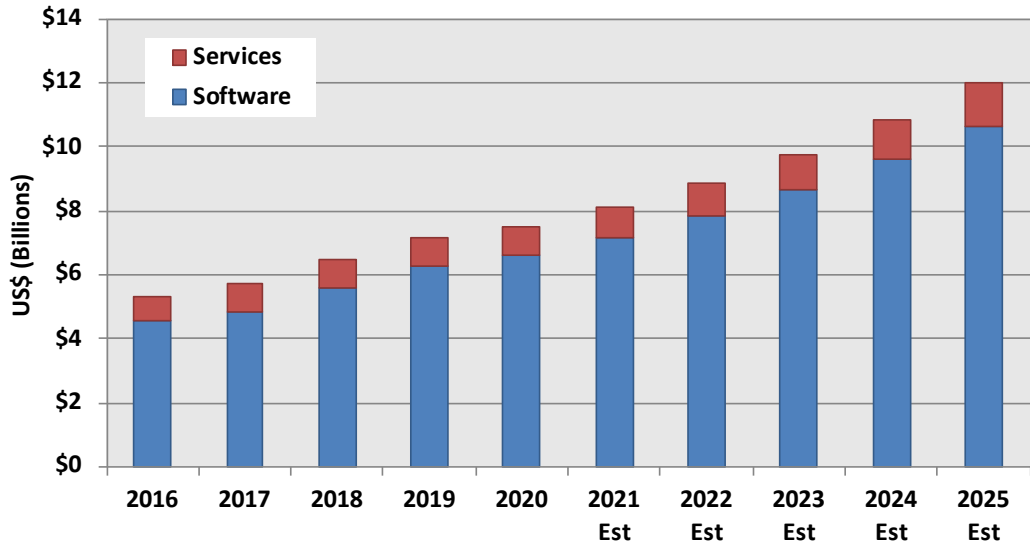
In 2020, S&A revenues grew to just under \$7.5 billion, an increase of 4.2% over the nearly \$7.2 billion in 2019.¹² This growth reflects the increasing importance of S&A as part of product development and the need for companies to deploy better S&A solutions and environments, even in the face of a global pandemic. Figure 28 presents CIMdata's estimate of software plus services revenues for the S&A segment of the PLM market from 2016 through 2020 and a forecast for the segment through 2025. CIMdata expects that S&A will be one of the more rapidly growing segments within the tools sector of PLM over the next five years, and forecasts that this market sector will reach \$12 billion in 2025, with a 10% CAGR. For 2021, CIMdata forecasts that the S&A sub-sector will grow 8.1% overall and have revenues of over \$8 billion.

¹⁰ gpdisonline.com

¹¹ <https://www.assessinitiative.com/>

¹² It is important to note the impact of a new accounting rule change (ASC 606) on PLM market growth year-on-year (YoY) from 2017 to 2018. To put it simply, new revenue recognition rules can have the effect of moving multi-year subscription revenues (and other revenue) from recognition over the term of the contract to recognition in the year the contract is signed. This could have the most impact on firms for which a high percentage of their revenues is by subscription. The impact can be several percentage points increase for a given company in 2018 compared to 2017. This is one additional possible explanation for the high YoY growth between 2017 and 2018 reported in CIMdata's MAR reports. CIMdata's standard practice in our quantitative market research is to ensure the revenues we report are consistent with the revenues reported to government agencies such as the Securities and Exchange Commission in the United States to the greatest extent possible.

Figure 28:
S&A Revenue—History
and Forecast



The S&A market differs from the overall PLM market in its distribution of revenues between software and services. For instance, the cPDM segment of the PLM market is services intensive, with software representing approximately 40% of total revenue and services of different types representing the other 60%. For the S&A segment, services represented 11.7% of total revenues in 2020. Figure 29 shows that implementation services are only 7.9% for the S&A segment.

Figure 29:
Distribution of S&A
Revenues
US\$ (Millions)

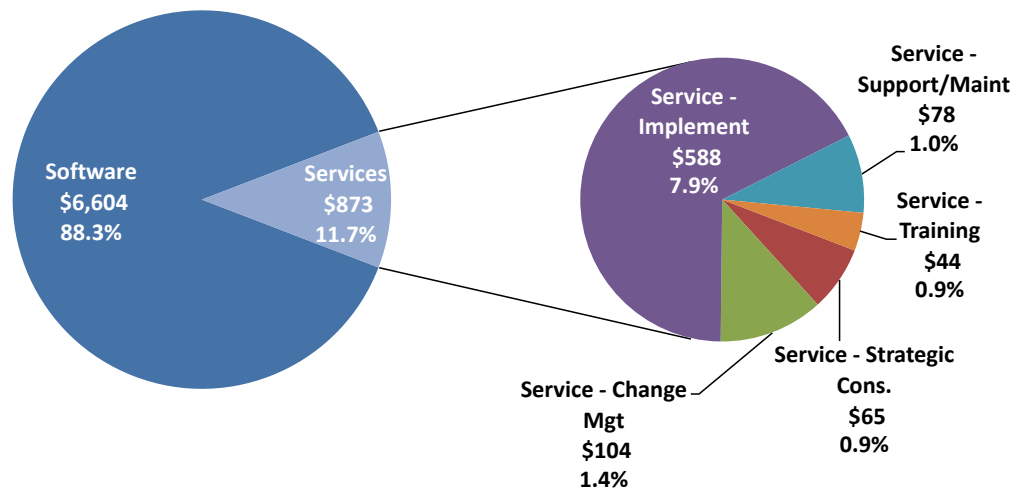
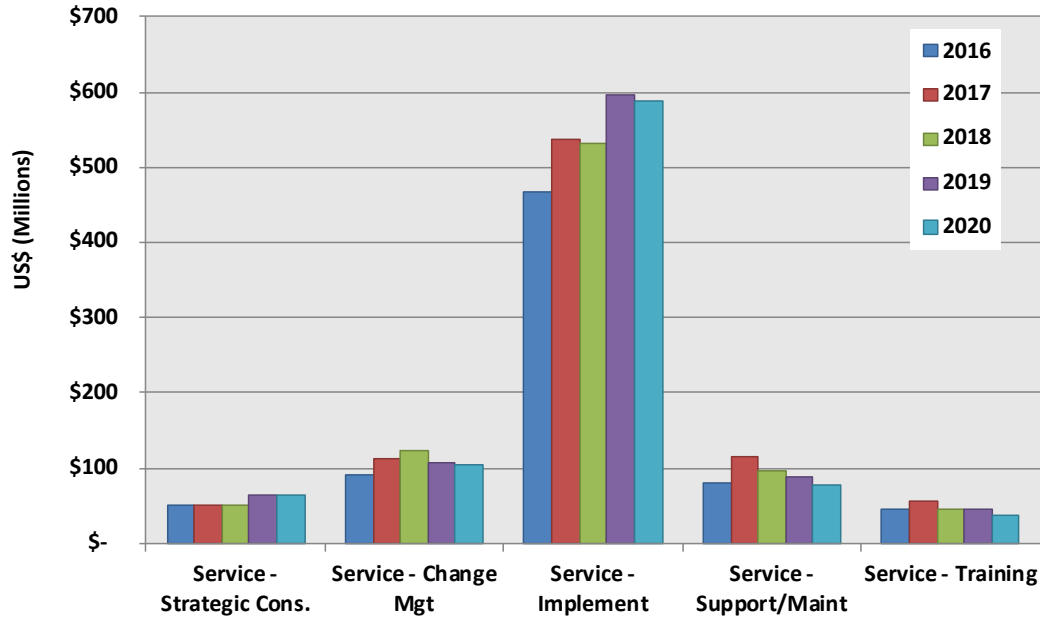


Figure 30 presents the history of S&A revenues by segment (other than for software which is shown in Figure 28) from 2016 through 2020.

Figure 30:
History of S&A
Revenues by Segment



S&A Industry Analysis

CIMdata tracks S&A revenues for the following industry segments as defined by the North American Industry Classification System (NAICS) codes:

- Aerospace and Defense: airframe, aircraft, missiles, weapons systems
- Automotive and Other Transportation: automotive, trains, buses, motorcycles
- Electronics and Telecommunications: electronics, high-tech, semiconductors, telecommunications, medical devices, satellites
- Fabrication and Assembly (F&A): mechanical machinery, heavy equipment, household appliances, footwear and apparel, toys, small appliances, consumer goods, other discrete products
- Process/petrochemical: bulk chemical, oil and gas extraction (including platforms and rigs)
- Process/user consumables: pharmaceutical, consumer packaged goods, food and beverage (F&B)
- Utilities: electricity and power grids, gas and transmission pipelines, telecommunications operators, water and drainage
- Construction (e.g., engineering, procurement, and construction (EPC); civil engineering; and home building)
- Infrastructure (e.g., railway systems, roadways, harbors, airports)
- Shipbuilding
- Other: financial/investment, insurance, services

Figure 31 shows the industry distribution of S&A revenues for 2020. The S&A industry distribution tracks closely with spending on MCAD, which makes sense

given the historical investment in MCAD technologies in those manufacturing segments and the disproportionate use of S&A in mechanical design settings.

Figure 31:
S&A Revenues by
Industry Segment
US\$ (Millions)

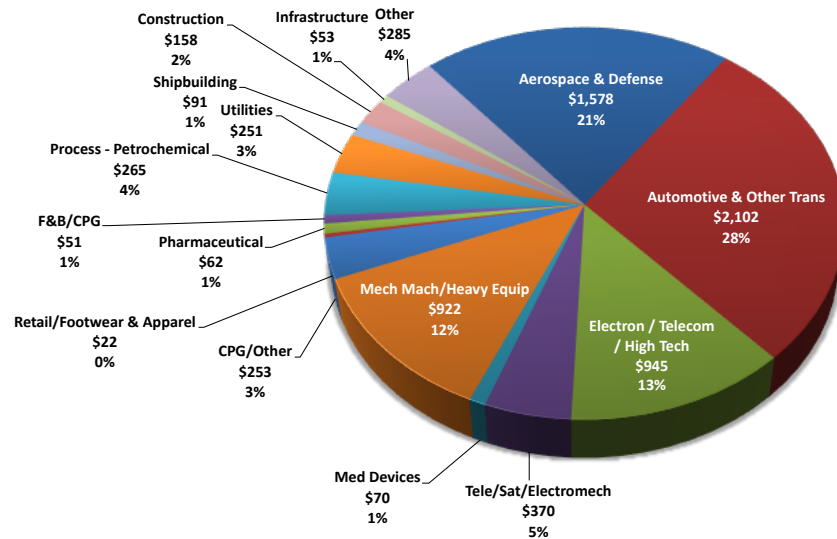
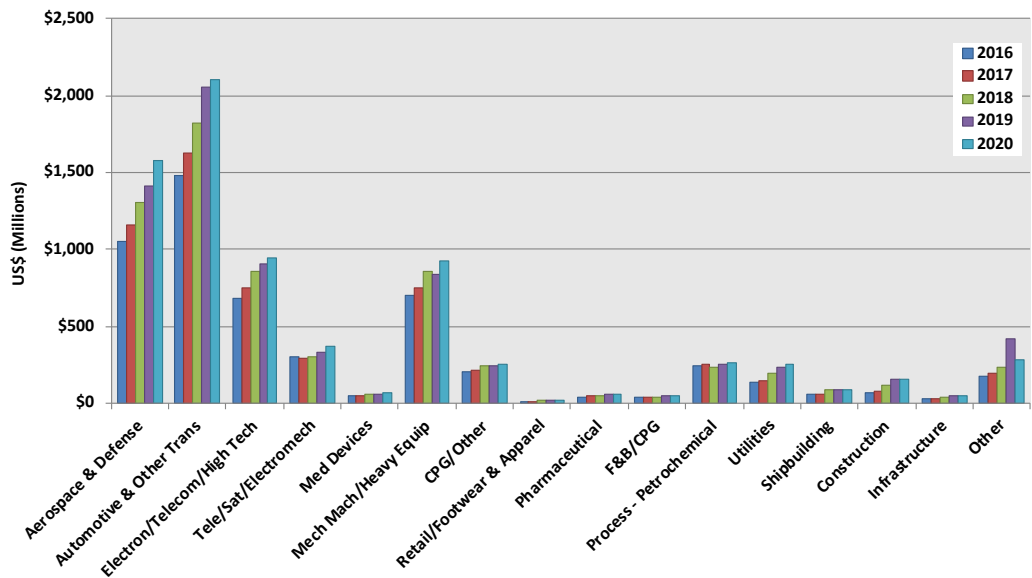


Figure 32 presents the history of S&A revenues by industry segment from 2016 through 2020.

Figure 32:
History of S&A
Revenues by Industry
Segment



S&A Geographic Analysis

CIMdata tracks S&A revenues for the following geographic regions and countries:

- Americas
 - United States
 - Canada
 - Mexico and Central America
- Argentina
- Brazil
- Venezuela
- Rest of Americas

- Europe, Middle East, and Africa (EMEA)
 - Benelux
 - Austria
 - Germany
 - Switzerland
 - Czech Republic
 - France
 - Italy
 - Poland
 - Scandinavia
 - Spain and Portugal
 - Russia
- The United Kingdom (UK)
- Rest of Europe
- Middle East
- Africa
- Asia-Pacific (AP)
 - Australia and New Zealand
 - China
 - India
 - Japan
 - Korea
 - Taiwan
 - Rest of AP

Figure 33 shows the geographic distribution of worldwide S&A revenues for 2020. Unlike the other Tools segments tracked by CIMdata, S&A is one segment in which EMEA and Asia-Pacific lead the Americas.

Figure 33:
Geographic Distribution
of Worldwide S&A
Revenues
US\$ (Millions)

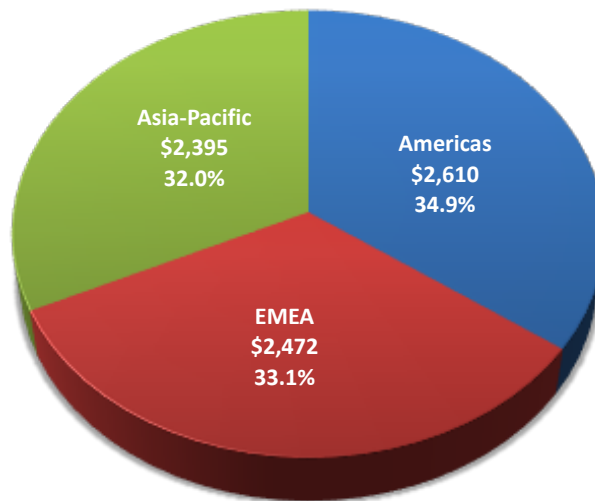


Figure 34 presents the history of S&A revenues by industry segment from 2016 through 2020. The chart illustrates the growth in the S&A segment over the last several years, particularly in the EMEA and AP regions.

