Roadmap for Advanced Simulation and Visualization for Steel Optimization
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The ideas presented in this report are a reflection of the contributors and not necessarily the entire steel industry. As such, these ideas should be viewed as a snapshot of important perspectives, but not necessarily as all-inclusive. The participants were selected based on their high level of technical knowledge related to steel and MSV technologies, systems, and practices, and are considered experts in the field.
Technology Roadmap for Advanced Simulation and Visualization for Steel Optimization

Prepared by the Center for Innovation through Visualization and Simulation (CIVS), Purdue University Northwest, the Steel Manufacturing Simulation and Visualization Consortium (SMSVC), and Energetics Incorporated

For the

National Institute of Standards and Technology,
U.S. Department of Commerce
This report was commissioned as part of a grant from the U.S. Department of Commerce, National Institute of Standards and Technology, under the AMTech Program. Launched in 2013, AMTech is a competitive grants program aimed toward establishing new or strengthening existing industry-driven consortia addressing some of the challenges that limit the growth of advanced manufacturing in the United States. The AMTech program encourages participation across the value chain, including companies of all sizes, universities, and government agencies. As part of its efforts, AMTech supports the development of technology roadmaps for critical advanced manufacturing technologies and associated long-term industrial research challenges.

In addition to supporting development of the Technology Roadmap for Advanced Simulation and Visualization for Steel Optimization, for which activity began in late 2014, the AMTech Planning Grant was instrumental in the formation and launch of the Steel Manufacturing Simulation and Visualization Consortium (SMSVC) in January 2016. The SMSVC is a nationwide, industry-led consortium of steel producers, suppliers, and users—including energy suppliers/utility companies—whose purpose is to address major technological issues and barriers related to growth, and to ensure a competitive advantage for American Steel manufacturing. The SMSVC mission is to develop and implement innovative technical solutions through the integration of advanced computer simulation and visualization technologies across the steel value chain in the United States.

The primary objective of this report, as its title indicates, is to provide a technology roadmap for advanced simulation and visualization for steel optimization. Secondary but no-less-important objectives of this report are to demonstrate what implementation of such a roadmap looks like in terms of research already undertaken and tangible results already achieved (to date); to inform potential Roadmap users of the expanding horizons possible through technological innovation; and to encourage current and potential Roadmap users’ participation in future research and development efforts.

The Roadmap has been both revised and implemented since its inception; thus, the implementation examples presented herein broadly represent some “initial returns” on the use of modeling, simulation, and visualization in steel manufacturing. These returns are both impressive and a mere beginning: as the plethora of articles in recent peer-reviewed journals suggests, steelmaking advancements using modeling, simulation, and/or visualization technologies are undergoing exponential growth.

This report was prepared under the oversight of the primary recipients of the AMTech Grant: Purdue University Northwest, Center for Innovation through Visualization and Simulation (CIVS), and the American Iron and Steel Institute (AISI), with assistance from Energetics Incorporated.
ACKNOWLEDGMENTS

The framework for this report is based on the results from a series of workshops, held in October and December of 2014, which focused on utilizing and leveraging the capabilities of advanced simulation and visualization for optimizing steel processing. Further contributions to the overall Roadmap vision and structure were also provided by members of the National Institute of Standards and Technology; the Center for Innovation through Visualization and Simulation (CIVS) of Purdue University Northwest; the American Iron and Steel Institute (AISI); the Association for Iron & Steel Technology (AIST); the Steel Manufacturing Simulation and Visualization Consortium (SMSVC); and many, many others. The extensive contributions of the expert participants who attended the workshop series, and/or provided their discernment and analysis in the review-and-refinement process, are highly appreciated, and this report would not have been possible without their insights. A full list of contributors is provided, with grateful thanks, in Appendix A.

The workshops that helped generate this Roadmap, the formation of the Steel Manufacturing Simulation and Visualization Consortium, and the ensuing succession of collaborative research studies and implemented technological advancements that began in 2014 and are still ongoing, were made possible through a grant provided by the National Institute of Standards and Technology (NIST), an agency of the U.S. Department of Commerce.

