Maturity Model for Advancing Smart Grid Interoperability

M. Knight, Member, IEEE, S. Widergren, Sr. Member, IEEE, J. Mater, Member, IEEE, A. Montgomery

Abstract—Interoperability is about the properties of devices and systems to connect and work properly. Advancing interoperability eases integration and maintenance of the resulting interconnection. This leads to faster integration, lower labor and component costs, predictability of projects and the resulting performance, and evolutionary paths for upgrade. When specifications are shared and standardized, competition and novel solutions can bring new value streams to the community of stakeholders involved. Advancing interoperability involves reaching agreement for how things join at their interfaces. The quality of the agreements and the alignment of parties involved in the agreement present challenges that are best met with process improvement techniques. The GridWise Architecture Council (GWAC) sponsored by the United States Department of Energy is supporting an effort to use concepts from capability maturity models used in the software industry to advance interoperability of smart grid technology. An interoperability maturity model has been drafted and experience is being gained through trials on various types of projects and community efforts. This paper describes the value and objectives of maturity models, the nature of the interoperability maturity model and how it compares with other maturity models, and experiences gained with its use.

Index Terms—architecture, energy management, information technology, intelligent systems, interoperability, maturity model, software engineering, system integration

I. INTRODUCTION

Interoperability is “the capability of two or more networks, systems, devices, applications, or components to exchange information between them and to use the information so exchanged.” [1] While implicitly recognized since the dawn of engineering, interoperability has only relatively recently received formal attention in the form of modeling. Interoperability is critical to the coordination of activities through messaging and has long been a part of military operations. The Romans would not have expanded their empire through conquest without well-coordinated armies and supply logistics. Interoperability has a high focus today including the measurement of interoperability maturity by GridWise Architecture Council (GWAC) [2] and by NATO [3]. In Roman times, as well as today, the timing, sequencing, and coordination of operations is critical, and to do that successfully requires messages and communications between parties to be unambiguously interpreted and understood.

With the advent of computers and electronic communication it became important to specify functions and formats so that data transmitted from one computer could be properly acted on when received by another computer. As a result of this the United States (US) government developed the Data Encryption Standard (DES) in 1972 as an interoperability standard, requiring complete specification of basic function and format yet remaining independent of physical implementation. Simulation interoperability discussions began seriously in 1980 with the Defense Advanced Research Projects Agency (DARPA) SIMNET effort. From this effort, the IEEE 1278 DIS standard (Distributed Interactive Simulation) evolved for the purpose of conducting real-time platform-level war games across multiple host computers.

Yet, despite the obvious importance of interoperability, little has been done until very recently in terms of developing a method for measuring levels of interoperability. This paper describes the work done by the GWAC to develop and trial an interoperability maturity model (IMM) based on the Interoperability Context-Setting Framework (The “GWAC Stack”) [4] and to test its application to smart grid demonstration grant projects co-funded by the US Department of Energy (DOE). These projects provide an opportunity to obtain early feedback on the strengths and weaknesses of trying to apply the IMM tools to real-world efforts [5].

There exist different types of maturity models to address various objectives. The IMM is sometimes confused with the Smart Grid Maturity Model (SGMM) managed by the Software Engineering Institute (SEI) at Carnegie Mellon. The two are different yet complementary maturity models that coexist to address different objectives, as explained later.

II. SMART GRID DRIVERS

Smart Grid is relevant to the entire energy infrastructure from generation to consumption. It embeds intelligence and active control, management, and interaction capabilities into the existing grid using advanced technologies, sensors, controls. Given the great number of parties involved, efforts are progressing to provide an open, standards based, framework for the integration of devices and services. The ability to manage the timing, sequencing, and coordination of operations in the manner intended is critical, and a high level of interoperability is required to achieve the objectives associated with enabling smart grid capabilities.

The nature of connectivity of devices and systems in smart grid applications requires the alignment of many stakeholders (multiple operators, technology suppliers, regulators, etc.). The characteristics of interoperability are best observed and
measured in a community or ecosystem of players. To have a situation where interoperability exists, we need multiple entities that are required to interact with each other, potentially at many different technical and business levels. Interoperability is a shared property of these entities that allows them to work together in the manner intended, including the proper interpretation and use of exchanged data. In other words it includes both technical and cognitive [3] abilities. Therefore measures interoperability must take into account technical, social, political, and organizational factors that impact system to system performance across multiple parties.