Figure 34:
History of Geographic
Distribution of
Worldwide S&A
Revenues

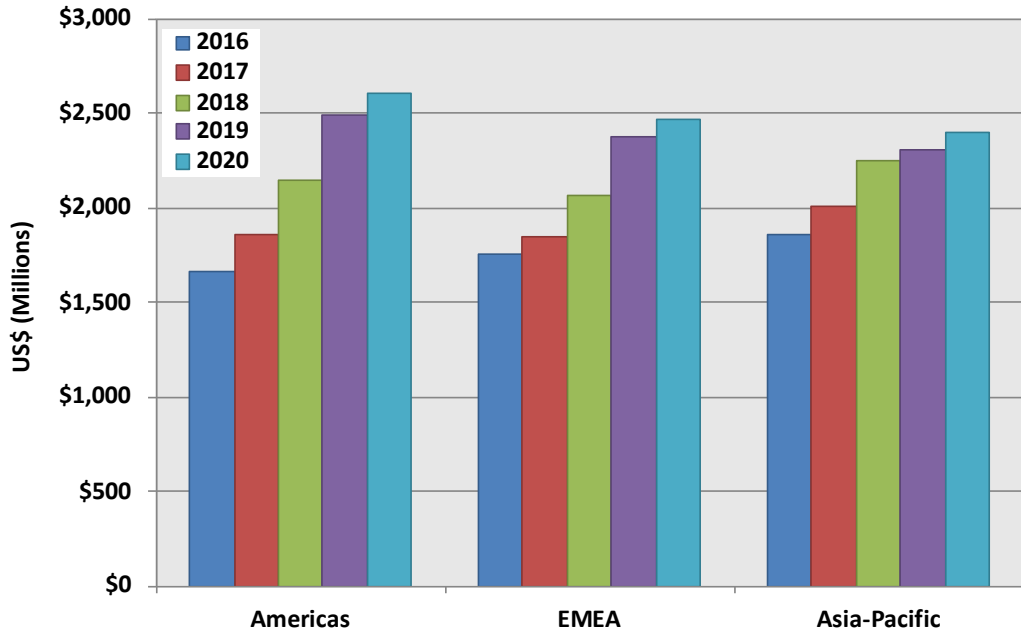
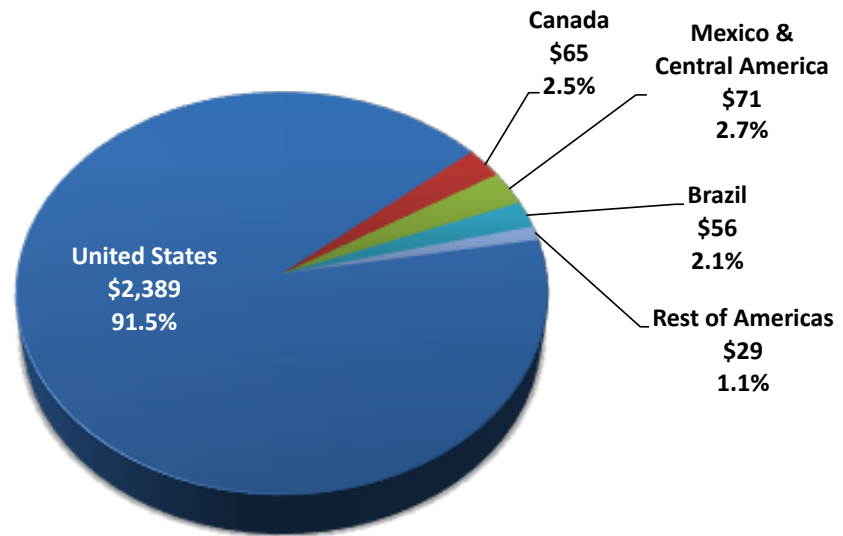


Figure 35 shows the distribution of 2020 S&A revenues in the Americas by country in the region.

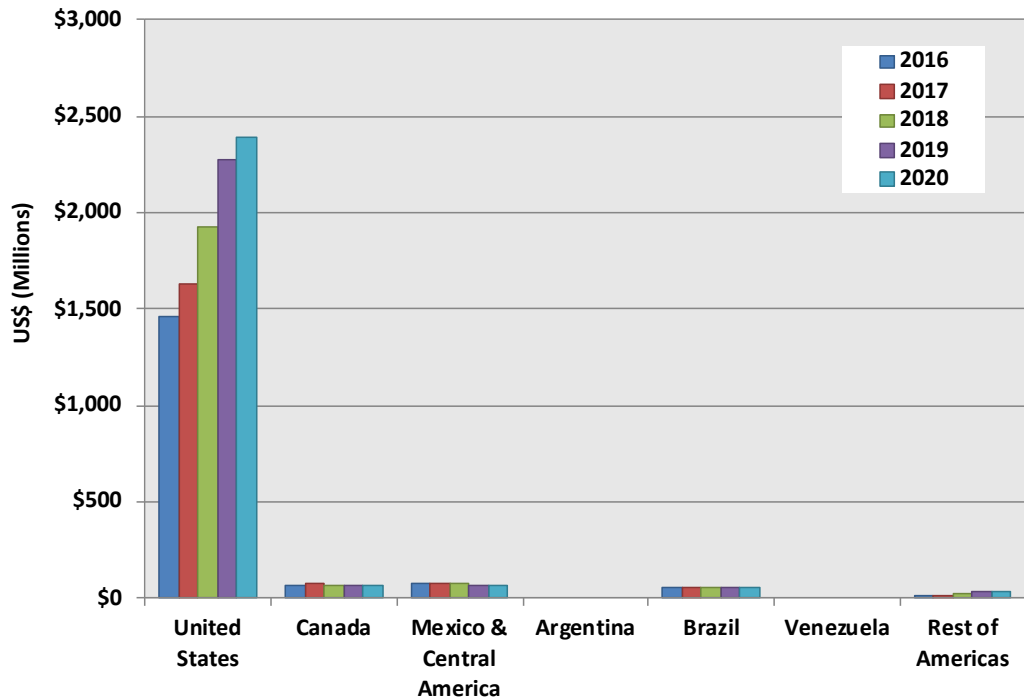
Figure 35:
Distribution of S&A
Revenues within the
Americas Region
US\$ (Millions)



As might be expected, the United States dominates the rest of the region with 91.5% of the 2020 revenues.

Figure 36 shows the historical distribution of S&A revenues in the Americas region for 2016 to 2020.

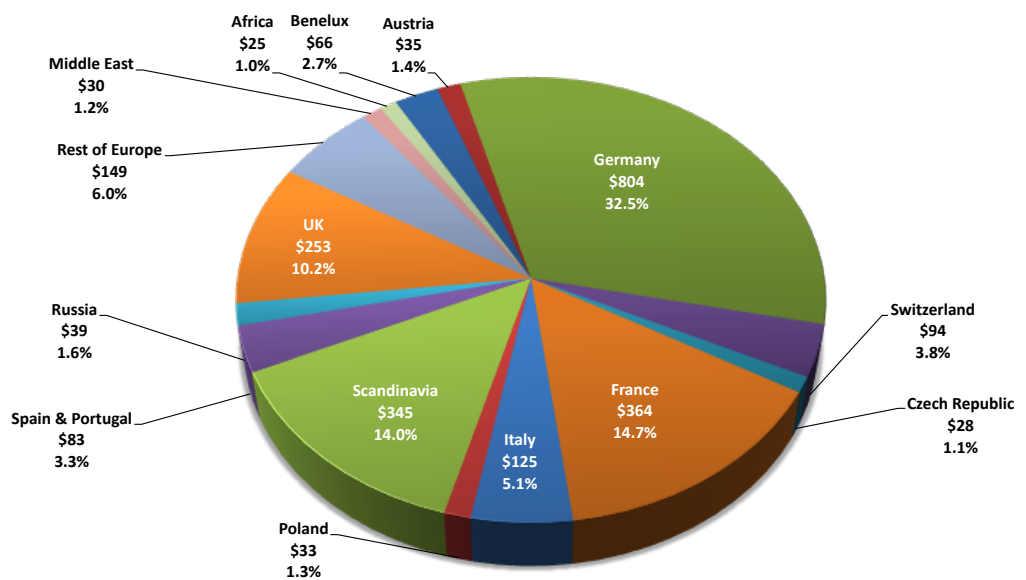
Figure 36:
History of Distribution of
S&A Revenues within
the Americas Region



CIMdata expects that spend on S&A solutions will continue to increase as the other major economies in the Americas region, such as Mexico and Brazil, start to design and manufacture complete products.

Figure 37 shows the distribution of 2020 S&A revenues in EMEA by country in the region.

Figure 37:
Distribution of S&A
Revenues within the
EMEA Region
US\$ (Millions)



Germany, with its large manufacturing base, dominates the EMEA region.

Figure 38 shows the historical distribution of S&A revenues in the EMEA region for 2016 to 2020.

Figure 38:
History of Distribution of
S&A Revenues within
the EMEA Region

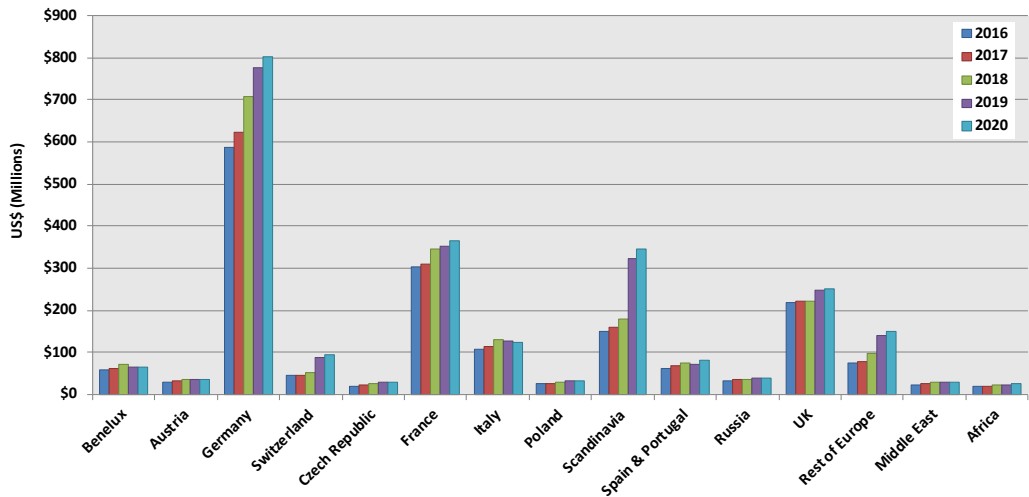


Figure 39 shows the distribution of 2020 S&A revenues in AP, by country in the region.

Figure 39:
Distribution of S&A
Revenues within the AP
Region
US\$ (Millions)

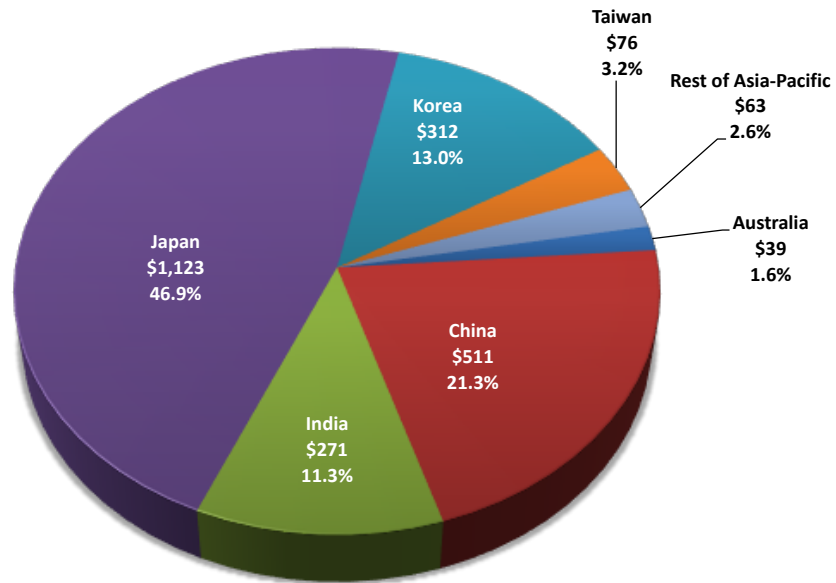
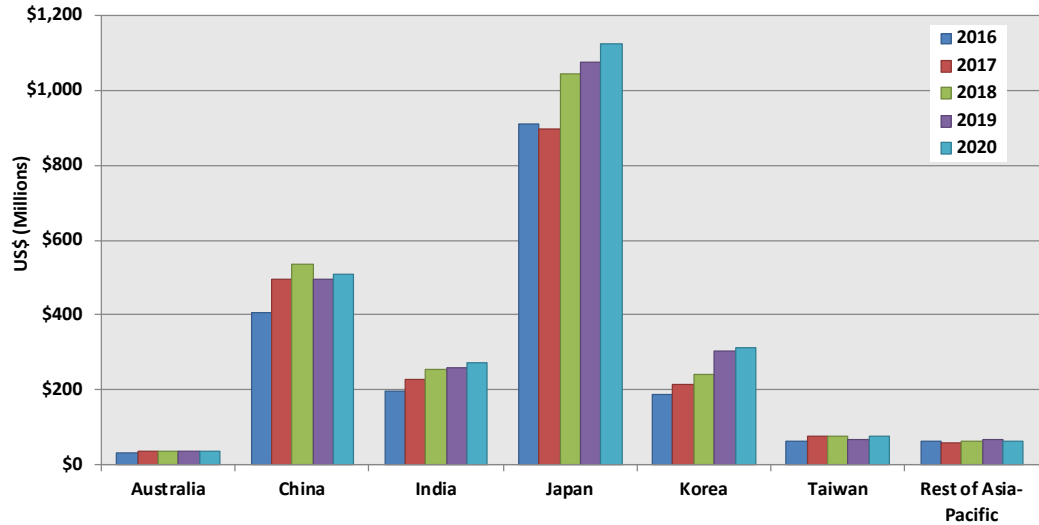


Figure 40 shows the historical distribution of S&A revenues in the Asia-Pacific region for 2016 to 2020. The Japan market growth can be partially explained by exchange rates. The CIMdata analysis is conducted in US dollars, which has been very strong against the Yen over the last several years. This strength hid some of the organic growth in the Japanese S&A market denominated in Japanese Yen during that period. In 2016, the Yen gained 11.3% against the US dollar which contributed to the large jump shown in Figure 40. In 2020, the Japanese Yen gained almost 5% on the US dollar, contributing to the jump last year.

Figure 40:
History of Distribution of
S&A Revenues in the
AP Region



Note: In 2021, CIMdata will publish PLM Market Analysis Reports focusing on the following individual countries for calendar year 2020: Brazil, China, France, Germany, India, Italy, Japan, Russia, South Korea, the United Kingdom, and the United States. Please see the [CIMdata reports website](#) for more details.