Thanks are extended to the NIST, CIVS, and AISI organizers as well as the speakers who provided their perspectives on new technologies and the challenges impacting the steel industry. The service and contributions of all current and past SMSVC board members and project technical committee (PTC) members, whose efforts have already given rise to the many technological implementation examples distributed throughout this Roadmap, are gratefully acknowledged. Finally, thanks are extended to the Energetics Incorporated team for their assistance in facilitating the workshop and assisting with the preparation of this report. Special mention and thanks are due to the following individuals for their key role in the creation and redaction of the Roadmap:

Ron Ashburn, Executive Director, Association for Iron & Steel Technology (AIST)

Ron Ashburn has served as AIST’s Executive Director since the organization’s founding in 2004, and previously served as Managing Director of the Association of Iron and Steel Engineers (AISE), which merged with the Iron and Steel Society to form AIST. Mr. Ashburn started his career in the steel industry as a Mechanical Engineer at SMS Demag (now SMS Siemag), where after 10 years he was appointed first as Director of Technology for Steelmaking and Casting, and eventually as Vice President of Operations for the Steelmaking and Casting Division. Currently, Mr. Ashburn oversees staff, operations, and strategic planning initiatives for AIST and the AIST Foundation.

Jeffrey Becker, Research Consultant, United States Steel Corporation

Jeff Becker is a Research Consultant at United States Steel Corporation focusing on innovation and emerging technologies throughout the steel value chain. Mr. Becker has a B.S. in Materials Science and Engineering from the University of Michigan, and an M.S. in Materials Science and Engineering and MBA from the University of Pittsburgh. He joined U. S. Steel in 1997 in Quality Assurance at Gary Works, before transferring to Research in 2001. Technical focus areas are steelmaking and casting and hot dip coating, with a more general focus on the overall production of automotive, tinplate, and tubular steels.
Rick Bodnar, Director of Research & Development, SSAB Americas

As Director of Research & Development at SSAB Americas since 2009, Rick Bodnar helped design, construct, equip, and staff a new R&D facility in Montpelier, Iowa, which opened in 2010. In addition, he helped achieve Leadership in Energy and Environmental Design (LEED) certification for the building; initiated and organized an R&D Seminar Series to provide advanced training for both engineers and analysts; and maintained responsibility for steel product and process development and improvement, customer technical support, technique development, and other project work.

Prior to joining IPSCO/SSAB North America in 2005 as Director of Applications Engineering & New Product Development, Mr. Bodnar earned a Master of Science in Engineering, Metallurgy and Materials Science at the University of Pennsylvania. He worked successively as a Mill Metallurgist, Research Engineer, Senior Research Engineer, and Research Supervisor at Bethlehem Steel (later the International Steel Group and then Mittal Steel), where he won the D. J. Blickwede Research Recognition Award for outstanding research in heavy forgings. He has won numerous industry awards, including being a three-time winner of the AISI Institute Medal and AIST Gilbert R. Speich Award, and was a 2018 recipient of the AIST’s Distinguished Member and Fellow Award, presented at AISTech 2018 in Philadelphia. He is also a Fellow of ASMI (American Society for Materials International) and Alpha Sigma Mu, and he has held a professional engineer’s license since 1984.

Paul Carlson, General Manager, Northshore Mining Company/Cleveland-Cliffs Inc.

Paul Carlson was appointed General Manager at Northshore Mining/Cleveland-Cliffs Inc. in 2018, after serving at Cleveland-Cliffs/Hibbing Taconite/Cliffs Natural Resources in a variety of roles (Plant Manager, General Manager ECIO Logistics, Senior Director ECIO Operations Support, and Director – USIO Process Engineering) for the previous 30 years. Mr. Carlson received a Bachelor’s degree in Mechanical Engineering at Michigan Technological University, and is a newly elected (2017/2018) board member of the Iron Mining Association of Minnesota.

John D’Alessio, Director of Process Technology, Stelco

John D’Alessio is the director of Process Technology for Stelco with over 20 years of pyrometallurgical process engineering experience. Mr. D’Alessio earned a B.Eng. degree in Materials Science in 1993 and an M.Eng. degree in 1996, both from McMaster University. Mr. D’Alessio has held a sessional faculty position at McMaster University since 2007 and is currently instructing courses in both the Walter Booth School of Engineering Practice and Technology and the CCE Metallurgy of Iron Steel Program. He also held the committee chair position from 2011 to 2017 for the McMaster University Blast Furnace Ironmaking Intensive Short Course.

Mr. D’Alessio has co-authored many technical papers, received the J.F. Moore Prize for outstanding student of Metallurgy for the Class of 1993, has been a member of the Association for Iron & Steel Technology (AIST) since 1994, became a Professional Engineer registered with the Professional Engineers Ontario (PEO) in 1998, holds the 2006 Kapitan Award for best paper and the J. E. Johnson Jr. Award for 2008.