Inspired partly by the process improvement aspects of SEI’s Capability Maturity Model Integration® (CMMI®) [6], and the National E-Health Transition Authority (NEHTA) [7] in Australia, GWAC developed a maturity model for interoperability to help communities of organizations understand the maturity of their ability to interoperate. These activities started in 2007 and resulted in the publication of a beta version of the IMM by the GridWise Architecture Council (GWAC) [8] in December 2011.

III. THE “GWAC STACK” FOUNDATION

Deployments of smart grid capabilities need to address the integration challenges that go beyond single organizations or enterprises to address the interactions that span organizational entities. The GWAC was formed to promote and enable interoperability among the many entities that interact to make up the electric power system. While guidance, methods, and tools to enable interoperability can benefit all types of integration, the emphasis of the GWAC work is to enable interoperability between organizations.

Interoperability must deal with agreements between interacting parties who require the flexibility to address special arrangements and manage changes over time. To help assess and encourage behavior that improves interoperability over time the idea was to develop a smart grid interoperability maturity model for application to communities of organizations engaged in smart grid product and project implementations.

The GWAC Interoperability Context-Setting Framework shown in Fig. 1. GWAC Interoperability Context-Setting Framework provides a mechanism for exploring the multiple dimensions of interoperability at an interface between smart grid components; therefore, this model (shown below) is used as a structural landscape for identifying interoperability goals for the IMM. The Interoperability Context-Setting Framework builds upon the organizational, informational, and technical interoperability categories of the NEHTA model and identifies higher levels of granularity as inspired by other architectures.

The Interoperability Context-Setting Framework also has similarities to the Levels of Conceptual Interoperability Model (LCIM) [9] which also evolved over several years and various applications in different application domains, including ontology alignment [10] and intelligent power systems [11].

This framework identifies eight interoperability levels which are grouped into three categories (technical, informational, organizational) and ten cross cutting issues which are also grouped into three categories (Configuration & Evolution, Operation & Performance, and Security & Safety). This provides a two-dimensional landscape that helps to focus on specific areas of concern by creating nine Interoperability Areas (IA) where these categories intersect. The IMM is formed by establishing goals in each IA and defining metrics for assessing maturity in these areas.

IV. MATURITY MODELS

Maturity models provide a way to benchmark and assess the evolution of a set of characteristics against that benchmark. These benchmarks typically represent best practices and may be based around the use of standards or
other sets of processes or methods to be assessed against. In order to provide this type of benchmark, maturity models typically represent an evolutionary set of attributes, characteristics, patterns, or practices that are used as the basis of an assessment.

The first application of a staged maturity model was by Richard L. Nolan of Harvard University who, in 1973, published the stages of growth model for information technology (IT) organizations. This was around the same time that the Data Encryption Standard was being developed. The sponsors for the development of early maturity models and their users were the US military who wanted to develop a method to objectively evaluate software subcontractors' process capability maturity in order to reduce cost and schedule overruns and increase predictability of results. In the late 1980s and early 1990s, SEI developed the Capability Maturity Model® (CMM®) which captured organizational best practices for software development. Ultimately the CMM was superseded by the CMMI to sort out the problem of using multiple models that are not integrated within and across an organization for software and systems development processes.

By undertaking a maturity assessment against an industry standard model an organization can verify what it has achieved, where its strengths and weaknesses are, and then build a prioritized action plan to take it to improved levels of maturity (or capability) in specific areas of focus. The IMM, instead of looking at an organization, is focused on the maturity of an interface between members of a larger community of organizations and systems.

The reason that maturity models are able to help to provide objective assessments is because a good maturity model uses a consistent appraisal method that is applied to each and every assessment by trained assessors.

In general maturity models can be categorized [12] as one of the following three types:

**Progression** maturity models represent a simple progression or scaling of an attribute, characteristic, pattern, or practice where the movement up the maturity levels indicates some progression of maturity. This category includes many proprietary models often developed by companies such as consultancies or product vendors.

In a **capability** maturity model, the dimension that is being measured is a representation of organizational capability around a set of attributes, characteristics, patterns, or practices. This is important because it measures more than the ability to perform a simple (or complex) task and looks at a broader organizational capability that reflects the maturity of the culture and how well embedded the capabilities are.