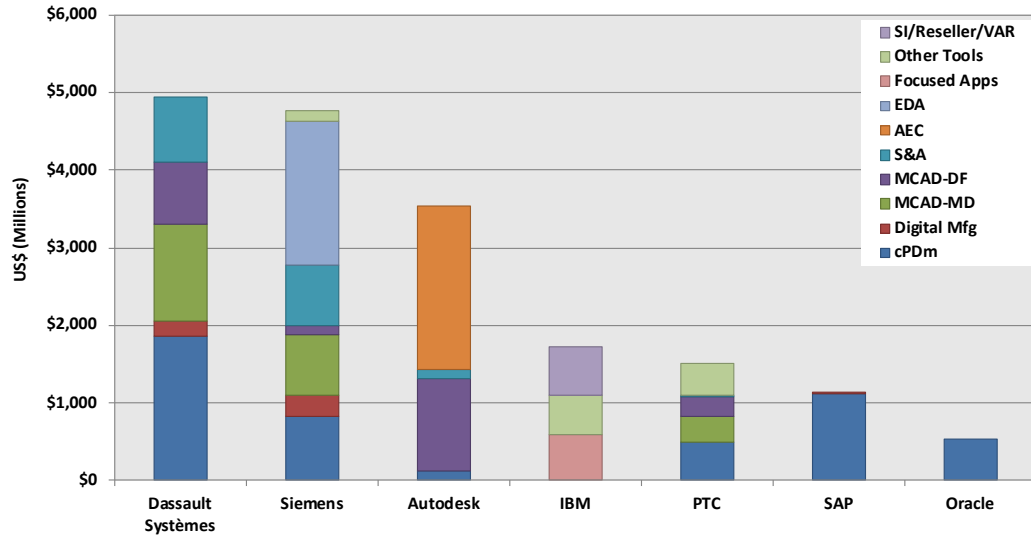
Solution Provider Analysis

The S&A Competitive Landscape

This section provides an analysis of the performance of the major S&A solution providers in terms of the revenues received for their products and services during 2020. The revenue of each solution provider includes two components—software (new, recurring, or right-to-use licenses, including software maintenance) and services.

A wide range of companies supply technologies and services to the S&A segment of the PLM market. As shown in Figure 41, several large PLM market players, including Dassault Systèmes, Siemens, and Autodesk generate significant revenues from the S&A segment.

Figure 41:
PLM Leaders' Revenue
by Market Segment



In many cases, S&A providers concentrate only on S&A. However, many other suppliers pursue markets in addition to S&A as defined by CIMdata. For example, some companies in the S&A market, most notably Altair, deliver engineering services beyond S&A and get significant revenues, which are not included in CIMdata's revenue model. For those companies, we include only that portion of their business actually directed toward S&A.

Other market leaders such as IBM do not provide S&A solutions per se but do have significant revenues in the area of systems engineering/MBSE, specifically for software engineering and general requirements management (the IBM Rational suite). Ironically, one company who is not included in our revenue analysis develops and supports the most widely used engineering calculations software on the planet—Microsoft Excel.

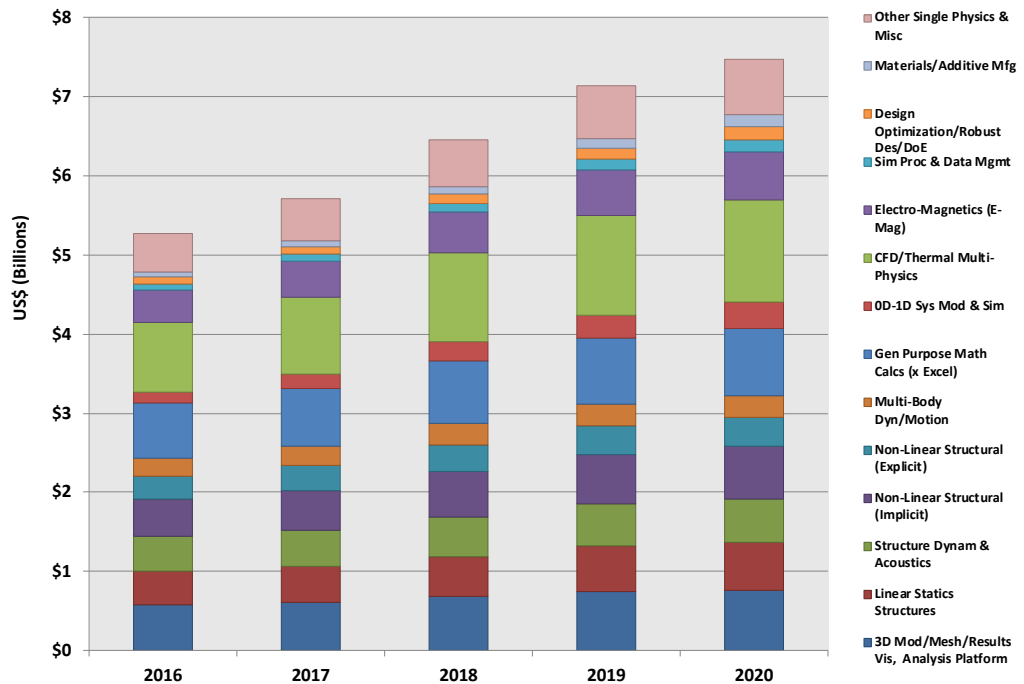
As noted in Table 4, the overall S&A market consists of a large number of applications based on different physics performance requirements.

The market leaders have solutions across many of these S&A application domains, but there are specialists that offer best-of-breed solutions in their specific segment. Consulting services is a bit different in the S&A segment vis à vis the other PLM segments, with more focus on specialized contract engineering analysis services in the consulting mix. We do not account for all of those types of project-centric engineering consulting revenues in our S&A market revenue data.

The S&A solution providers generally do not provide the investment community or the industry analyst community with revenue data for any of the major S&A application segments. We believe that in addition to being viewed as strategically confidential, the solution providers themselves often are hard pressed to track the user revenues specific to a given application segment. There is also not wide agreement on how to group the many different application areas. This can be partially due to the movement towards enterprise-wide software deals and a proliferation of “multi-physics license bundles,” as well as token type licensing systems that enable users to access any application within a solution provider's portfolio. As such,

CIMdata does not have detailed market survey data for each of these individual S&A application segments. We do, however, annually estimate revenues in a number of the application segments based on historical percentages and relative estimated market growth rates by application segment. We often use this information in our own consulting activities with the major solution providers, major industrial companies, and the financial investment community. Figure 42 presents CIMdata’s current best estimates for S&A market revenues for a selected set of S&A application segments.

Figure 42:
S&A Revenues by S&A
Application Segment

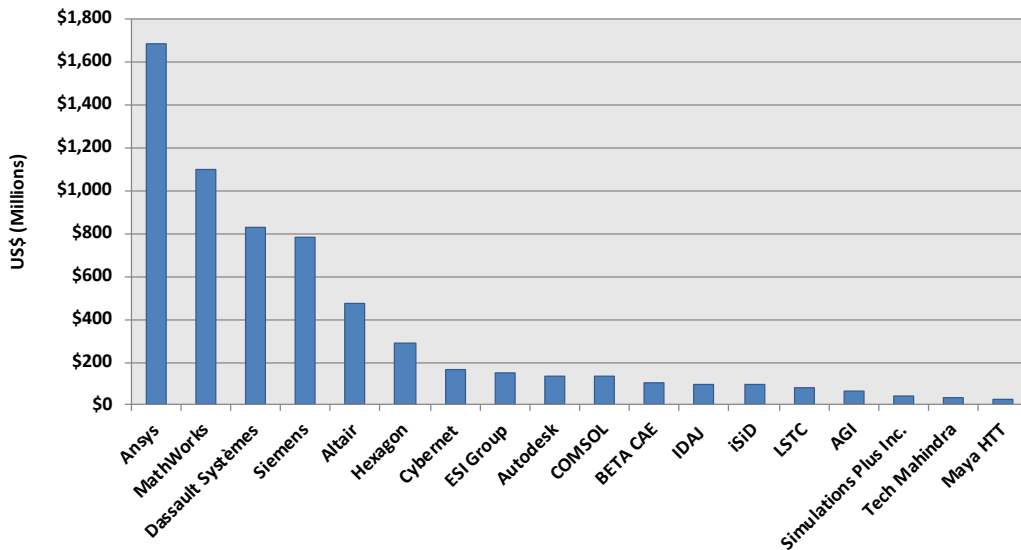


CIMdata believes that this is a reasonable breakdown of the revenues within each of the 14 application segments shown in Figure 42.

S&A Providers Analysis

The S&A market had the fourth largest increase (4.2%) of all the PLM tools sub-sectors in 2020, after leading the way the previous few years. PLM growth suffered in almost all segments during 2020 as a result of the COVID-19 pandemic. But the S&A segment did better than CIMdata’s forecast and the mid-2020 guidance for S&A-focused public companies showed the companies increasing optimism for the rest of the year. This reflects the growing importance of S&A as part of the product development lifecycle and the need to acquire and use validated simulation solutions. Many companies are providing S&A solutions, and many industrial companies have developed their own analysis codes. While a few providers lead this market, major opportunities still exist for new solutions and growth in this market sector. CIMdata expects continued mergers and acquisitions in the S&A market as the leading solution providers compete to offer broader solution suites by acquiring capabilities developed by specialist companies. Figure 43 presents S&A revenue leaders for 2020.

Figure 43:
S&A Revenues



Four of the top five firms grew in 2020, with Ansys at 10%, MathWorks at 8.5%, Altair at 2.4%, and Dassault Systèmes at 1.2% growth. Siemens was down 5.4% year on year. Figure 44 presents a revenue history of the leading S&A solution providers for the past five years. Companies recently added to our coverage may not be listed for all years unless historical information was available.

Figure 44:
S&A Leaders' Revenue Histories

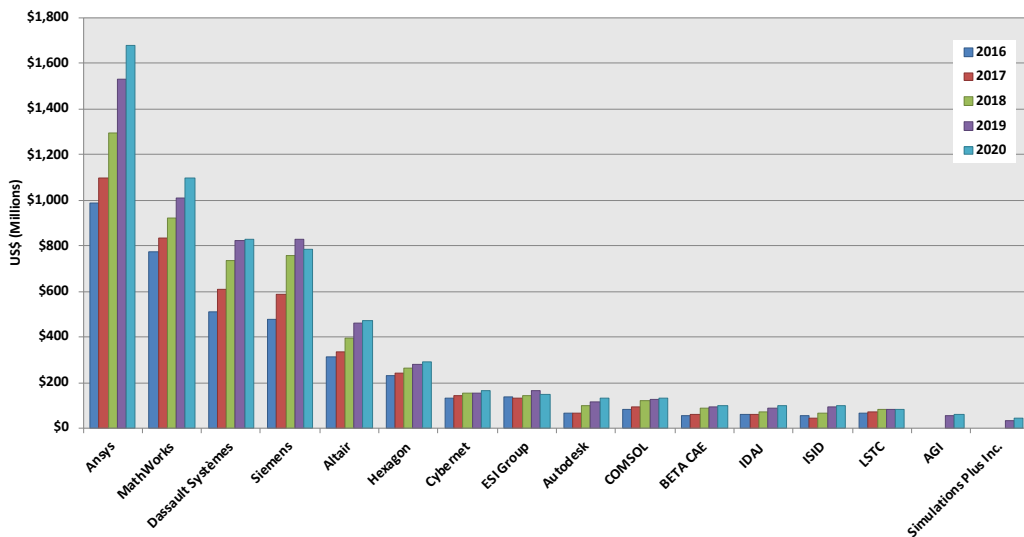


Figure 45 presents the market shares of the S&A segment leaders.

Figure 45:
S&A Leaders
Distribution
US\$ (Millions)

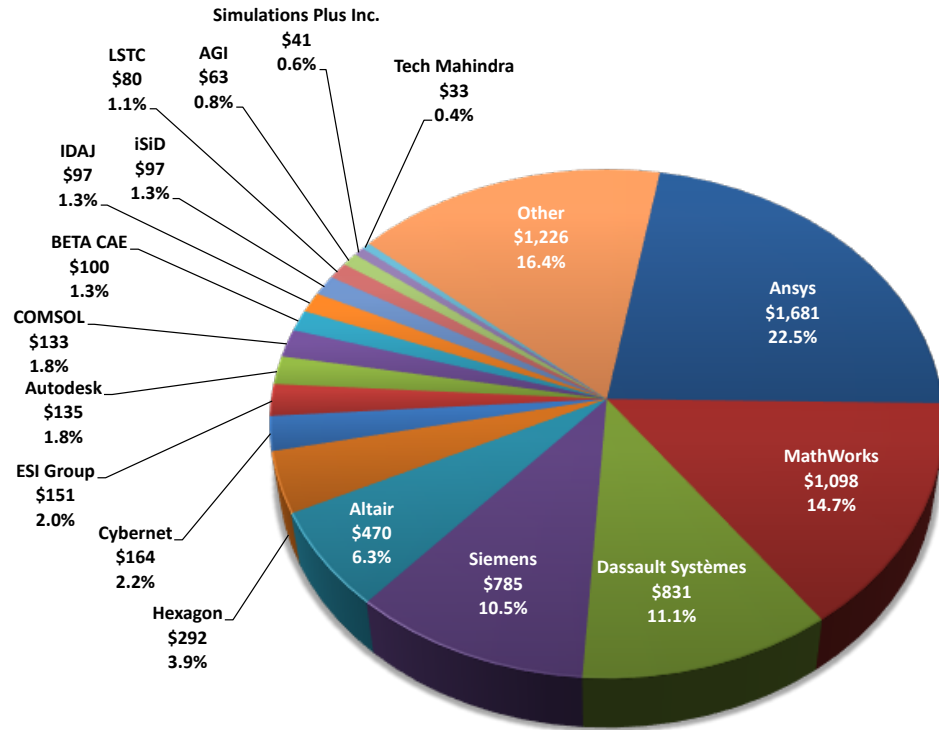
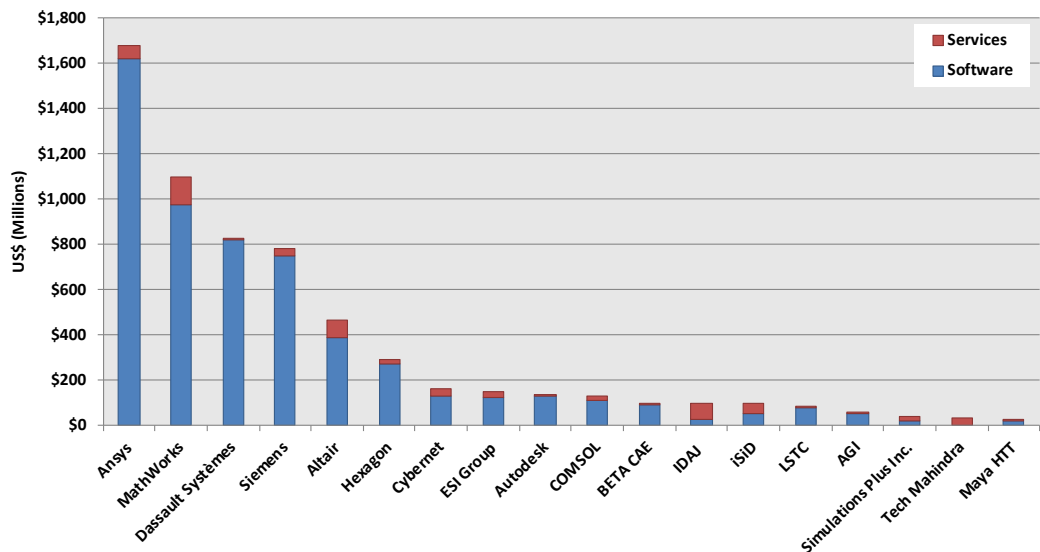


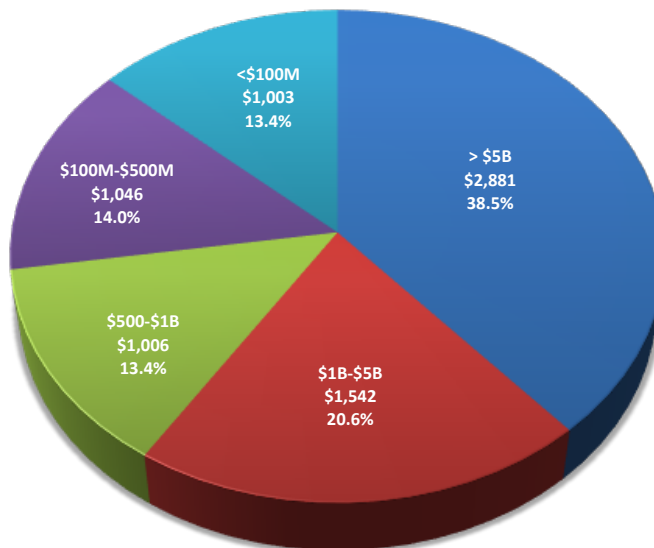
Figure 46 shows the split of 2020 software and services revenue for the leading S&A solution providers.