Mr. D’Alessio has been actively serving the academic community, continues to serve as committee member for the McMaster University Blast Furnace Ironmaking Intensive Short Course, worked closely for many years in liaison with Purdue University Northwest (formerly Purdue University Calumet), Center for Innovation through Visualization and Simulation, in ironmaking research and is a board member for the Steel Manufacturing Simulation and Visualization Consortium (SMSVC) and the Canadian Carbonization Research Association (CCRA).

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Mitch Day has been Strategic Account Director at Praxair, Inc. since 2013, prior to which he served as Pipeline Business Manager and in Global Procurement Management, Sales Support, and Account Management at Praxair. Mr. Day received his Bachelor of Science in Chemical Engineering at Rose-Hulman Institute of Technology and his Master of Science in Business Administration at the University at Buffalo School of Management, State University of New York. Mr. Day served on the board of directors of the Michigan Chemistry Council from 2011 – 2013 and has been a member of the board of directors for the Steel Manufacturing Simulation and Visualization Consortium (SMSVC) since 2015. He received the 2017 Outstanding Service Award for his support of the AIST Midwest Member Chapter.
Dave Dent, Manager of Strategic Power, Union Gas
Dave Dent, Manager of Strategic Power at Union Gas, has been appointed to the Technical Panel of Ontario’s IESO (Independent Electricity System Operator), which proposes and reviews amendments to the Market Rules and advises the Board of Directors on specific technical issues related to operation of IESO-administered markets.

Steven Hansen, Vice President & Chief Technical Officer, SSAB Americas
Steve Hansen is Vice President and CTO for SSAB Americas, a position he has held since 2007. In this role, he has overall responsibility for all technical support activities at SSAB’s North American steel plants and CTL lines, including quality assurance/quality control, applications engineering, continuous improvement, environmental and research and development.

After prior experience with Bethlehem Steel Corporation, Steve joined IPSCO in 2003 as Director – Technical Services, US Steel Operations. In 2004, he was named Corporate Director – Technical Services, responsible for all steel plant and tubular technical activities. When IPSCO was acquired by SSAB in July 2007, Steve was named to his current position.

Steve is a graduate of the Massachusetts Institute of Technology with S.B., S.M., and Sc.D. degrees in Metallurgy and Materials Science.

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Prior to becoming Principal Metallurgist at Concurrent Technologies Corporation in 2018, Robert Hyland was first Director of Product Technology (2009) and then Director of Process Technology (2011) at U.S. Steel Corporation in Pittsburgh, where he oversaw research and technology support of all plant primary and finishing processes for U.S. Steel’s North American integrated steelmaking facilities. Dr. Hyland also spent 10 years as a Scientific Associate and Principal Investigator at Alcoa in Pittsburgh. He received his bachelor’s, master’s, and Ph.D. in Metallurgical Engineering & Materials Science from Carnegie Mellon University.

Bill King, Process Research Manager, AK Steel
Bill King, Process Research Manager at AK Steel since 2015, joined AK Steel in 1995 first as an Associate Research Engineer and through serial promotions rose to Senior Research Engineer and eventually to his current position, during which time he brought automated scanning electron microscopy capability, and an ideation and project control system, to AK research facilities. Mr. King received his Bachelor of Science in Materials Science and Engineering from the Massachusetts Institute of Technology, a Master of Engineering in Materials Science and Engineering from Carnegie-Mellon University, and a Master of Business Administration (MBA) from Xavier University – Williams College of Business. Mr. King also serves as the current Chair of the Board of Directors for the Steel Manufacturing Simulation and Visualization Consortium (2017-2019).

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Ron Radzilowski, Principal Research Engineer, AK Steel
Ron Radzilowski, a Principal Research Engineer at AK Steel since 2014, has worked in operating and engineering functions in the metals industry for the past 40 years, specializing in ferroalloys, superalloys, stainless steel, and advanced high-strength steel. He has held additional positions of Senior Scientist, Group Leader, Electric Arc Melt Shop Manager, Rolling Mill Manager, Process Engineering Manager, Manager – Just-in-Time, and Director of Quality at companies such as Ford Motor Company Scientific Research Labs, Elkem Metals Co., Haynes International, Washington Steel, and Severstal North America/AK Steel Corp. Ron was elected Fellow of ASM International in 2009. He is chair of the ASM International Emerging Technology Awareness Committee from October 2017 to September 2019 and has served as mentor at Materials Teachers Camps (ASM) at the University of Michigan. Ron also is chair of the AISI Committee on Manufacturing Technology since 2013, and Best Paper Award chair on the AIST Metallurgy – Processing, Products & Applications Technology Committee since 2009. Dr. Radzilowski received a B.S. in Chemistry from the University of Detroit, an M.S. in Chemistry and an M.S.E. in Materials Engineering, and a Ph.D. in Metallurgical Engineering from the University of Michigan.