A **hybrid** maturity model can be created by overlaying characteristics of the progressive model with capability attributes from capability maturity models. This type of model reflects transitions between levels that are similar to a capability model but architecturally uses the attributes, characteristics, patterns, or practices of a progression model.

This makes it very useful for focusing on specific subject matter domains but assesses maturity from the perspective of how well standards and best practices have been integrated into the organizations' capabilities and culture. This institutionalizing of capability creates models that are relatively easy to use and understand but which can provide great value and the ability to use the model as a roadmap to improved maturity.

The SGMM is an example of a progression model, addressing progressive implementation of smart grid characteristics. The model describes eight domains, which contain logical groupings of incremental smart grid characteristics and capabilities that represent key elements of smart grid strategy, organization, implementation, and operation. The model further describes six maturity levels of progressive smart grid implementation. Utilities use the SGMM to assess their current state of smart grid implementation, compare themselves with their peers, define their vision and goals for a future state, and generate inputs into their road mapping, planning, implementation and progress measurement activities.

CMMI is an example of a capability maturity model, addressing continuous process improvement and institutionalization of improved processes in the organization.

Comparing and contrasting with the IMM, the SGMM is a management tool that utilities use to plan their smart grid activities. The main requirements of the IMM are that it be able to encourage the maturity of inter-organizational integration. It must be simple and straightforward to be usable and useful. While interoperability is complex, the maturity model has been organized to be readily understood at a high level with details and complex issues being addressed as users move further into the model. The model focuses on the interface between interacting organizations' automation systems, understanding that while true interoperability extends into the implementations on either side of the interface, the interface agreement needs to reflect the expectations of all parties and repercussions for failure to perform.

Organizational maturity as represented in a capability maturity model is an expression of the extent to which an organization consistently implements processes within a defined scope that contributes to the achievement of its business goals. To the extent that the IMM is focused largely on automated interfaces and embodies the use of standards, there may be consistency of implementation for a specific interface, and across multiple interfaces especially where integration tools are used.

However, the IMM is intended to be applied to a community and not a single organization and includes characteristics, patterns, and practices that may not represent broader organizational capabilities thus the IMM is an example of a hybrid maturity model.
V. STRUCTURE OF THE IMM

The IMM uses the GWAC Interoperability Context-Setting Framework to capture context in terms of relating the IMM to specific, measurable business and technical goals and then using these goals to provide further context in terms of metrics that can be used to assess interoperability maturity levels as it relates to these metrics. The IMM is designed to be applied to each Interoperability Area and by collecting interoperability maturity assessments for multiple metrics, a picture of overall interoperability maturity can be built for a specific Interoperability Area. The SG IMM identifies high-level goals for each level of the framework and for each cross-cutting issue. Within the structure of the framework, these goals intersect in a matrix that allows the creation of more-detailed statements in support of the intersecting goals.

Not every intersection of interoperability category goals with cross-cutting issues goals has a reasonable chance of being measurable, therefore the model strives to choose and compose metric statements with sensitivity to simplicity and usefulness. This creates metrics that can be used to assess the stated goals. While using the GWAC Stack as a reference framework and addressing both technical and cognitive interoperability, there are undoubtedly improvements that can be made to the IMM (discussed later).

VI. ACADEMIC AND PRAGMATIC INTEROPERABILITY

Advancing interoperability involves reaching agreement for how things join at their interfaces. Tolk et al address the mathematical foundations of interoperability [3] and state that the “interoperability of two systems implies mathematical equivalency of their conceptualization. In other words, interoperability is only given in the intersection of two systems. This is counterintuitive to many current views that assume that by interoperability the union of the provided capabilities becomes available. We therefore need an operational frame that helps to orchestrate individual and independent technical solutions.” This is entirely consistent with the approach taken by the IMM to assess interoperability from a community perspective at the interface.

Tolk et al also refer to the introduction of the Semantic Interoperability Logical Framework [13] (SILF) which prescribes four steps to increase semantic interoperability between NATO command and control systems. They note the requirement for a common reference model (CRM) which the GWAC Stack provides for the IMM, and that a robustly networked enterprise enables the widespread sharing of information; and that the widespread information sharing and collaboration in the information domain improves the quality of awareness, shared awareness, and collaboration.