Figure 46:
S&A Leaders' Software
and Services Revenue



As part of our data collection, CIMdata asks S&A solution providers to indicate the relative percentage of revenues obtained from end-user companies of different sizes: <\$100 million, \$100 to \$500 million, \$500 million to \$1 billion, \$1 billion to \$5 billion, and greater than \$5 billion. Figure 47 shows the split of 2020 S&A revenues by size of end-user company.

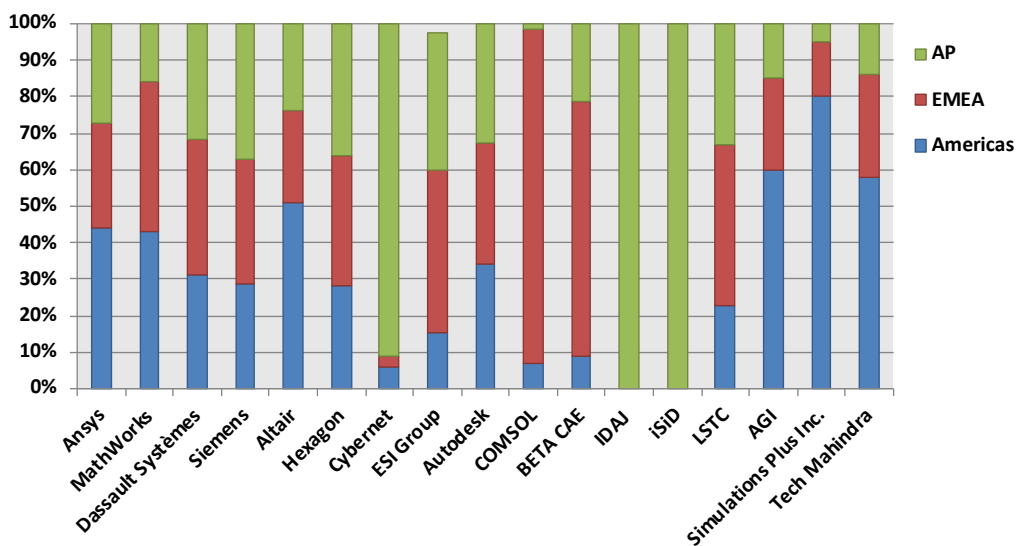
Figure 47:
S&A Leaders' Revenues
by Company Size
US\$ (Millions)



Based on CIMdata's estimates, the use of S&A is still mainly the province of larger companies. Several solution providers in this market segment have emphasized the democratization message, which will help drive S&A investments in smaller firms.

As part of our data collection, CIMdata also asks S&A solution providers to indicate the relative percentage of revenues obtained from end-user companies in different regions and countries. Figure 48 depicts the 2020 revenues of the S&A market leaders split by geographic region.

Figure 48:
S&A Leaders' Revenues
by Geography



Most solution providers in Figure 48 show a solid distribution of revenues in the three major geographies. Cybernet, IDAJ, and iSiD focus mainly on the Asia-Pacific market.

Major S&A Solution Providers

This year CIMdata is departing somewhat from the traditional format and content of the S&A solution provider descriptions. Since so much information is readily available on the internet and company web sites about their products and services, we focus less on the historical background and more on the significant product offerings and events occurring during 2020 such as acquisitions, partnerships, and new technology announcements.

Ansys

Headquartered in Canonsburg, PA, Ansys (NASDAQ: ANSS) is the undisputed market leader in S&A revenue. Their 2020 revenues of just over \$1.6 billion were a 10% increase over 2019. Ansys stock is a component of the S&P 500 index with a market capitalization exceeding \$29 billion. Ansys spent approximately 21.1% of their 2020 revenue on internal research and development, in addition to new technology acquisitions.

The Ansys sales model combines a geographically based sales organization with industry marketing, product experts, and local channel partners (resellers and distributors). Ansys has more than 75 strategic sales locations throughout the world with a network of channel partners in 40+ countries.

Ansys has technical and marketing relationships with the leading PLM, MCAD, and EDA solution providers, including Autodesk, Cadence, Dassault Systèmes, Mentor Graphics, PTC, Siemens, and Synopsys to provide direct links to the core Ansys products. Ansys also has relationships with leading computer hardware suppliers including Intel, AMD, Microsoft, NVIDIA, Hewlett-Packard, IBM, Dell, Cray, QLogic, Mellanox, Platform Computing, and other leading regional resellers and system integrators. They have also partnered with Amazon Web Services and Microsoft to provide cloud-based offerings for the Ansys suite of multi-physics solutions. [Ansys® Cloud™](#), the underlying platform for running Ansys products in the cloud, integrates Microsoft Azure cloud and HPC services with Ansys' simulation technologies. Ansys partners with SAP on providing physics-based digital twin capabilities.

To help extend the depth and breadth of the Ansys portfolio, their Enhanced Solution Partner Program encourages specialized software developers to use Ansys technology as a development platform for their applications. In 2020, Ansys had over 100 active enhanced-solution partnerships. The applications include electronics, mechanical simulation, fluid simulation, acoustics, turbomachinery, and CAD.

Ansys continues to execute their aggressive growth strategy that includes acquiring industry leading technology in carefully selected multi-physics simulation technology segments which complement and extend the Ansys vision for pervasive engineering simulation, the integration of simulation across the product lifecycle on a single platform.

Ansys R&D and investment strategy is focused on 2 major areas:

- Enhancing the Ansys Workbench platform and core multi-physics functionality (~75-80% of spend)

- Next generation technologies for targeted growth areas such as autonomous vehicles, additive manufacturing, 3D integrated circuits, system on a chip (3D IC/SoC), 5G, Digital Twin/IIoT and digital design exploration (~20-25% of spend)

Market Leadership through Acquisitions

Most notably over the past decade, Ansys has made major investments to acquire industry leading software technologies in multiple engineering domains such as CFD; electromagnetics analysis; electronic systems design analysis, embedded software simulation for mission-critical applications; chemical reaction simulation; and 3D geometric direct modeling technology. A history of Ansys acquisitions going back to CY 2012 can be found at <https://investors.ansys.com/company-information/acquisitions-and-partnerships/>

Ansys continues to acquire companies that provide complementary niche technologies to their multi-physics and multi-domain analysis software portfolio:

- **Analytical Graphics Inc.**—A U.S.-based provider of innovative mission-driven simulation, modeling, testing, and analysis software for aerospace, defense, telecommunication, and intelligence applications. The acquisition of AGI will expand Ansys' simulation footprint into customers' mission of operations, an area of systems-level simulation beyond the traditional component or product design level. This will be crucial for understanding the interactions of products with the built and natural world, a key element of the Industry 4.0 vision.
- **Lumerical, Inc.**—Lumerical provides a comprehensive set of tools for the design and analysis of integrated photonic components and systems, similar to the traditional electronic design automation (EDA) environment. Lumerical complements Ansys SPEOS by serving as a de facto light source for predicting the illumination and optical performance of systems such as interior automobile lighting.

While many of the recently acquired products and technologies are still available as stand-alone solutions, all of these new technologies have been or are in the process of being integrated to work within the Ansys Workbench platform to provide a collaborative multi-physics and multi-domain platform for systems modeling and performance modeling of complex multi-domain cyber-physical systems, often comprised today of mechanical hardware, embedded software, controls, and electronics.

In addition to integrating these acquired simulation technologies; Ansys provides enhanced functionality for complex systems modeling and simulation of large-scale assemblies and complex multi-physics calculations. For example, Ansys offers high-performance computing (HPC) solutions with world class performance on parallel computing facilities to address fluids, structures, and electromagnetic simulations. Organizations can leverage this power on any IT configuration from desktops to cloud environments to obtain their simulation results faster.

CIMdata believes that the Ansys modeling and simulation platform represents a significant step forward in providing a unified multi-physics, multi-domain, and

multi-scale platform for behavior modeling and simulation of complex products and cyber-physical systems. Ansys Workbench is continuously evolving from a portfolio of simulation and analysis software tools into an integrated behavior modeling and simulation environment that supports and enhances the ability of engineers across multiple domains to collaborate in the design and optimization of innovative products and cyber-physical systems in the evolving “Internet of Things” environment.

Ansys’ CEO is Dr. Ajei S. Gopal, a technology industry veteran who has served as a member of the Ansys Board since 2011 and was appointed CEO effective January 1, 2017. Dr. Gopal has strong ties to the high technology and venture capital segments from past executive positions with Silver Lake Partners, Hewlett Packard, CA Technologies, Symantec Corporation, and IBM. Dr. Gopal served briefly as the Ansys Chief Operating Officer during the transition period of August 2106 thru December 2016 prior to being officially elevated to CEO.

Dr. Gopal’s impact on the Ansys business has been notable as evidenced by Ansys return to double digit growth over the past several years and a dramatic increase in the market capitalization of the company. The company has been re-organized into a number of more autonomous business units focused on specific market segments and growth initiatives. Dr. Gopal has guided the Ansys senior management team to pursue and develop several major strategic go-to-market partnerships to expand the penetration of Ansys solutions into new industry segments such as fully autonomous vehicles as well as into adjacent markets within the PLM solution space leveraging Ansys technologies for physics-based digital twins. Several notable examples of these new partnerships during 2020 include:

- **Digital Twin Consortium**—To help accelerate the adoption and implementation of physics-based digital twin technologies across multiple industries, Ansys is partnering with Microsoft, Dell, and Lendlease on the steering committee of the [Digital Twin Consortium](#). The Consortium represents an international ecosystem of pioneering technologists that are influencing digital twin development, usage, and standards. For more details, see <https://investors.ansys.com/news/news-details/2020/Ansys-Microsoft-Dell-and-Lendlease-Unite-to-Expedite-Digital-Twin-Adoption/default.aspx>
- **EOS**—EOS and Ansys are collaborating to deliver an enhanced, streamlined user experience for developing additive manufacturing (AM) metal parts. EOS' advanced industrial 3D printing systems will be interoperable with Ansys simulation solutions, empowering AM engineers to create highly precise parts, boost productivity, reduce development time, and expedite new products to market.
- **Electro Magnetic Applications, Inc.** (EMA) partnership to deliver an enhanced design to validation workflow solution called Ansys EMA3DCable for certifying cable harness models in aircraft and automobiles. This new workflow promises to greatly reduce electromagnetic interference (EMI) risks to cable harnesses in aircraft

and vehicle applications, slash development time, speed certification, and expedite new products to market faster.

- Microsoft—Ansys expanded its partnership with Microsoft to integrate Microsoft Azure digital twins with the Ansys Twin Builder™ to help customers better understand the current and future performance of operational assets and improve in-service operations.
- Ansys 2020 R1 was officially released in January of 2020. For more details on what was included in this release, refer to:
<https://investors.ansys.com/news/news-details/2020/Ansys-2020-R1-Digitally-Threads-Simulation-Across-Product-Lifecycle-Processes/default.aspx>

New sales leadership, many with an EDA industry background, is providing a greater focus on enterprise-wide long-term relationships that are resulting in larger deal sizes and extended time durations. Both of these initiatives are recognition that to continue to grow Ansys at double-digit rates as a billion-plus dollar technology provider requires some changes to the success model that served Ansys so well in the past as the company grew from a \$200M niche provider in 2005 to the S&A industry leader.

While continuing to grow at double digit rates presents a real challenge for a \$1.5+ billion software organization, Ansys is bolstered by a very strong balance sheet and is well positioned to maintain its industry leadership position by providing comprehensive and high-performance multi-physics and multi-domain systems modeling and simulation capabilities for a wide range of engineers in globally distributed enterprises—especially in the cyber-physical systems domain. The major question for both Ansys management and investors is can Ansys continue to grow at well above double digit annual rates without making any major acquisitions. And the list of potentially available companies above the \$50-100M range of annual revenues is quite small in the traditional mechanical S&A domain. Will Ansys decide to expand its focus in EDA or AEC or even mechanical design? Only time will tell.

MathWorks

Founded in 1984, MathWorks is a leading provider of general-purpose mathematical computing software (MATLAB) as well as tools for dynamic modeling of complex systems (Simulink and Simscape). Privately owned, the company employs over 3,000 people in fifteen countries, with approximately 30% located outside the U.S. For the purposes of this analysis, CIMdata does not include their significant academic sales and estimates their 2020 revenue at \$1.1 billion. MathWorks has been highly profitable every year for over two decades and has largely developed their technology in-house with a very limited number of acquisitions.

MathWorks is still run by an inner circle of co-founders and longtime employees, who have used their expertise in mathematics, engineering, and computer science to develop MATLAB, a programming environment for algorithm development, data analysis, visualization, and numeric computation. Another primary offering, the Simulink product family, provides a graphical environment for simulation and model-based design of multi-domain, dynamic systems, and embedded software systems. MathWorks also offers a physical modeling suite called Simscape that

leverages the core Simulink System Composer module. This MBSE tool provides an environment for modeling and simulating physical systems spanning mechanical, electrical, hydraulic, and other physical domains. Simscape models can be deployed to other simulation environments, including hardware-in-the-loop (HiL) systems, via automated C-code generation. Another major product family is the Polyspace suite.¹³

As is true with all of the S&A industry leaders, MathWorks has continued to add new capabilities for users to leverage the latest advances in computing and IoT technologies. An excellent example of this is ThingSpeak, an IoT analytics platform service that allows engineers to aggregate, visualize, and analyze live data streams in the cloud. Users can send data to ThingSpeak from mobile or desktop devices, create instant visualizations of live data, and send alerts using web services like Twitter and Twilio. With MATLAB analytics inside ThingSpeak, users can write and execute MATLAB code to perform preprocessing, visualizations, and analyses. ThingSpeak enables engineers and scientists to prototype and build IoT systems without setting up servers or developing web software.