Scott Rasmussen, Director – Cliffs Technology Group, Cleveland-Cliffs Inc.
Scott Rasmussen was appointed Director – Cliffs Technology Group at Cleveland-Cliffs Inc. in 2018, after having worked at Cliffs’ Tilden Mine since 1988 in a succession of positions, including Concentrator Plant Metallurgist, Area Manager Concentrator Operations, Area Manager Pellet Plant Operations, Area Manager Metallurgical Processing, and Area Manager Plant Operations. Mr. Rasmussen also spent more than 4 years as Turn Foreman, Plant #2 BOF for Inland Steel. Mr. Rasmussen has over 30 years of experience in the iron ore and steel industries in a variety of supervisory, technical, and department managerial positions. Mr. Rasmussen received his B.S. in Metallurgical Engineering from Michigan Technological University.

Kurt Sangster, Director of Operations & Maintenance, NIPSCO
Kurt Sangster was named Director of Operations & Maintenance at NIPSCO in 2017, having previously served as Vice President, Major Projects and Vice President – Projects and Construction, Electric at NiSource/NIPSCO and prior to that, as Project Manager at NIPSCO. As Director of Major Projects, Mr. Sangster oversaw the flue gas desulphurization (FGD) installation at the coal-powered generating station in Michigan City, and was part of the NIPSCO team awarded an Owner Excellence in Leadership in 2016 by the Northwest Indiana Business Roundtable (NWIBRT) Construction Advancement Foundation (CAF). Mr. Sangster received his Master of Science degree in Mechanical Engineering from Southern Illinois University.
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Andrew Spencer has been a Process Metallurgist at Steel Dynamics, Inc., since 2014, prior to which he worked as both a Copper Metallurgist Intern (at Steel Dynamics LaFarga Copper) and a Steel Metallurgist Intern (at Steel Dynamics, Inc.). As a full-time process metallurgist, Mr. Spencer’s focus has been on improving existing practices and solving quality and process issues in electric arc furnace operations. Mr. Spencer received his B. Eng. in Metallurgical Engineering from Dalhousie University and his Master of Engineering from Indiana University – Purdue University Fort Wayne (IPFW). Mr. Spencer has been a recipient of an AIST Ronald E. Lincoln Memorial Scholarship and a Natural Sciences and Engineering Research Council of Canada (NSERC) Undergraduate Student Research Award.

Karl Stanley, Vice President, Commercial Operations, NIPSCO
Karl Stanley has been Vice President, Commercial Operations at NiSource since 2010, and previously held a number of high-level positions at NiSource/NIPSCO, including Executive Director, Energy Supply & Trading; Director, Energy Supply Services; Manager, Energy Trading; Director, Risk Management & Capital Allocation; and Risk Management Specialist. Mr. Stanley also worked for The Gelber Group for 8 years as a Trader/Analyst, managing domestic and international futures market investment and exposure and trading energy/commodity futures contracts. Mr. Stanley received his B.A. in Chemistry from the University of Chicago and his MBA in Finance from the University of Chicago – Booth School of Business.

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Bin Wu, Project Manager, NIPSCO
Bin Wu, currently a Project Manager at NiSource/NIPSCO, was a Research Engineer at Purdue Northwest’s Center for Innovation through Visualization and Simulation (CIVS) and was part of the team awarded the 2017 Hunt-Kelly Outstanding Paper Award – First Place from the Association for Iron & Steel Technology (AIST), as well as the Joseph S. Kapitan Ironmaking Best Paper Award, at AISTech 2017. Mr. Wu received his master’s degree from Purdue University Northwest (Calumet) in 2009.

Mike Zdyb, Director – Major Accounts, NIPSCO
Mike Zdyb, Director – Major Accounts, NIPSCO (retired) has worked for NiSource/NIPSCO in a variety of positions, including Director – Customer Service, Director – Regulated Strategy, and Vice President – Business Development for NET (NiSource Energy Technologies). Mr. Zdyb received an MBA from the University of Notre Dame – Mendoza College of Business.