This reinforcement of the importance of semantic interoperability is an important part of cognitive interoperability and its importance can be seen in the GWAC stack in layer 4 (Semantic Understanding) and in the cross cutting issues (Shared Meaning of Content).

VII. FIELD TRIALS OF THE IMM

In its present beta version form, the IMM provides a starting place for engaging the smart grid community, but practical applications are required to discover its strengths and shortcomings. Each interface and stakeholder community that uses the IMM will test the model to varying degrees. The IMM team members are gaining experience through two trials. The process used to test the IMM in the trials includes the following steps:

1. Define target: identify the interface between components to which the IMM is to be applied
2. Define domain: identify the stakeholders that form the boundaries of the targeted interface who need alignment behind a common set of objectives.
3. Define goals: using the IMM, define the goals and associated metrics covering the interoperability areas that apply to the target interface.
4. Identify practices: gather evidence, describe the processes and interface-related artifacts that support the interoperability area goals.
5. Assess: use IMM evaluation tools to evaluate the evidence and determine the interoperability maturity level(s). Note areas where the model is helpful and where there are problems or shortcomings.
6. Recommend improvements: review the assessment process to develop a set of recommendations to refine the model and propose ideas to enhance evaluation tools.

In late 2011, members of the IMM team began to apply the beta version of the Interoperability Maturity Model to the DOE Pacific Northwest Smart Grid Demonstration Project (PNWSGDP).

For the project, the target interface identified was the Transactive Control Interface that communicates energy cost and anticipated system response information between participants. The IMM assessment process relied on the knowledge of project members familiar with developing the Transactive Control Interface and IMM team members. The objectives of the IMM trial were:

1. Test the process outlined for an IMM assessment
2. Evaluate the applicability of the goal statements and metrics in this case and select the goal statements relevant to the project
3. Develop a preliminary assessment of the project using the IMM and specify steps for refining the assessment
4. Provide insights and direction for further development of the IMM and an assessment process

The initial assessment effort identified some key shortcomings and suggested improvements for the IMM:

1. Attempting to develop specific scores and comments
on most of the Goal Statements and Metrics is very challenging without more specific guidance as to what data should be collected or questions asked to develop an assessment rating. It would be helpful if specific questions or data to be collected for each of the Goal Statements and Metrics is developed and included as one of the assessment tools.

2. It is not specified who should be approached; who should be interviewed (or for that matter whether interview, self-assessment, or both are preferable); how long should interviews be; what sort of senior management sponsorship is required/desired; how the Goal Statement Maturity scoring is computed, etc. It would improve the IMM to develop a “Guide to IMM Assessments” to address these kinds of questions and standardize the assessment process.

3. Although this assessment did not require selling it to senior executive sponsors, if this were necessary, it would be critical to have a document aimed at executive level decision-makers that explains the goals, potential benefits and process of the IMM. Associated material, such as a slide presentation to accompany such a document, would also be useful.

4. A model for how to summarize and present the results to operating managers in an actionable format would improve the reporting and provide a powerful communications vehicle to decision-makers in a community.

It is planned to extend the PNWSGDP trial to include additional participants. Additional findings and recommendations for the IMM will emerge as a result of the experience.

Another trial of the IMM took place in June 2012 for another DOE smart grid demonstration project that is integrating many smart grid technologies. American Electric Power (AEP) is the project leader for the gridSMART® demonstration project. AEP is interested in making integration, reliability of operation, cost of maintenance, and ambiguities, and gaps in areas that affect the ease of benefits of interoperability by revealing inconsistencies, that can assist stakeholder communities to advance the integration aspects rather than interoperability areas that affect the ease of integration, reliability of operation, cost of maintenance, and choice of smart grid products and services.

Lessons from supply chains in other sectors indicate advancements in their maturity to address interoperability issues reap significant benefits [14]. The IMM presents a tool that can assist stakeholder communities to advance the benefits of interoperability by revealing inconsistencies, ambiguities, and gaps in areas that affect the ease of integration, reliability of operation, cost of maintenance, and choice of smart grid products and services.

Early trials indicate that, while there are many areas for improvement, the IMM provides a framework to assess the complexities involved to identify interoperability areas that need attention. Each interface and every community or enterprise. As such the trial emphasized enterprise integration aspects rather than interoperability between components in a multi-stakeholder community. While the tool helped articulate some enterprise integration issues, little new knowledge was revealed to justify going to higher levels beyond a project level.