MathWorks is recognized globally as a leader in the growing areas of embedded software/controls, data analytics, artificial intelligence, and machine learning.

MathWorks has well over one million MATLAB users worldwide in both industry and academia (at over 5,000 colleges and universities). These offerings have a significant ecosystem of third-party developers of over 500 solutions that build on MATLAB and Simulink. These solutions help develop a wide range of advanced products, including automotive systems, aerospace flight controls and avionics, telecommunications and other electronics equipment, industrial machinery, and medical devices. Their website provides a broader list of industrial applications, adding biotech, pharma and medical, consumer goods, Earth and ocean sciences, financial services, process industries, semiconductors, and utilities and energy.

MathWorks' solutions are available through both direct sales and channel partners. The company has sales offices in Australia, China, Finland, France, Germany, India, Italy, Japan, Korea, The Netherlands, Russia, Spain, Sweden, the United Kingdom, and the United States. MathWorks offers both scheduled and on-site product training, as well as consulting services supporting projects in model-based and system-level design, application development, embedded systems development, and enterprise-wide integration of MathWorks products. Training, consulting, and system integration services are also available from their system integrator, service, and sales partners in many countries around the world. To illustrate the global reach of their solutions, the company claims that over 1,700 MATLAB-based books are available in twenty-eight languages.

Dassault Systèmes

Dassault Systèmes (NASDAQ: DASTY; Euronext Paris: #13065, DSY.PA) was the top overall PLM revenue generator in 2020. Their 2020 S&A revenue of \$831 million

¹³ More information on the MathWorks suite of software solutions can be found at https://www.mathworks.com/products.html?s_tid=gn_ps

was up 1.2% from 2019. This constitutes 16.8% of Dassault Systèmes' total 2020 PLM revenues.

Dassault Systèmes uses both direct and indirect sales models. Their direct Business Transformation sales team focuses on large accounts. Their Value Channel partners serve small- to medium-sized companies interested in the full Dassault Systèmes PLM portfolio, and their Professional Channel focuses on delivering the SOLIDWORKS portfolio, which includes SOLIDWORKS Simulation Premium and several other offerings. Nearly one-third of the company's employees are in R&D.

Dassault Systèmes offers one of the broadest and deepest suites of PLM offerings in the industry. Their **3DEXPERIENCE** portfolio is built on the evolved MatrixOne platform that includes an emphasis on supporting multi-physics simulation and analysis as well as systems engineering.

The corporate focus on the S&A segment is the SIMULIA brand, created in 2005 with the acquisition of Abaqus, Inc. based in Providence, RI. The SIMULIA division also includes the CATIA Analysis products team, based in France and the Cosmos team (part of SOLIDWORKS since the SRAC acquisition in 2001), as well as their many S&A acquisitions since.

SIMULIA offers an advanced simulation product portfolio widely used by CAE experts, including Abaqus, Isight, Tosca, fe-safe, Simpoe-Mold, Simpack, and SIMULIA SLM. In addition, SIMULIA solutions enable realistic simulation for both designers and design engineers currently working in the CATIA V5 or **3DEXPERIENCE** environments. These integrated analysis solutions eliminate geometry transfer and translation and allow users to perform analysis directly on their reference geometry model in CATIA.

Acquisitions

As with the other PLM/S&A solution providers, Dassault Systèmes has grown its S&A technology portfolio and revenues substantially over the past decade with a number of strategic acquisitions including iSight, SFE GmbH, FE-Design, SIMPOE, Safe Technology Ltd. Realtime Technology AG, SIMPACK, Accelrys, Computer Simulation Technology (CST) of Germany, Exa Corporation (EXA) and COSMOLogic.

In addition, 2018 saw Dassault Systèmes complete the acquisition of No Magic, the provider of the MagicDraw systems architecture modeling tools that enable MBSE. This acquisition reinforces and expands upon their existing MBSE capabilities within CATIA that were based on the Dymola acquisition. It will be interesting to observe if, how and when they integrate the world-class MBSE capabilities of MagicDraw/CAMEO within the **3DEXPERIENCE** platform.

With these acquisitions, it is clear that Dassault Systèmes has the technology to create powerful S&A tools for optimizing product designs early in the development cycle, as well as extending the S&A usage across more domains and later in the lifecycle than ever before, including manufacturing and in-service S&A applications. Beyond the standalone SIMULIA product releases, Dassault Systèmes S&A product R&D

efforts are focused on the Dassault Systèmes **3DEXPERIENCE** platform, an evolution from V5 into an integrated enterprise PLM/SDPM platform that includes an integrated suite of robust S&A capabilities. The base S&A capabilities include multi-physics solutions based on Abaqus, Exa, CST, and other S&A technologies, process orchestration and optimization (as found in Isight), and data analytics. Simulation data and process management is also tightly integrated, not an add-on. Such platform solutions provide an environment for data sharing and team collaboration that enables cross-domain digital engineering processes.

For more detailed information on the DS **3DEXPERIENCE** and SIMULIA portfolios, see <https://www.3ds.com/products-services/simulia/>.

With all of these acquisitions, it is important for Dassault Systèmes to maintain the openness of the SIMULIA portfolio and other acquired S&A tools to continue support for substantial customer base that does not use other core Dassault Systèmes offerings such as CATIA and ENOVIA or the **3DEXPERIENCE** environment.

The Dassault Systèmes CAA Partner program encourages software development partners to build their offerings on the Dassault Systèmes platform. The CAA V5 program was quite successful. Several analysis solution providers are CAA partners and offer solutions tightly integrated with CATIA V5. The **3DEXPERIENCE** versions of these same integrations are under development and the program is ongoing.

Siemens Digital Industries Software

Siemens Digital Industries Software, a business unit of Siemens AG (NYSE: SI; Deutsch Börse: SIE), sustained its position as one of the major providers of PLM solutions during 2020. In this report we have referred to Siemens Digital Industries Software as Siemens. Their 2020 S&A revenue of \$785 million was down 5.4% from 2019. This constitutes 16.5% of Siemens total 2020 PLM revenues. Growth was primarily organic and revenue impact from new acquisitions.

The Siemens Simcenter portfolio is sold using both a direct sales force as well as partner channel sales. Siemens has over 550 channel partners globally and most sell and support the Simcenter and NX portfolios.

Since the closing of the LMS acquisition in 2013, Dr. Jan Leuridan, ex-CTO of LMS, has been responsible for all of the Siemens simulation, analysis, and testing business worldwide as Senior VP of Simulation and Test Solutions (STS). Dr. Leuridan continues to be an S&A industry pioneer and thought leader and comes from a technical background developed over four decades of problem-solving consulting using both test and analysis methods within the automotive and transportation, aerospace and defense, and heavy machinery industries worldwide. However, CIMdata understands that Dr. Leuridan will be retiring in 2021. So, it will be interesting to see who is chosen to lead up this business going forward.

Siemens is focusing on the next generation of integrated, analytics-driven performance engineering solutions that will enable companies to address the business and engineering challenges that industry faces. Siemens domain expertise and technology advancement track record within the simulation, analysis, and

physical testing segments spans more than 40 years leveraging the SDRC I-deas Simulation and Nastran tools, as well as the acquired technologies and products from LMS, CD-adapco, TASS, and the Mentor simulation suites. The Mentor Graphics acquisition by Siemens included S&A revenues and S&A technology assets, most notably the former Flomerics Group CFD portfolio, acquired by Mentor Graphics in 2008, and the Flowmaster Group portfolio, acquired in 2012. There were no substantial S&A-focused acquisitions during 2020 but Siemens has continued to expand on the legacy of previous acquisitions to solidify the Simcenter brand. For example, in December 2020 Siemens acquired Culgi, a niche provider of chemical modeling and simulation applications.

The Simcenter suite of simulation, analysis and test solutions resides within the Xcelerator portfolio, an integrated portfolio of software, services and an application development platform whose goal is to speed the digital transformation cycle and merge the boundaries between traditional stand-alone engineering domains such as electrical, mechanical and software. Simcenter is now the umbrella brand for the entire Siemens portfolio of model preparation and simulation, optimization analysis, testing, and related analytics capabilities.

Simcenter supports next generation model-based engineering (MBE) processes as well as traditional product verification and validation activities across the entire business lifecycle from ideation to realization and into utilization. Digital twin-related solutions are being tailored by user persona to address needs for design engineers, dedicated analysts, test engineers, domain specialists, and decision makers while enabling collaboration within the broader enterprise. Significant R&D investments are going towards supporting major industry trends such as 3D printing and additive manufacturing, autonomous systems, electrification, 5G, MBSE, and IIoT. Siemens strategy emphasizes a hybrid approach that combines the strengths of simulation and analysis with physical testing and data analytics to accelerate all phases of development for complex systems.

Simcenter works with Siemens' open IoT ecosystem, MindSphere, for incorporating analytics into virtual simulations for predictive engineering. Simcenter is also integrated with the Siemens collaborative product development backbone (Teamcenter) for simulation and test data management and overall performance engineering process management. With recent product releases, such as the Simcenter Webapp Server, Simcenter also harnesses the power of Mendix within the Xcelerator platform, to enable consumption of simulation models throughout the enterprise, which is essential to enabling and deploying Model Based Engineering approaches.

As such, CIMdata believes that the Simcenter portfolio represents a major step forward as a comprehensive enterprise-level solution for multi-physics and multi-domain behavior modeling and simulation of complex products and cyber-physical systems that can truly make simulation and analysis an integral element of an end-to-end digital engineering environment.

Siemens created Simcenter to provide the breadth and depth of capabilities needed by manufacturing organizations and their global supply chains to deliver timely

simulation-driven product decisions at any stage in the product design process. The Simcenter portfolio is based on an open platform strategy. For example, Simcenter 3D simulation solutions based on the NX geometry kernel (Parasolid) are interoperable with all major mechanical CAD solutions and support a host of industry data exchange standards as well as a number of third-party simulation solutions (e.g., MSC Nastran, Ansys, LS-DYNA, and Abaqus). As a result, even in companies where there is no use of NX CAD or the Teamcenter collaboration backbone, CAE analysts requiring a CAD-agnostic, advanced multi-physics modeling and simulation environment use the applications available within the Simcenter portfolio. Other solutions in the Simcenter portfolio similarly offer varying degrees of interoperability with third-party solutions.

Simcenter 3D represents an extensive set of CAD-neutral modeling with multi-discipline solutions for structural, motion, thermal, advanced materials and composites, acoustics, flow simulation, both low- and high-frequency electromagnetics, environment simulation, and design optimization. Capabilities from the former NX CAE suite are integrated with Simcenter Nastran along with the former LMS 3D Simulation solutions (LMS Virtual.Lab and LMS Samcef) as well as other industry vertical solutions into a single, multi-discipline environment for the CAE analyst. These simulation capabilities are available both standalone as well as fully integrated into the NX product development application for ease of use by design engineers. Other solutions tailored to use by design engineers include Simcenter FLOEFD and Simcenter Flotherm from the Mentor acquisition

Siemens also offers Simcenter Femap within the Simcenter portfolio, a CAD-agnostic, standalone FE modeling environment that is also available integrated with the Solid Edge design solution. Simcenter Femap offers direct interfaces with other widely-used CAE/simulation solutions, including MSC Nastran, Abaqus, Ansys, and LS-DYNA.

Simcenter Nastran is Siemens' version of the widely used Nastran structural FEA solver based on the source code obtained from MSC Software in 2005. While maintaining full compatibility with the long-established Nastran input and output file formats, Siemens has invested significantly in new functionality to ensure that Simcenter Nastran provides world-class FEA capabilities at a very competitive price.

Simcenter STAR-CCM+ is a multiphysics engineering solution for CFD engineers. It integrates comprehensive physics with intelligent design space exploration in a single CAD-to-solution environment to automate the prediction of product performance and to guide product design. The physics models in Simcenter STAR-CCM+ include fluid dynamics, solid mechanics, electromagnetics, heat transfer, multiphase flow, particle dynamics, reacting flow, electrochemistry, aero-acoustics, and rheology. Simcenter STAR-CCM+ offers intelligent design exploration (see reference to HEEDS below) built directly into the engineer's familiar simulation workflow, leveraging its automated meshing, repeatable workflow, accurate physics, and scalability to overcome the complexities that have historically prevented CFD simulation from being used in this way. This significantly improves the analysis process from running single point simulations to analyzing hundreds of design variants to determine the key trade-offs in design.

Simcenter also includes easy-to-use design exploration capabilities delivered through the HEEDS technology. HEEDS integrates with existing design and simulation tools and leverages high-performance computing infrastructures to automate design exploration studies and augment engineering decision-making.

The Simcenter System Simulation portfolio includes the 0D/1D systems design and analysis capabilities of Simcenter Amesim enhanced by the special purpose Simcenter Flomaster 1D product for modeling and analyzing complex piping systems. Other capabilities that help enable model-based systems engineering include Simcenter System Architect and Simcenter Embedded Software Designer (now also part of the Capital E/E Systems Simulation solution). The system simulation offerings also include dedicated solutions for the automotive industry such as Simcenter Prescan for ADAS and AV system simulation.

With the acquisition of MultiMechanics, and through a partnership with Citrine, an AI based innovation leader for materials development, Simcenter is rapidly expanding its capabilities to fuse materials engineering and product engineering, so that the microstructure of materials can be used as a degree of freedom in the optimization of a product for weight and performance. Such capability is essential in the application of composites, and off course for products that are manufactured through 3D printing and additive manufacturing processes.

The Simcenter portfolio also includes a suite of physical test data acquisition and data analytics solutions that complement and enhance the simulation suite to provide integrated hybrid digital/physical solutions (i.e., digital twins) for closed loop performance engineering across the entire product lifecycle.

Simulation data and process management capabilities, for simulation and test data and workflows, are delivered through a dedicated module of Teamcenter called Teamcenter Simulation along with Simcenter Sysdm (0D/1D only), thus ensuring that all simulation and verification activities are managed as part of an organization's PLM strategy and linked to other lifecycle activities.

Based to a large extent on the SDRC, LMS, and CD-adapco acquisitions, Siemens also offers engineering consulting services ranging from testing and mechanical simulation to solve product development issues related to noise, vibration, and harshness (NVH), acoustics, durability, crash, dynamics, performance, flow, fuel economy, energy management, autonomous vehicles, and controls development as well as process consulting focused on implementing model-based engineering best practices combined with technology transfer to customers.

For more detailed information on the Siemens Simcenter portfolio, see <https://www.plm.automation.siemens.com/global/en/products/simcenter/>.