Chenn Zhou, Director, CIVS and Steel Manufacturing Simulation and Visualization Consortium (SMSVC)
Dr. Chenn Zhou is the founding Director of both the Center for Innovation through Visualization and Simulation, and the Steel Manufacturing Simulation and Visualization Consortium, based at Purdue University Northwest in Hammond, IN; she is also a Professor of Mechanical Engineering at PNW and Professor by Courtesy at Purdue University West Lafayette. She received her PhD in Mechanical Engineering from Carnegie Mellon University and has more than 35 years of experience in relating research in computational fluid dynamics (CFD), multiphase reacting flows, and combustion into practical application for steelmaking process simulation and optimization.

With Appreciation
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1949-2015
Industry/Organization Participants [Enterprise Status]

Air Products and Chemicals, Inc. [Large enterprise]
AK Steel [Large enterprise]
American Iron and Steel Institute (AISI) [Nonprofit organization]
ArcelorMittal USA [Large enterprise]
Association for Iron and Steel Technology (AIST) [Professional association]
Berry Metal Company
Carnegie Mellon University [Academia]
Center of Workforce Innovations (CWI) [Nonprofit organization]
Cliffs Natural Resources/Cleveland-Cliffs Inc.
CMC Americas (now part of Tata Consultancy Services) [Large enterprise]
Enhanced Technology Services, LLC [Small/micro enterprise]
Falcon Foundry Company
Globex Corporation [Small to medium enterprise]
Hatch
Indiana Economic Development Corporation (IEDC) [Public-private company]
Lawrence Livermore National Laboratory [Federal laboratory]
Los Alamos National Laboratory [Federal laboratory]
Michigan Technological University [Academia]
National Institute of Standards and Technology (NIST)
NiSource [Large enterprise]
Northern Indiana Public Service Company (NIPSCO) [Large enterprise]
Northwest Indiana Forum [Development association]
Nucor [Large enterprise]
Oak Ridge National Laboratory [Federal laboratory]
Praxair [Large enterprise]
Purdue University Northwest [Academia]
Severstal USA [Large enterprise]
SNC Lavalin [Large enterprise]
SSAB Americas [Large enterprise]
Steel Dynamics, Inc. [Large enterprise]
Stelco (formerly U.S. Steel Canada) [Large enterprise]
Tenova Core/Tenova Inc.
TimkenSteel Corporation [Large enterprise]
Tri-Creek School Corporation [Academia]
Union Gas
U.S. Department of Energy, Advanced Manufacturing Office [Federal agency]
U.S. Steel Corporation [Large enterprise]
Whiting Services [Small to medium enterprise]
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EXECUTIVE SUMMARY

The U.S. steel industry is the backbone for many of our strongest manufacturing industries, supplying products for transportation, construction, industry, infrastructure, defense, appliances, and many other purposes. In 2014, the U.S. steel industry operated more than one hundred steelmaking and production facilities, producing 98 million tons of steel shipments with a value of $75 billion. The steel industry also employs about 150,000 people in the United States, and supports more than one million U.S. jobs in related industries and sectors throughout its value chain.

Manufacturing represents one of the most important applications of modeling, simulation, and visualization (MSV). MSV can be a valuable tool for evaluating the effect of capital investment in equipment and physical facilities, such as new factory space, warehouses, and distribution centers. MSV can be effectively applied to predict the performance of a system and/or to compare alternative technology solutions, leading to optimized efficiencies and sustainable practices. MSV can also provide effective training tools that enhance workplace safety, improve equipment reliability, and teach plant personnel how to do their jobs and make key decisions more productively.

Purdue University Northwest and the American Iron and Steel Institute hosted two workshops in late 2014 to explore the challenges and future needs for MSV in the steel industry. These events were made possible with support from the National Institute of Standards and Technology (NIST) through a grant from the AMTech Program. The combined events brought together over 65 interdisciplinary experts from industry, government, national laboratories, and academia with a dual interest in the steel industry and MSV.

This Technology Roadmap for Advanced Simulation and Visualization for Steel Optimization is based on the expert views that emerged from these events and additional insights of others. It will be useful to both public and private decision-makers in furthering the capabilities of MSV and expanding their use in the steel industry.

Within the eight priority roadmap focus areas, the major goals identified for MSV for steel optimization are shown in Figure ES-1. These reflect the big-picture goals that could potentially be achieved over the next 5 to 10 years in the areas important to steel production and operations.

Achieving these goals will lead to the successful outcomes shown in Figure ES-2. These outcomes illustrate some of the broad potential benefits to be gained through greater use of modern computational and visualization techniques.