2. The IMM recognizes maturity at the project level, and then jumps to the community level for higher levels of maturity. As a hybrid model, it does not recognize the improvement within an enterprise of supporting multiple projects.

3. The terminology “business process” is used in the IMM to refer to any process interaction. Users can be confused by wanting to distinguish a business process from a technical process, when there is no distinction in the IMM.

4. While there are broad statements about testing the interface in the IMM, details are missing. That can have many facets for improvement. This could be an area to enhance with another layer of detail in a future version of the model.

5. As this interface was an enterprise interface, many of the technical levels are addressed by the enterprise polices that cover the goals in a consistent fashion. For example, the same corporate messaging middleware may meet high maturity technical goals and be specified for all enterprise interfaces. The tool might be improved with some simple questions that distinguish this situation and tell the user to skip questions or sections in the tool.

A particularly high level of maturity was observed in the information layers of the model. The interface adopted an international standard information model and message syntax associated with metering information exchange. Changes to the model that were needed as a result of the implementation experience where fed back to the associated standards organization for future versions of the standard.

VIII. CONCLUSION

Interoperability is critical to the achievement of the objectives associated with enabling smart grid capabilities. Lessons from supply chains in other sectors indicate advancements in their maturity to address interoperability issues reap significant benefits [14]. The IMM presents a tool that can assist stakeholder communities to advance the benefits of interoperability by revealing inconsistencies, ambiguities, and gaps in areas that affect the ease of integration, reliability of operation, cost of maintenance, and choice of smart grid products and services.

Early trials indicate that, while there are many areas for improvement, the IMM provides a framework to assess the complexities involved to identify interoperability areas that need attention. Each interface and every community or enterprise. As such the trial emphasized enterprise integration aspects rather than interoperability between components in a multi-stakeholder community. While the tool helped articulate some enterprise integration issues, little new knowledge was revealed to justify going to higher levels beyond a project level.

2. The IMM recognizes maturity at the project level, and then jumps to the community level for higher levels of maturity. As a hybrid model, it does not recognize the improvement within an enterprise of supporting multiple projects.

3. The terminology “business process” is used in the IMM to refer to any process interaction. Users can be confused by wanting to distinguish a business process from a technical process, when there is no distinction in the IMM.

4. While there are broad statements about testing the interface in the IMM, details are missing. That can have many facets for improvement. This could be an area to enhance with another layer of detail in a future version of the model.

5. As this interface was an enterprise interface, many of the technical levels are addressed by the enterprise polices that cover the goals in a consistent fashion. For example, the same corporate messaging middleware may meet high maturity technical goals and be specified for all enterprise interfaces. The tool might be improved with some simple questions that distinguish this situation and tell the user to skip questions or sections in the tool.

A particularly high level of maturity was observed in the information layers of the model. The interface adopted an international standard information model and message syntax associated with metering information exchange. Changes to the model that were needed as a result of the implementation experience where fed back to the associated standards organization for future versions of the standard.

VIII. CONCLUSION

Interoperability is critical to the achievement of the objectives associated with enabling smart grid capabilities. Lessons from supply chains in other sectors indicate advancements in their maturity to address interoperability issues reap significant benefits [14]. The IMM presents a tool that can assist stakeholder communities to advance the benefits of interoperability by revealing inconsistencies, ambiguities, and gaps in areas that affect the ease of integration, reliability of operation, cost of maintenance, and choice of smart grid products and services.

Early trials indicate that, while there are many areas for improvement, the IMM provides a framework to assess the complexities involved to identify interoperability areas that need attention. Each interface and every community or enterprise. As such the trial emphasized enterprise integration aspects rather than interoperability between components in a multi-stakeholder community. While the tool helped articulate some enterprise integration issues, little new knowledge was revealed to justify going to higher levels beyond a project level.

2. The IMM recognizes maturity at the project level, and then jumps to the community level for higher levels of maturity. As a hybrid model, it does not recognize the improvement within an enterprise of supporting multiple projects.

3. The terminology “business process” is used in the IMM to refer to any process interaction. Users can be confused by wanting to distinguish a business process from a technical process, when there is no distinction in the IMM.

4. While there are broad statements about testing the interface in the IMM, details are missing. That can have many facets for improvement. This could be an area to enhance with another layer of detail in a future version of the model.