With the major acquisitions of the past several years, the modeling and simulation capabilities of the Siemens portfolio now span the major engineering domains (mechanical, electrical/electronics, controls, and embedded software) and the multi-physics-based disciplines that need to be integrated to produce and manage today's complex cyber-physical products, systems, and systems of systems. The strong ties to Siemens AG corporate headquarters and its Industry 4.0 initiatives combined with

access to the many industrial products divisions of Siemens AG provides a special perspective on how to define the next generation of product innovation technologies and a product innovation platform environment that facilitates collaboration across global enterprises, including their supply chain partners. The challenge now for Siemens is to provide all of those integrated PLM and IoT technologies to a wide spectrum of end users in a manner that is readily useable, managed, and sharable to enable their best practice processes and cross-domain collaboration requirements.

Altair

Founded in 1985, publicly traded Altair (NASDAQ: ALTR) has a track record of providing high-end software for engineering and computing, enterprise analytics, and product design and development. Their 2020 S&A revenue of \$470 million was up 2.4% from 2019.

Altair has regional offices throughout North America, South America, Europe, and Asia-Pacific. In 2013, Altair expanded their presence in the Middle East by opening offices in Greece and Israel. Altair has more than 3,500 employees located in 22 countries serving over 5,000 clients in the aerospace, automotive, consumer products, heavy equipment, government and defense, and oil and gas industries. Altair's research and development team consists of over 1,000 people worldwide. The majority of research and development staff is still based in Michigan and India; however, Altair also maintains research and development centers with specific technical expertise in other locations based on regional needs and due to the numerous acquisitions completed over the past five years. While Altair has a long history and strong presence in the automotive and transportation industry, they are also making steady inroads into other market segments such as high-tech electronics, aerospace and defense, consumer products, medical equipment, energy, and AEC.

The company achieved a major milestone in its illustrious history by conducting a very successful IPO in November of 2017. The Altair IPO was over-subscribed, and the stock price has appreciated almost 400% since the initial offering with the company valued now at over \$4.8B.

Altair has evolved significantly over the past several decades from being a niche provider to a global enterprise-class engineering technology company. From their roots in structural analysis software such as Hypermesh, Altair now provides software and cloud solutions in the areas of simulation-driven product development, high performance computing (HPC) and data intelligence. Similar to the other major S&A platform companies, Altair is focused on enabling innovation, reducing product development times, and lowering costs for its customers throughout the entire product lifecycle from concept design to in-service operation. Altair's simulation-driven approach to innovation is powered by an integrated suite of software that helps optimize design performance across multiple disciplines encompassing structures, motion, fluids, thermal management, electromagnetics, system modeling, and embedded systems, while also providing data analytics and true-to-life visualization and rendering.

Altair's strategic vision to revolutionize product development centers on enabling model-driven design, where models of different fidelity levels encapsulate product

performance data and enable collaboration and concurrent development across multiple engineering domains and different physics disciplines. Altair's technical strength in simulation-driven design optimization is also a key factor in this vision.

Altair delivers a comprehensive multi-physics suite of engineering analysis software and is constantly extending the breadth and depth of their performance modeling and simulation capabilities. Altair's software products, available under the HyperWorks, solidThinking, Inspire, Altair PBS, SmartWorks, and KnowledgeWorks brands, represent a comprehensive, open architecture computer-aided engineering simulation platform. Altair's broad suite of product capabilities can be categorized by the following application areas:¹⁴

- CAE Solvers & Optimization—HyperWorks suite
- CAE Modeling & Visualization—HyperWorks suite
- Systems Modeling/MBD—Compose, Activate, and Embed
- Electronic Design Automation—PollEx, ElectroFlo, and Embed, Accelerator
- Industrial & Concept Design—solidThinking and INSPIRE
- Internet of Things—SmartWorks, Panopticon, KnowledgeHub, and Embed
- Analytics and AI/Machine Learning—KnowledgeWorks
- HPC— PBS Works suite, Altair Access, SAO, Monitor, and Allocator

Altair goes to market using both direct sales and a global network of channel partners. Altair's large engineering services group brings in significant revenues. Altair also manages several software and services partner programs. In their HyperWorks Partner Alliance program, independent software solution providers (ISVs) make their technology available on the Altair platform. The ISV Integration partner integrates their applications with Altair's technology platforms; the customer uses the partner's software under one license using Altair's on-demand, token-based software licensing system. Over 60 independent software companies have joined the program, effectively extending the HyperWorks platform from a suite of 35+ internally developed Altair solutions to almost 100 unique applications. Altair customers can invoke these third-party applications at no incremental cost and paperwork using their existing HyperWorks token-based licenses.

Technology partners also provide hardware and peripheral technology, and implementation partners help bring technology to customers. Overall, Altair manages relationships with over 250 partners across all programs including go-to-market sales and support channels.

Over the last decade, Altair has demonstrated their leadership and commitment to cloud computing for S&A applications. In June 2011, Altair announced HyperWorks On-Demand. During Q4, 2014, Altair announced the opening of a high-powered data center in Troy, Michigan to house their HyperWorks On-Demand (HWOD)

¹⁴ For a more complete description of the Altair products portfolio, see <https://www.altair.com/>

cloud-based S&A solution. HWOD uses Altair's patented token-based licensing system to provide access to HyperWorks on a modern scalable HPC infrastructure using a secure web-based platform.

Altair has continued to broaden the scope of their cloud offerings. They offer a cloud appliance as well as a hardware-plus-software solution that includes unlimited use of the HyperWorks software suite that can be installed as a private cloud resource within a customer's firewall. The Altair Simulation Cloud Suite offers pre- and post-processing, solving, and data and process management accessible through a web browser interface.

Altair has taken innovative access to CAE software and HPC resources to the next level by offering a complete range of cloud-based solutions. Users are able to run CAE simulations instantly on their desktops by leveraging Altair's Hosted HyperWorks Units (HHWU). For enterprise capabilities, customers can scale on premises (HyperWorks Unlimited) or on the cloud (HyperWorks On-Demand) while simultaneously managing the entire simulation data lifecycle with Altair's Simulation Cloud Suite.

HyperWorks Unlimited, an innovative HPC appliance for CAE, is delivered as a turnkey system to the customer's site. It comes fully configured with HPC hardware and Altair software, offering unlimited private cloud use of all Altair HyperWorks engineering applications.

Altair has been extremely active in acquisitions within the past decade as it worked to expand the scope of its multi-physics, multi-domain, and data analytics offerings and fill in the gaps in its strategic product plans. Acquisitions have brought in new technologies and expertise in the areas of 3D solid modeling; electromagnetic interference and wave propagation simulation; electromagnetic field analysis of 3D structures; composites design, micromechanics of materials; fatigue analysis; bulk materials simulation; high frequency noise, vibration, and acoustics simulation; electronics systems design and analysis; IoT big data analytics; and AI/Machine Learning. Acquisitions in 2020 included newFASANT, S&WISE Co. Ltd., Univa, Ellexus, and M-Base Engineering + software GmbH. We expect this aggressive M&A activity will continue as new business opportunities arise.

The Altair management and product development organization has demonstrated a strong track record in successfully integrating many niche CAE technologies into the HyperWorks platform as well as extending into new domains such as high-performance computing and IoT, all while maintaining above market growth rates. CIMdata expects Altair to continue to expand their S&A and data analytics offerings into new vertical market segments beyond their traditional strengths in automotive/vehicles and industrial equipment.

MSC Software (Hexagon)

MSC Software Corporation was formed in 1963 under the name MacNeal-Schwendler Corporation (MSC) and was recently recognized as one of the "ten original software companies." In 1965 MSC won the contract to develop and commercialize MSC NASTRAN through a NASA-sponsored project. Once a public

company, MSC Software was acquired in July 2009 by the private equity firm Symphony Technology Group. During April 2017, the company was acquired by Hexagon AB of Sweden for ~\$835 million. Hexagon AB is a leading global provider of information technologies that drive productivity and quality across geospatial and industrial enterprise applications. Other well-known software brands in the Hexagon portfolio include Intergraph, Leica, and Vero Systems. At the time of the acquisition, MSC Software employed over 1,200 engineering professionals in 20 countries.

MSC Software is a fully owned subsidiary of Hexagon and now operates under the Manufacturing Intelligence (MI) Division of Hexagon AB. MI's main business is in the automotive, aerospace, machinery, consumer electronics, and other discrete manufacturing markets, and is increasingly focused on offering end-to-end solutions for use cases in these segments.

MSC Software offers a broad portfolio of technologies to support a range of S&A scenarios: systems and controls, rotor dynamics, explicit dynamics, structural analysis, thermal analysis, multi-physics, multidiscipline, motion analysis, noise and vibration, nonlinear analysis, composites, design improvement and optimization, process automation, and simulation data and process management. Their 2020 S&A revenue was \$283 million, up 6.5% compared with 2019.

MSC Software operates both global direct sales and support organizations and has an extensive VAR program for their simulation business. Their Global Engineering Services group maintains offices in Newport Beach, California; Munich; Tokyo; and Singapore. The group offers a standard range of software support services, as well as staff augmentation and simulation projects.

MSC Software has three types of technology partners:

- Performance Partners including AMD, HP, Intel, Cray, IBM, Oracle, NVIDIA, SGI, and others, provide optimized hardware and software.
- Software Community Partners including Aras, AVEVA, AVL, BetaCAE, CONTACT Software, ESTECO, Infolytica PTC, Phoenix Integration, SmartUQ, Vistagy), and others build and market products that incorporate or interface with MSC Software technology.
- Technology from Software Solution Partners including Dassault Systèmes, Siemens, Fraunhofer SCAI, CAEfatigue, VCollab, KISSsoft, nCode, Distene, and others, supply technologies that are incorporated into products built and marketed by MSC Software.

In 2013, MSC Software formally announced the long-rumored Predator R&D project, and first released a commercial product during 2015 under the Apex brand name. The goal of Apex is to transform the way engineers perform simulations by reducing critical CAE modeling and process time from days to hours and provide integrated multi-physics solutions. Apex will ultimately serve as the next generation MSC platform for a broad range of multi-physics modeling and vertical analysis applications that MSC Software intends to introduce over the next several years. The Apex platform employs built-in geometry and meshing technology designed to facilitate faster simulation workflows.

During the first quarters of 2019 and 2020, MSC announced the latest releases of Apex which enables enhanced interoperability between MSC Apex and MSC Nastran. With the new FEM pre-processing workflow, MSC Apex users can now import MSC Nastran models, modify mesh topology, attribute the model, create scenarios, and generate a ready-to-run Nastran file for external Nastran solvers very quickly. MSC Nastran results files can also be imported into MSC Apex for users to conduct post-processing in MSC Apex after the MSC Nastran analysis is finished, and use the new results exploration capabilities in MSC Apex.

This capability has been a long time coming but it is certainly a major step forward for Apex to have the features and capabilities to be able to augment and potentially replace the legacy Patran and SimXpert pre- and post-processing software products. However, Apex is fundamentally a different user paradigm than a first-generation modeling product such as Patran. As such, to our knowledge, there is currently no formally announced plan for migrating or retiring those widely-used legacy tools, especially in mission critical aerospace and defense applications where MSC tools such as PATRAN and Nastran have been tightly embedded in validated S&A processes and engineering workflows for over 40 years. Fortunately for MSC, change comes very slowly in the S&A market and there is time for them to continue to mature the Apex offerings with key customers who rely on their S&A technologies.

Hexagon's strategic focus for MSC Software's R&D efforts has had a substantial impact on the strategic direction and scope of the MSC portfolio as Hexagon places increased emphasis on integrating MSC Software tools into vertical applications for generative design, manufacturing process simulation, metrology and material simulations, physics-based digital twins, and autonomous vehicle design and development.

MSC Software had been relatively low profile in the S&A market over 5+ years as a private company owned by the Symphony Technology Group but is now beginning to re-emerge in market visibility under Hexagon AB leadership. During Q2 of 2019, Hexagon's Manufacturing Intelligence division announced that Hexagon entered into a definitive agreement to acquire [AMendate](#), a German-based start-up providing simulation software solutions that support the generation and optimization of designs for additive manufacturing. AMendate joins Hexagon's MSC Software business in providing CAE simulation software and services with a focus on generative design solutions for additive manufacturing processes.

In Q1, 2020 Hexagon AB announced the signing of an agreement to acquire Romax Technology Limited, a leading provider of CAE software for electromechanical drivetrain design and simulation. Headquartered in Nottingham, UK, Romax Technology has approximately 240 employees globally serving more than 250 customers in the automotive, aerospace, wind power, marine, bearing, and rail industries. The company will operate in partnership with MSC Software as part of Hexagon's Manufacturing Intelligence division.

Hexagon also added CAEfatigue Limited located in London, England to the MSC Software portfolio during 2020. CAEfatigue provides a random response post processor and a vibration fatigue solver. It works with mixed random and

deterministic loading to provide fatigue life and damage predictions as well as several forms of response statistics.

For more information on the current MSC Software portfolio, see <https://www.mssoftware.com/>.

A new MSC senior management team is now in place including a CEO and several other key players who came to Hexagon/MSC Software via acquisitions. The business now has eight distinct product groups, each with their own product leader. So it will be very interesting to monitor Hexagon MI's progress as their plans for MSC Software mature into new commercial software offerings and dictate what areas MSC Software will continue to be a major player in the S&A software market.

ESI Group

The ESI Group (Euronext Paris: #4110310, ESI) is a global provider of virtual prototyping, systems simulation, and virtual reality solutions used for virtual product performance analysis, and manufacturing process engineering. Their 2020 S&A revenue of \$151 million was down 7.8% from 2019. ESI was founded in France in 1973 and had its initial public offering in July 2000. The company employs approximately 1,200 people worldwide. Headquartered in Paris, the company and its global network of agents and distributors provide sales and technical support to customers in more than 40 countries. The ESI Group serves customers in the automotive and transportation, A&D, heavy industry and energy, electronics, and consumer goods industries. The company offers a range of services, including engineering, methodology development, process automation, training, and technical support.

ESI operates several partner programs. Software partners include various independent solution providers (ISVs) such as Altair, Dassault Systèmes, Microsoft, Oracle, and others. Hardware partners, including AMD, Bull, HP, IBM, Intel, Sun, Cray, and SGI, work with ESI to tune software solutions and achieve best-in class performance. The third-party partner category captures custom partnerships. ESI is also active in industry consortia and other special projects.

Like many of the leading S&A multi-physics platform solution providers, ESI has a comprehensive vision of a virtual prototype that minimizes or even replaces physical prototypes and testing spanning conceptual product engineering, detailed design development, and validation. But perhaps what is most compelling about ESI's approach is their strength and additional focus on design simulation for materials selection and optimization of selected manufacturing processes. And more recently, ESI has focused its market positioning around the concept of the Hybrid Twin™. ESI positions its Hybrid Twin solutions as representing the product in its development phase (what they call traditional PLM), as well as in its 'in-service' operational conditions (what ESI calls the Product Performance Lifecycle™, "PPL"). As part of its global strategy, ESI has reorganized to bring the group's business and executive management in line with ESI's new Hybrid Twin value proposition. ESI Group's organization is now structured around three business pillars: Engineering (design and development of industrial Products), Manufacturing (manufacturing of Products) and In-Service (usage, control and maintenance of

products, from launch to withdrawal, in alignment with meeting the challenges of Industry 4.0, the Smart Factory, and the Outcome Economy.