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### Figure ES-1. Major Goals to Achieve Outcomes

#### Workplace Safety
- Reduce preventable workplace fatalities to zero while also minimizing non-fatal injuries and incidents
- Achieve continuous safety learning processes based on observations of what went wrong during incidents (e.g., translate historical knowledge into learning)

#### Energy Efficiency
- Reduce energy intensity significantly in 10 years through new technologies (e.g., low fuel rate operation of blast furnace) and smart approaches that optimize energy resources (long-term goal)
- Optimize the electrical energy inputs to the overall plant; achieve maximum internal electricity generation
- Achieve optimum usage of waste gas as energy resource, including blast furnace (BF) and other waste gases
- Recover sensible heat

#### Production Efficiency
- Reduce cycle yield times significantly through start-to-finish visualization that enables streamlining of processes
- Maximize the use of inexpensive and newly abundant natural gas via new technology or by improvements to existing technology
- Achieve improvements to processing and development of advanced high-strength steels (AHSS)
- Lower raw material costs through better utilization and recycling; maximize re-use of fines

#### Reliability and Maintenance
- Substantially reduce and minimize current nonconformance conditions, from safety to downtime and quality, with a priority of zero nonconformance from safety
- Increase mean time before failure
- Reduce unplanned breakdown days to near zero over the long term

#### Environmental Impacts
- Improve by-product utilization by reducing generation and improve by-product beneficiation to significantly reduce landfilling needs
- Reduce CO2 emissions through more energy efficient processes, recuperation of process gases, and CO2 capture processes
- Develop CFD process models for emissions that could be based on raw materials composition and process parameters

#### Raw Materials
- Minimize the generation and need for beneficiation of by-products through improved process efficiency (e.g., improved skimming operation, better separation of scale/oil)
- Develop advanced by-product beneficiation technologies to increase recycling rates and value of by-products
- Develop techniques to reduce degradation during handling, and improve sizing of raw materials
- Develop optimization tools to optimize the use and flow of raw materials plant-wide
- Develop process models that could relate raw material characteristics like size, strength and chemistry to process performance including productivity, quality and environmental aspects
- Develop optoelectronic sensing (sensing of optical properties), to achieve significant reduction in impurities (e.g., 50% in 5 years) (long-term goal)

#### Smart Steel Manufacturing
- Achieve high-speed simulations and visualizations that allow for iterative design and operational insights
- Improve and optimize product quality through effective modeling and simulation, including integrated processing, improved structure-property, and multi-scale models
- Achieve a comprehensive hot strip finishing mill with broad capabilities for simulation to improve and optimize product quality

#### Workforce Development
- Achieve full connection and awareness of the workforce opportunities in the steel industry, beginning with education and carrying through to workforce
- Achieve across-the-board occupational competence throughout the entire organization
- Optimize/enhance intellectual capital and company success via knowledge, training, and understanding of new technology
### Figure ES-2. Successful Outcomes

<table>
<thead>
<tr>
<th>Greater Workplace Safety</th>
<th>Efficient Use of Energy Resources</th>
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<tbody>
<tr>
<td>The production and operational environment is made safer through modern, cost-effective training techniques and increased operator safety awareness.</td>
<td>Simulation and visualization methods enable better management and use of energy resources, as well as recovery and use of valuable waste heat.</td>
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<tr>
<th>Streamlined, Efficient Production</th>
<th>Optimized Maintenance and Reliability</th>
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<tbody>
<tr>
<td>New technologies and simulation techniques lead to reduced cycle times, increased yields, and optimization of production efficiency.</td>
<td>Greater confidence and reliability in equipment, processing, and product quality is achieved via enhanced training and early preventive maintenance tools.</td>
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<tr>
<th>Sustainable Production</th>
<th>Economic, Reliable Raw Materials</th>
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<tr>
<td>New simulation tools allow for optimization of processes and identify opportunities for recycling, leading to fewer emissions and less landfilled or treated waste.</td>
<td>Better materials utilization, yields, and recycling are made possible through advanced simulation methods, leading to fewer materials supply issues and lower costs, while optimizing product quality.</td>
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<tr>
<th>Agile, Smart Manufacturing Systems</th>
<th>Next Generation Workforce</th>
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<tbody>
<tr>
<td>Advanced computational methods for operations and enterprise management enable a smart, agile manufacturing environment and supply networks that are responsive to customer demands.</td>
<td>Greater awareness of opportunities in the steel industry and excellent educational and plant personnel training programs yield a highly trained, retained manufacturing workforce.</td>
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</tbody>
</table>

A number of **broad challenges** were identified that currently impede the use of modeling, simulation, and visualization for steel optimization. These challenges are economic, cultural, and technical, as illustrated in Figure ES-3.