5. As this interface was an enterprise interface, many of the technical levels are addressed by the enterprise polices that cover the goals in a consistent fashion. For example, the same corporate messaging middleware may meet high maturity technical goals and be specified for all enterprise interfaces. The tool might be improved with some simple questions that distinguish this situation and tell the user to skip questions or sections in the tool.
ecosystem will face unique challenges. Because of this, the IMM will need to be refined and improved to address a variety of situations. Multiple objectives for assessments, such as the need to prioritize limited resources to address the most cost-beneficial issues first, may require the creation of new tools.

Lastly, the smart grid community is gaining multiple maturity model tools to address different areas. These include the SGMM for advancing utility smart grid functionality progress, a cyber security maturity model (ESC2M2), and the IMM. Coordination between these efforts will ensure their complementary nature and reduce confusion between them by members of the smart grid community.

IX. ACKNOWLEDGEMENTS

The authors wish to recognize the following individuals who contributed to the development of the IMM: Stephan Amsbary, Rik Drummond, Tony Giroti, Doug Houseman, Mark Knight, Alex Levinson, Wayne Longcore, Randy Lowe, James Mater, Austin Montgomery, Terry Oliver, Phil Slack, Andreas Tolk, and Steve Widergren. Special recognition is extended to Ron Melton of the Pacific Northwest Smart Grid Demonstration Project led by Pacific Northwest National Laboratory and Frank Wilhoit of the American Electric Power gridSMART® project for their hard work and keen insights in the trial applications of the IMM.

REFERENCES


X. BIOGRAPHY

Mark Knight (M’2006) is a member of CGI’s USEM IP Solutions & Global Delivery Business Unit where he is committed to delivering value to CGI’s Energy & Utilities clients to enhance operations and business practices. Mark draws upon 25 years of experience to deliver business solutions that leverage the integration of people, business (processes, systems, data), and technology to support innovative, effective, and practical solutions for CGI’s clients. Mark's background includes a mix of information technology work and business process work both as a consultant and as a utility employee in the UK and the US and has spanned several areas including distribution, transmission, metering, systems integration, deregulation, interoperability, asset management, and risk management. Mark is also a member of the GridWise Architecture Council and a graduate of Imperial College, London.

Steve Widergren (M’1978, SM’1992) contributes to new solutions for reliable operation of electric power systems. Common throughout his career is the application of information technology to power engineering problems including, simulation, control, and system integration. He is a principal engineer at Pacific Northwest National Laboratory where he has worked with NIST and the GridWise Architecture Council to advance interoperability of automated systems related to the electric system. He is also the Plenary Chair of the NIST Smart Grid Interoperability Panel. Prior to joining the Laboratory, he engineered and managed energy management systems products for electric power operations and supported power system computer applications in both supplier and utilities sectors. Application areas include information modeling, SCADA systems, and power system reliability assessment tools. He received his BS and MS degrees in electrical engineering from the University of California, Berkeley. He is actively involved in the IEEE Power Engineering Society and participates in standards efforts that bridge power engineering with information technology.

James Mater founded and has held several executive positions at QualityLogic, Inc. from June 1994 to present. He is currently Co-Founder and Director working on QualityLogic's Smart Grid strategy including work with GWAC, the Pacific Northwest Smart Grid Demonstration Project, SGIP Test and Certification Committee, UCA's OpenSG Conformity Work Group, and giving papers and presentations on interoperability. From 2001 to October, 2008, James oversaw the company as President and CEO. From 1994 to 2001 he founded and built Revision Labs which was merged with Genoa Technologies in 2000 to become QualityLogic. Prior to QualityLogic, James held Product Management roles at Tektronix, Floating Point Systems, Sidereal and Solar Division of International Harvester. He is a graduate of Reed College and Wharton School, Univ of Penn.

Austin Montgomery is smart grid program lead for the Software Engineering Institute (SEI) at Carnegie Mellon University. SEI collaborates with government and industry to address security, architecture, interoperability, process improvement and other software and systems engineering challenges of grid modernization. Montgomery spent the first part of his career as M&A attorney, investment banker and management consultant. Prior to joining the SEI he was a founder and senior executive of several start-up companies developing innovative software and wireless communication technologies. He received a BA in Economics from Harvard University, JD from the University of California, Hastings College of the Law, and MBA from the Simon School of the University of Rochester and the Erasmus University in the Netherlands.