Based on a single common core data exchange paradigm across engineering and manufacturing application domains, the ESI platform is designed to provide a unified environment for multi-physics and multi-domain behavior modeling and simulation of complex cyber-physical systems that is collaborative, visually robust, data-managed, and predictive analytics-centric. See www.esi-group.com.

ESI's Product Performance Lifecycle (PPL) value proposition is based on a three-phase transformative strategy of developing, validating, and continuously enhancing industrial systems and their manufacturing processes, what ESI refers to as "hybrid digital twins" that span the entire product lifecycle. They describe the main principles as:

- Understand the Physics—Build, exercise, and evaluate the "as designed" product using digital prototypes across multiple performance domains that represent the real-world usage of the product. This includes virtual prototyping for not only the conceptual design and development of the product, but also for simulation of key manufacturing systems and processes required to build the product (e.g., stamping, forging, subtractive techniques, etc.).
- Experience the Virtual Design—Design, manufacturing, and operations teams interact collaboratively with the functional 3D "hybrid digital twins" in an immersive 3D virtual reality environment.
- Enable Real World Decisions—Link the hybrid digital twins with the physical product (as designed, as built, and in service) to discover correlations and variances in system performance characteristics and to drive better next generation product design decisions via model-based predictive analytics.

The ESI virtual PPL portfolio has been expanded significantly by a series of strategic acquisitions of simulation and related IT technologies. Significant focus is now being placed on realizing the desired business benefits of digitalization across the virtual enterprise. Hybrid digital twins enabled by machine learning, artificial intelligence, predictive analytics, and virtual reality are rapidly gaining the attention of both product manufacturing organizations as well as their supply chains, customers, and operations support partners.

ESI's corporate business and product strategy includes a strong focus on acquiring and integrating niche simulation technologies to complement and round out their portfolio of virtual prototyping and digital twin solutions. ESI continues to execute on this corporate strategy to provide multi-domain and multi-fidelity solutions for realistic virtual prototyping of both components and systems by unifying the detailed 3D/4D capabilities of FEA, SEA, and CFD with the 0D/1D systems simulation space, as evidenced by S&A acquisitions of the OpenFOAM, Efield, PRESTO, Ciespace, and SimulationX technologies.

With all of this acquired technology and associated people expertise, ESI is now focused on creating the next generation of cloud-based and integrated multi-physics

performance modeling and simulation solutions that will help companies address future business and engineering challenges in the environments of IoT and Industry 4.0 (the Industrial IoT), Smart Factory, and the Outcome Economy.

ESI's ultimate goal is to tightly link the PPL virtual and physical worlds for targeted industry applications using a model-based product development environment coupled with virtual reality and real-world predictive data analytics and physics-based digital twins.

Cybernet Systems

Established in April 1985, Cybernet Systems was spun out of Control Data Corporation (CDC) and is located in Japan. Cybernet has customers in the automotive, power electronics, heavy industry, transportation equipment, machinery, electronics, electrical, semiconductor, healthcare, medical, and AEC industries. Special skills and offerings include machinery, mechatronics, embedded systems, control systems, and optical analysis.

Their 2020 S&A revenue was \$164 million, up 5.2% over 2019. The company reports ~600 full-time employees with another 370+ working as contractors or part-time staff. The majority of the company's S&A revenues are derived from the sale of third-party commercial software and associated engineering services. The company is organized by S&A solution, and each group has its own sales and marketing organization. The company operates subsidiaries in the United States, China, South Korea and Taiwan, and includes Sigmetrix in Texas (a July 2009 acquisition for their tolerance analysis solutions), Maplesoft based in Ontario, Canada (acquired in September 2009 for analytical and systems modeling software), and Noesis Solutions NV based in Leuven, Belgium (acquired in July 2010 for robust design and optimization). The Maplesoft and Noesis software products and services businesses owned by Cybernet account for approximately \$20-25M of their S&A total revenues.

Cybernet's broad range of services includes providing contracted analysis services, as well as building models and custom analysis software development.

Cybernet's sales efforts focus on six areas:

- **Multi-Domain Solutions:** This category focuses on multiphysics and highlights how Cybernet can craft custom solutions by combining heterogeneous S&A tools like Ansys, MapleSim, and OrCAD. Cybernet is a major channel partner for Ansys in Asia/Pacific.
- **CAE Solutions:** Their portfolio includes mostly offerings they resell, including Ansys, CETOL, Invention Machine (now part of IHS), Cadence, CODE V, LightTools, Optimus and Maplesoft.
- **Product Design Innovation:** The group focuses on supporting Invention Machine's Goldfire for innovation, Optimus for process automation, and CETOL 6 σ for tolerance analysis.
- **3D Visualization & Tolerance Analysis Solutions:** Offers a range of organic solutions including Sigmetrix and resells some others.

- IT Solutions: A more traditional IT services organization, Cybernet offers security, compliance, infrastructure, and smartphone support.
- Engineering Services: A range of services supporting tools such as MATLAB/Simulink, MapleSim, NOESIS Optimus, Ansys, CODE V, LightTools, PCB Design, and other tools are available. Areas of expertise include optics, optimization, process integration, tolerance analysis, and visualization.
- For more information on Cybernet Systems software portfolio see: <https://www.cybernet.jp/english/company/about/group/>

Autodesk

Autodesk (NASDAQ: ADSK) is a global design software and services company that serves customers in architecture, engineering, and construction; manufacturing; and digital media and entertainment. Autodesk is organized in four operating segments:

- AutoCAD and AutoCAD LT
- Architecture, Engineering, and Construction (AEC)
- Manufacturing (MFG)
- Media and Entertainment (M&E)

Autodesk has historically been considered primarily a design solution provider with AutoCAD, Inventor, and Vault in their Product Design and Manufacturing segment and AutoCAD and Revit in the AEC segment. Through acquisitions over the last 6 to seven years, Autodesk has built a significant S&A portfolio, including Blue Ridge Numerics for CAD-integrated CFD; Moldflow for injected molded plastics manufacturing simulation; Algor for general purpose structural and thermal analysis; Firehole Technologies for design analysis and failure prediction of products made from advanced composite materials; and most recently in 2014, NEi Software for advanced structural analysis based on a proprietary version of the widely used Nastran finite element solver. By the end of 2014, Autodesk had invested over \$550 million on acquisitions and internal developments in the S&A space. There were no significant S&A acquisitions since then and Autodesk has certainly been much less proactive in promoting its S&A portfolio since the flurry of acquisitions and new product announcements that occurred between 2012 and 2014. While several of the acquired technologies are now available on the Fusion 360 platform, it is not clear to CIMdata how much the strategic focus on S&A has diminished within Autodesk over the past several years.

Autodesk's 2020 S&A revenue of \$135 million was up 17.7% from 2019, largely a result of their license model transition from perpetual licensing to subscription. This constitutes 3.8% of Autodesk's total 2020 PLM revenues. It is important to note that Autodesk has transitioned from perpetual licensing to subscription-based licensing for almost all of their products. This license model change impacts revenues in the short term and, based on the experience of other companies like Adobe, it can take several years for the company to return to similar revenue levels. In fact, Autodesk told the investment community that their annual revenue would decrease by about 25%, consistent with these results. Autodesk has progressed through the transition,

with revenues increasing over 20% in their last fiscal year. Analysts predict that this transition will help keep Autodesk's growth in the high double digits for the next several years. As a result, we expect to see a substantial increase in their S&A revenues as well.

Globally, Autodesk sells and supports their products mostly through indirect channels of distributors and resellers (typically over 80% of total revenue). A small portion of their revenue is from direct sales to large corporations. Autodesk has a network of approximately 2,500 resellers and distributors worldwide.

Autodesk is often cited as an innovative company. This is evident in their use of technology, such as high-end rendering across the domains of creative design, AEC, CAD, and physics-based simulation. The company has also shown a strong willingness to experiment, often introducing beta code from their Autodesk Labs. Many projects focus on two very different delivery models.

In September 2013, Autodesk announced the Autodesk Cloud (now Fusion 360), a collection of more than a dozen web-based products and services, highlighting their commitment to cloud-based services. Sim 360 makes high-performance computing for simulation available on the cloud, includes simplification and editing tools similar to Fusion 360, and features an intuitive interface that enables users at any level to perform simulations and finite element modelling. Sim 360 promises to greatly reduce the hassle and cost of entry to simulation for small companies and occasional users of advanced simulation and HPC.

The acquisition of Moldflow provided complete plastic injection molding capabilities to optimize product design, mold design, and related manufacturing processes to create high-quality plastic products and avoid potential manufacturing defects.

Autodesk extended its cloud-enabled simulation portfolio with the addition of products based on the acquired NEi Nastran technology: Nastran In-CAD (versions 2019 and older) or Inventor Nastran (versions 2020 and newer).

The Autodesk Nastran solver can be used directly with the Inventor Simulation Mechanical suite as well as with many of the popular FE modeling tools such as Siemens' Femap and MSC Patran. Nastran In-CAD is a version of the NEi technology that is tightly integrated with Autodesk Inventor as well as with SOLIDWORKS. Nastran In-CAD offers a wide range of simulation capabilities that span both linear and nonlinear structural analysis, thermal analysis, and other physics.

In November of 2019, Autodesk and Ansys announced a strategic partnership to provide a higher level of integration between Autodesk Fusion 360 and Ansys Mechanical. The collaboration connects Fusion 360, integrated design, and manufacturing software, with Ansys Mechanical simulation solutions.

This integration breaks down silos in the product development process by driving a connected and interoperable designer-to-analyst workflow for Autodesk Fusion 360 users. As engineers leverage Fusion 360, their results are automatically available in Ansys Mechanical for further refinement and validation.

For more information on the Autodesk portfolio of design analysis capabilities, see: <https://www.autodesk.com/solutions/simulation/overview>.

Autodesk has a special focus on small businesses and professional companies comprised of an office with two or three engineers or architects. To that end, they have concentrated on tools to democratize simulation and make S&A tools available to a wider audience of non-experts at a very attractive price point. That focus is dramatically different from all of the other major PLM and S&A leaders.

BETA CAE Systems

BETA CAE Systems was founded in the early 1990s in Greece. The company is still privately owned and has grown organically at a very steady pace of 10 to 15% per year over the past decade. The company moved its corporate headquarters to Switzerland during 2018 but most of its technical R&D staff remains in Greece.

Their flagship product is ANSA, widely used in the vehicle, transportation, and heavy equipment industries for structural NVH analysis (noise/vibration/harshness), crash simulation, and occupant safety certification. Another core product offering is META, a high performance multi-disciplinary CAE post-processor.

While the vast majority of BETA CAE's \$100 million in revenues during 2020, an increase of 75.% over 2019, still comes from these industry sectors, they are experiencing solid growth in other markets such as aerospace, defense, shipbuilding, process and energy, electronics, and consumer products. BETA CAE is highly regarded within the global S&A user community as a technology-driven company of high integrity with a very strong focus on customer support and satisfaction.

While ANSA and META are widely used with many of the leading CAE solvers such as LS-DYNA, Nastran, ABAQUS and RADIOSS, BETA CAE also entered the structural analysis solutions market during 2016 by releasing its own FEA-based solver called EPILYSIS. The solver is tightly integrated with the ANSA/META environment and is focused on enabling analysis for basic physics applications such as linear static and dynamic structural, structural implicit nonlinear and sub-structuring. EPILYSIS is also designed to take advantage of HPC capabilities to rapidly solve very large and computer-intensive simulation models.

During 2017, BETA CAE introduced RETOMO to address the need of contemporary industry to embed new approaches, such as Computer Tomography (CT), and the resulting data into the CAE process. This new software couples simulation and physical objects even for high-end complex, multi-material structures. RETOMO enables the correlation of CT with CAE and CAD data, by applying high-end methods to read, process, reduce, reconstruct, and visualize CT images, and output them as tessellated models.

BETA CAE also now offers a simulation process, data, and resources management (SPDRM) solution, which integrates well with several major PDM and SPDM offerings such as Teamcenter and MSC SimManager.

BETA CAE significantly expanded its sales and technical support channel during 2017 via several acquisitions. After more than 15 years of a successful business partnership in Japan and Southeast Asia, BETA CAE acquired Top CAE

Corporation of Japan in February 2017. Based on the strong growth of the company's products in the Asia/Pacific region, this acquisition augments BETA CAE's presence in the region, and further enhances the relationship with its major customers in Japan and Southeast Asia. In another high growth S&A market, BETA CAE acquired VARDAR CAE Technologies Pvt. Ltd. of India, its sales and support partner since 2013.

As 2020 came to end, BETA CAE announced a major release of its latest software suite (21.1.0) with significant new enhancements in multidisciplinary modeling for electromagnetics, thermal, and explicit non-linear analysis with leading third-party solvers such as MSC MARC and EST's Pam-crash. They also continue to expand the scope and performance of post-processing capabilities within META, as well as the optimization capabilities with their EPILYSYS solver.

BETA CAE can now truly be considered an S&A platform provider, albeit with more limited offerings today in the realm of multi-domain, multi-physics, and design optimization capabilities versus the top tier S&A solution providers Ansys, Altair, Dassault Systèmes, and Siemens. For more information on the BETA CAE solutions portfolio, see www.beta-cae.com. CIMdata expects BETA CAE to continue to add to their global sales presence and their portfolio of solutions over the coming years, most likely via more niche in-house technology development, targeted acquisitions and partnerships, and sales channel expansions.

COMSOL Group

The privately-owned COMSOL Group AB provides software solutions for multi-physics modeling. The company offers a suite of discipline-specific add-on modules for structural mechanics, chemical engineering, high- and low-frequency electromagnetics, heat transfer, earth science, and acoustics. COMSOL operates offices in Denmark, the UK, France, Germany, the Netherlands, India, Italy, and the US. Dr. Svante Littmarck and Farhad Saeidi founded the company in 1986. The company's offerings had their start in a graduate course at the Royal Institute of Technology in Stockholm. In 1998, they released their COMSOL Multiphysics platform and have worked to expand their portfolio with a set of discipline-specific capabilities, including electrical, mechanical, fluid, acoustics, electromagnetics, chemical, and multipurpose modules. The company has over 450 employees in 20 offices worldwide and estimated 2020 revenues of \$133 million, up 6.5% over 2019. It's extended global sales channel includes a network of distributors.

COMSOL Multiphysics is a finite element-based solution for analyzing physical systems, including solid mechanics, electromagnetic field theory, and transport phenomena. It allows conventional physics-based user interfaces as well as coupled systems of partial differential equations (PDEs). COMSOL provides an integrated environment and unified workflow for electrical, mechanical, fluid, and chemical applications. An API for Java and LiveLink for MATLAB may be used to control the software externally, and the same API is also used via the Method Editor.