**Topic-specific challenges** were also identified for the eight priority roadmap areas. Many of these are broad technical challenges and not necessarily specific to MSV, while others are directly related. In energy efficiency, for example, a significant challenge is the availability of cost-effective technology for capturing low-quality waste heat. Reducing heat losses (or increasing recovery) from mature processes is also challenging as it requires economically and technically feasible retrofits. In workplace safety, adverse operator perceptions of the utility and value of new MSV tools for safety and training can be an impediment to use. A complete set of challenges identified for each priority roadmap area is outlined in the respective chapters in this report.
Eighteen **priorities** were identified for accelerating the development and use of modeling, simulation, and visualization in a wide range of companies and facilities across the steel industry. A set of roadmap action plans was developed for each of these priorities and can be found in the respective sections of this report.

While these roadmap priorities relate specifically to optimization of steel production, processing, and operations, they will have impacts across the steel value chain, from raw materials to distribution of products. More reliable operations, for example, will lead to higher product quality and fewer defects, with concomitant cost reductions. Smart steel manufacturing systems will enable greater customization and agility for meeting changing customer demands and expectations.
Figure ES-4. Eighteen Top Priorities for MSV for Steel Optimization

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<tr>
<th>Workplace Safety</th>
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<tr>
<td>Virtual Safety Training for Improved Workplace Safety – Comprehensive training library and tools for operators based on common failure scenarios</td>
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<th>Energy Efficiency</th>
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<tr>
<td>Optimization of Steel Mill Energy Efficiency – Tools to optimize energy efficiency in core processes, powerhouse boilers, and gas recovery</td>
</tr>
<tr>
<td>3D Integrated Blast Furnace MSV Capability – Rapid, 3D capability to improve fuel efficiency and enable fast optimization of furnace operations</td>
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<tr>
<td>Optimized Blast Furnace Fuel Injection – Raceway model to optimize fuel injection via comparative analysis of injectants and process conditions</td>
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<tr>
<td>Reduction in Energy Losses between Core Processes – Simulations to analyze energy/heat losses and prioritize optimization</td>
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<th>Production Efficiency</th>
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<tr>
<td>Improvement of Control Strategies for the Strip Steel Run-Out Table – Hardware-in-the-loop simulator to improve performance and resource efficiency of the run-out table cooling system</td>
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<tr>
<td>Simulation and Optimization of Alternative Ironmaking Processes – Models/tools to optimize alternative/ emerging ironmaking processes toward lowest resource requirements</td>
</tr>
<tr>
<td>Modeling of Steel Cleanliness Practices for Low-Temperature Cast Steel – Modeling/visualization to improve cleanliness and overall efficiency of steel caster</td>
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<tr>
<td>Simulation of Hot Rolling of Advanced High-Strength Steels – Integrated multi-scale modeling to eliminate use of empirical methods for thermomechanical rolling simulations</td>
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<th>Reliability and Maintenance</th>
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<tr>
<td>Early Preventive Maintenance Tools for Breakdown Avoidance – Predictive models, visualization, sensors, and training to avoid breakdowns and downtime</td>
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<th>Environmental Impacts</th>
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<tr>
<td>Zero By-Product Fuel Flare – Virtualization and modeling of flamed by-product gases to allow for better design of solutions for flare gas reduction</td>
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<th>Raw Materials</th>
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<tr>
<td>Optimized Raw Material Handling Designs and Practices – MSV for better material handling designs and materials management to reduce yield losses</td>
</tr>
<tr>
<td>Optimization of Raw Material Inputs into EAF – Technologies and models to optimize raw materials for EAF via better consistency and optimized composition</td>
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</table>
### Smart Steel Manufacturing

<table>
<thead>
<tr>
<th>Expert System for Integration of Scheduling, Production, and Material Flow</th>
<th>Integration of Sensors/Data with Process Control Systems for Production Planning</th>
<th>Optimized Material Flows through a Constrained Facility – Production planning execution model that enables operation of the constrained facility at a world class utilization rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated inventory, schedule, price and control management tool to improve operational efficiency</td>
<td>Automated sensor-driven smart system to optimize materials, manpower, downtime, and product quality</td>
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### Workforce Development

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<tr>
<th>Interactive Student-Steel Industry Program and Tools</th>
<th>Virtual Simulation and Visualization Training – Virtual training tools to enhance operator performance and productivity</th>
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<tbody>
<tr>
<td>Training, outreach, and curricula program to introduce students to the steel industry</td>
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1. **INTRODUCTION**

1.1. **Advanced Manufacturing**

Manufacturing is fundamentally important to the economy and national security of the United States. The manufacturing sector fuels economic growth, provides highly skilled jobs, and produces the equipment and products that are vital to every sector, from energy and water to defense and homeland security.