The wide range of available coupled physics formulations makes it applicable to the design of high-technology products like batteries and electromechanical devices. It can be run in conjunction with MATLAB as part of a system model, and it features

optimization and two-way associativity for geometry in most major CAD packages. It also provides connections with the leading ECAD packages.

COMSOL contains an Application Builder which can be used to develop independent domain-specific apps with custom user-interfaces. Users may use drag-and-drop tools (Form Editor) or programming (Method Editor). Specific features may be included from the model or new features may be introduced through programming. It also contains a Physics Builder to create custom physics-interfaces accessible from the COMSOL Desktop with the same look-and-feel as the built-in physics interfaces.

The Application Builder allows specialist analyst engineers to create applications based on their simulation best practices. The engineer creating the application customizes the interface and controls the inputs and outputs that the app user will be allowed to manipulate. The apps can then be made available to other non-CAE engineers involved in the design and manufacturing process.

COMSOL Server is the software and engine for running simulation apps and the platform for controlling their deployment and distribution. User developed apps can be run in COMSOL Server through web browsers or a Windows-installed client.

COMSOL sells their solutions both directly and through a global partner network. The company has offices in Brazil, China, Denmark, Finland, France, Germany, India, Italy, The Netherlands, Norway, Russia, Sweden, Switzerland, the United Kingdom, and the United States. COMSOL has partners in Australia, the Czech Republic, Egypt, Hungary, Israel, Japan, Malaysia, Singapore, Spain, South Korea, Taiwan, and Turkey.

To maintain quality in delivering and applying their offerings, COMSOL operates a certification program for consultants. COMSOL Certified Consultants use COMSOL Multiphysics and related products to deliver a wide range of modeling projects, producing ready-to-run models and in-depth analysis reports of the simulation results. COMSOL partners with leading hardware and software companies including AMD, Autodesk, SOLIDWORKS, MathWorks, PTC, and Siemens (including Siemens PLM Components).

COMSOL is one of the last remaining medium-sized S&A companies (\$50 to \$150M in annual revenues) that continues to grow and thrive without a reliance on making major technology acquisitions, much like MathWorks and BETA CAE.

Analytical Graphics Inc.

The privately-owned Analytical Graphics Inc. (AGI), based in Exton, PA is a global organization of over 250 professional staff with sales and support offices in all major parts of the world. AGI's estimated software and services revenues in 2020 were approximately \$63M. Ansys announced their acquisition of AGI in 2020.

AGI develops, applies, and supports software for the development and deployment of space, defense, and intelligence applications. AGI's flagship Systems Toolkit (STK) systems modeling, analysis, and visualization suite is used in both engineering and operations by industrial companies and government organizations involved in

the development of space, cyberspace, aircraft, missile defense, C4ISR, and electronic systems.

Founded in 1989, AGI began its business focused primarily on the development of satellite systems and, in fact, the original name of the core STK product stood for Satellite Tool Kit. As the company has grown over the past 30 years, they have expanded the use of their technology into new mission critical aerospace and defense domains and rebranded the STK product to the more generic Systems Tool Kit. STK provides an environment to model complex land, sea, air, or space systems and evaluate their performance in real or simulated time. STK supports timely decision-making in a mission context about complex, inter-related systems; and can be applied at any stage in their lifecycle: from planning and design to training and operations.

Today, AGI positions their value proposition to industry in the context of the term Digital Mission Engineering (DME)—the integration of the mission environment and operational objectives into the digital thread throughout the entire product lifecycle including operations and sustainment. To achieve the DME vision and business value, AGI is partnering with S&A solution suppliers such as Ansys, MathWorks, and Phoenix Integration, as well as specialized technology providers such as AER, Alion Science and Technology, Orbit Logic, Remcom, SAIC, and VT MAK to provide an integrated solution suite for DME.

PTC

Even though PTC has long been a leader in the overall PLM market, their market share in the S&A segment is relatively small and has diminished over the past decade. PTC does not provide a comprehensive multi-physics and multi-domain S&A portfolio and is therefore not in the top tier of our S&A market leaders. But they do provide some value added capabilities for CAD-integrated design simulation.

Best known for its Creo product line, PTC has expanded its CAD offerings in recent years with Onshape and Frustum. PTC sees Onshape, a cloud-based design and data management solution, as the foundation of its new Atlas platform of SaaS-based offerings that includes access to new S&A offerings. The Frustum acquisition brought enhanced generative design and artificial intelligence capabilities to inform the design process.

First, Creo. PTC has long offered Creo Simulate (obtained decades ago via an acquisition and formerly called ProMechanica), which has two primary modules, Structural/Motion and Thermal. In integrated mode, the designer performs Creo Simulate functions from within Creo Parametric, while a standalone version is intended for analysts who do a limited amount of modeling or who need to run simulation studies that are independent of Creo.

While their PLM competitors bulked up in S&A with their M&A activity, PTC stayed largely on the sidelines, focusing instead on other segments, like IoT. To advance their S&A capabilities, PTC has partnered with Ansys to extend simulation into other physics domains and design user interactions. In 2018, PTC and Ansys announced the release of PTC Creo Simulation Live, a solution that allows designers to access Ansys Discovery Live from within Creo Parametric. When Creo Simulation Live is

enabled, changes to the CAD model automatically update the simulation, creating a visualization of the results. As of Creo 8, Simulation Live includes static structural, thermal, fluid, and modal analysis, with the companies promising more capabilities in coming releases. The partnership between Ansys and PTC is strategic. Both intend to disrupt the traditional, time-intensive design process with instant feedback through real-time simulation done by Creo mechanical designers without relying on real time support from experienced CAE analysts.

Also in the PTC portfolio, MathCAD provides a design integrated capability for doing a wide range of standard engineering calculations with accuracy and precision, while, as opposed to using spreadsheets, also enabling traceability, protecting intellectual property, and documenting an engineer's work in a digital notebook form. Most importantly, the MathCAD calculation capabilities with live mathematical notation and units intelligence produce far more accurate and high precision results than a spreadsheet can typically provide. Using PTC Mathcad's wide array of mathematical functionality, designers and engineers can document their most critical engineering calculations as easily as they could write them down in a notebook.

In 2018, PTC acquired Frustum, which had developed a platform for the additive manufacturing world and in support of GenDes. Traditional manufacturing relies on relatively simple shapes; 3D printing can create far more complex shapes with lattice structures to reduce weight without sacrificing strength. Frustum combines generative design simulation with artificial intelligence to rapidly identify the few "best" choices. Frustum's topology optimization functionality is being incorporated into Creo to enable users to generate more conceptual design alternatives and create complex geometries more easily. Today, PTC customers can access Frustum technology within both Creo and Onshape.

Onshape is a SaaS CAD solution that runs in a browser, meaning it requires no downloads or installations. Administrators can instantly provision and de-provision seats—of both Onshape CAD and S&A partner products—to meet fluctuating needs. This cloud-based simulation, on a pay-as-you-go basis, has attracted users new to S&A. Onshape partner products include solvers from Altair, MathWorks, and others, as well as solvers accessible via OnScale, SimScale, and other cloud simulation providers. Onshape was actually much more aggressive than PTC in partnering with third-party S&A providers.¹⁵

In conclusion, PTC is focusing on its core PLM/MCAD/PDM, manufacturing and IoT domains while partnering to add easy-to-use yet state of-the art S&A functionality to its offerings via the Onshape acquisition and a strategic partnership with Ansys. We do not anticipate that changing in the near future short of a major industry event such as a merger with Ansys or one of the other major PLM or ERP solution providers.

Gamma Technologies

Gamma Technologies, based in Westmont, Illinois, is an independent provider of engineering simulation software solutions for multi-physics systems simulation

¹⁵ See: <https://appstore.onshape.com/apps/Simulation?sort=featured>

focused primarily on the vehicle engine and powertrain segments. Their flagship product is GT-Suite which provides integration of capabilities for lower fidelity (0D/1D) systems modeling and simulations as well as detailed 3D modeling and simulation capabilities, with built-in structural and thermal 3D FEA solvers (including meshers), a 3D multi-body dynamics solver with flexible body capabilities, and 3D CFD solvers. These are complemented by CAD modeling and automatic model generation from 3D MCAD models.

GT-Suite also provides a comprehensive set of component libraries which are used to simulate the physics of fluid flow, thermal, mechanical, electrical, magnetic, chemistry, and controls. From those libraries, one can build accurate models of almost any engineering system, including vehicles, engines, drivelines, transmissions, general powertrains, other mechanical systems, hydraulics, lubrication and friction, thermal management, cooling, chemistry, engine after treatments, and more. In addition, a broad array of built-in advanced features such as DoE, optimization, and distributed and parallel processing enhance user productivity and effectiveness.

In a significant departure from the industry norms, every GT-Suite license contains all of the above features in a single package.

During 2018, Gamma Technologies acquired privately held AutoLion. AutoLion is the advanced Lithium-Ion battery simulation software used by battery suppliers and OEMs for both 1D and 3D battery analysis and design. It is a predictive, physics-based simulation tool that complements the capabilities of GT-Suite and is of high interest to industry given the strong global push towards more electric vehicles.

In November of 2020, the founder of Gamma Technologies, Dr. Thomas Morel, stepped back from his long time role as CEO to become Chairman of the Board. Mr. Dimple Shah took over the role of CEO. Mr. Shah is a 25-year veteran of the CAE industry and brings to GT executive leadership experience that has driven transformative growth with a focus on simulation-powered industry innovation.

Gamma Technologies is privately owned and venture capital backed and does not disclose their annual revenues to outside organizations. For that reason, we do not include them in our S&A leaders charts. However, CIMdata estimates Gamma Technologies annual revenues to be in the range of \$25 million.

Maya HHT (Heat Transfer Technologies) Ltd.

Headquartered in Montreal, Canada, Maya Heat Transfer Technologies (HTT) whose business model includes software technology, product development, contract engineering services, value-added reselling of Siemens software and related S&A training and implementation services. www.mayahtt.com. Maya HTT has approximately 150 software developers, technical support engineers, and senior management staff located in the Canadian HQ as well as a sales and marketing team of approximately 100 staff located across several offices in North America and one European office located in the UK.

Maya develops a number of OEM products and translators that are an integral part of the Siemens Simcenter 3D portfolio as part of a partnership originally formed with SDRC in the early 1990s. In addition to this software development activity,

Maya engineers also developed some complementary software tools for which they own the IP and sell through their own sales channel. Maya also acts as a value-added reseller of the entire Siemens Simcenter portfolio of S&A tools in selected accounts in North America and western Europe, providing training and implementation services in addition to contract product engineering resources

As a result, while the majority of their S&A software and services revenues are related to the extremely close strategic partnership with Siemens, they also provide software and services to non-Siemens customers.

Simulations Plus, Inc.

Simulations Plus is a publicly traded company (NASDAQ: SLP) with annual revenues of approximately \$41.6M in 2020. Simulations Plus develops and sells drug discovery and development software based on mechanistic modeling and simulation, and machine-learning based prediction of molecular structure properties for use in drug discovery and development.

It sells its pharmaceutical/chemistry software to pharmaceutical, biotechnology, agrochemical, cosmetics, and food companies. The company was founded in 1996 and is headquartered in Lancaster, California.

This falls outside of the traditional S&A realm usually tracked by CIMdata but we feel it is now worth noting given the overlap that continues to occur across engineering domains with the aggressive M&A activity by the leading PLM and S&A providers such as Dassault Systèmes acquisition of Accelrys.

Major S&A Solution Resellers

Several of the companies in our leadership chart (see Figure 41) are primarily resellers of S&A solutions developed by one or more of the major solution providers. This includes IDA-J of Japan, ISI-Dentsu of Japan, Tech Mahindra in India, and CENIT with multiple locations in North America, Germany, and central Europe. These groups involved with providing PLM/S&A technology and services are also typically part of larger IT technology organizations and provide some level of custom software solutions that they develop, sell, maintain, and support as commercial PLM/S&A tools.

For instance, ISI-Dentsu is a large global IT services organization but their Japanese operations developed a web-based simulation data and process capability called CAE One offered to Japanese customers alongside COTS solutions they sell and support from Siemens, MSC Software, Altair, and others. They also have a systems engineering-type solution called iQuavis which they develop, sell, and support—see www.isid-industry.jp/product_and_service/detail/Product_Development/iquavis.

So while these IT services/reseller organizations do generate some S&A software revenues, it is actually a fairly small portion of their overall annual revenues and of the global S&A market segment as a whole.

Conclusion

In 2020, S&A revenues grew by 4.2% to nearly \$7.5 billion. The S&A segment been the growth leader of the PLM market for the last decade and suffered a pause due to COVID19 in 2020.

Going forward, CIMdata expects that S&A will be one of the more rapidly growing segments within the Tools sector of PLM over the next five years and will reach \$12 billion in 2025, with a 10% CAGR. For 2021, CIMdata forecasts that the S&A sub-sector will grow 8.1% overall and have revenues of just under \$8.1 billion.

This strong growth forecast reflects the increasing importance of S&A as part of product development and the need for companies to deploy better S&A solutions and user environments that can spread the use of simulation and analysis to the typical product design and manufacturing engineer (i.e. expanding the “democratization of simulation”). The trends in the S&A market should drive more investment across the product development lifecycle. Clearly more will be spent on the left side of the Vee and new materials and manufacturing processes should also drive investment in validation on the right side of the Vee as well as the movement to create physics-based digital twins that will be used for in-service operations as well as throughout the entire product lifecycle.

About CIMdata

CIMdata, a leading independent worldwide firm, provides strategic management consulting to maximize an enterprise’s ability to design and deliver innovative products and services through the application of Product Lifecycle Management (PLM) solutions. Since its founding over thirty years ago, CIMdata has delivered world-class knowledge, expertise, and best-practice methods on PLM solutions. These solutions incorporate both business processes and a wide-ranging set of PLM-enabling technologies.

CIMdata works with both industrial organizations and providers of technologies and services seeking competitive advantage in the global economy. CIMdata helps industrial organizations establish effective PLM strategies, assists in the identification of requirements and selection of PLM solutions, helps organizations optimize their operational structure and processes to implement solutions, and assists in the deployment of these solutions. For PLM solution providers, CIMdata helps define business and market strategies, delivers worldwide market information and analyses, provides education and support for internal sales and marketing teams, as well as overall support at all stages of business and product programs to make them optimally effective in their markets.

In addition to consulting, CIMdata conducts research, provides PLM-focused subscription services, and produces several commercial publications. The company also provides industry education through PLM certificate programs, seminars, and conferences worldwide. CIMdata serves clients around the world from offices in North America, Europe, and Asia-Pacific.

To learn more about CIMdata's services, visit our website at www.CIMdata.com or contact CIMdata at: 3909 Research Park Drive, Ann Arbor, MI 48108, USA. Tel: +1 734.668.9922. Fax: +1 734.668.1957; or at Oogststraat 20, 6004 CV Weert, The Netherlands. Tel: +31 (0) 495.533.666.