U.S. manufacturers continue to face tremendous challenges in today’s globally competitive marketplace. While the domestic high-tech manufacturing industries retain leadership in total global output, the U.S. share has fallen significantly since 1998. In spite of competition and downturns, manufacturing remains as the largest employer in the United States and a substantial jobs growth engine. In a recent survey, 79% of Americans agreed that a strong manufacturing base is a national priority (Deloitte 2011).

The manufacturing sector is also a driver for innovation, inventions, scientific breakthroughs, and a myriad of products that contribute to our quality of life. During the last two decades, tremendous changes have occurred in information technology (IT), telecommunications, and advanced materials. Technological capabilities and economic pressure are leading the manufacturing sector to revolutionize and revitalize the way it operates and creates products.

Digitization of equipment, processes, and enterprises is occurring across organizations, enabling new opportunities for customization, advanced design and production capabilities, and innovative ways of doing business. These trends toward advanced manufacturing are impacting every aspect of this important sector. As this report will demonstrate, the benefits and opportunities made possible through advances in IT, and in particular modeling, simulation, and visualization (MSV), are vital to driving future growth and innovation in the U.S. manufacturing sector.

1.2. **Iron and Steel: Backbone of Manufacturing**

The U.S. steel industry is the backbone for many of our strongest manufacturing industries, supplying products for transportation, construction, industry, infrastructure, defense, appliances, and many other purposes. In 2014, the U.S. steel industry operated more than one hundred steelmaking and production facilities, producing about 98 million tons of steel shipments with a value of approximately $75 billion. The steel industry also employs about 150,000 people in the United States, and supports more than one million U.S. jobs in related industries and sectors throughout its value chain (AISI 2014).

1.2.1. **The Steel Value Chain**

The steel value chain, depicted in Figure 1.1, illustrates the many components of today’s modern steel industry. The main segments of the steel value chain have disparate needs, barriers, and drivers but are also integrally connected with synergistic challenges. For example, changes in upstream financial conditions have direct impacts on components all along the value chain. Players along the value chain will be faced with some common challenges over the next decade, including a multispeed world (e.g., global supply and demand factors), increasing power and sophistication of steel buyers, and higher price levels and volatility in raw materials markets (McKinsey 2013).
Implementation of modeling, simulation, and visualization tools for steel production and operations can have impacts all along the steel value chain. For example, improvements in process control and production efficiency can lead to better product quality that is passed along to end users. Modern, more sophisticated and data-driven automated production and scheduling management systems can make it easier and more cost-efficient for suppliers to serve their steel industry customers. Smart manufacturing systems that make use of MSV can impart agility and flexibility needed to allow for product customization and more readily meet consumer demand. Smart enterprise systems can more readily...
connect production with business operations – creating more seamless integration of technical and business and financial objectives.

1.2.2. Major Steel Processes

Two main processes are used for the production of steel. These include 1) integrated steelmaking, which combines a blast furnace (BF) with a basic oxygen furnace (BOF); and 2) electric arc furnace (EAF) steelmaking. Both are shown in Figure 1.2. The two processes are distinguished by their raw material inputs. The integrated BOF process consumes mostly agglomerated iron ore along with some scrap steel (up to 30%); the EAF process consumes mostly scrap steel as well as reduced iron, cast iron, and other iron-containing materials to produce raw steel. This report focuses on the use of MSV in all these processes, from raw material inputs to rolling mills, as well as the ancillary functions that are critical to steel operations, such as workforce safety, worker training and development, and managing environmental impacts.

![Figure 1.2. General Schematic for Steelmaking (AISI 2010)](image)

The main processes used in the production of steel and finished products include:

- **Ore agglomeration**: Ore agglomeration is used to enhance the iron content and physical properties of low-grade iron ore that will be used for ironmaking.

- **Cokemaking**: Coke is made in an energy-intensive process that involves feeding coal into a coke oven, where it is heated to high temperatures in an airless environment.

- **Ironmaking (traditional only)**: Ironmaking is the process used to convert iron ore into molten iron, also known as pig iron, and it is usually accomplished in a BF. Agglomerated iron ore, coke (coal), and limestone are fed into the furnace, where the coke is burned with air to heat and remove oxygen from the iron ore.
• **BOF steelmaking**: After the molten pig iron is produced in the BF, it is fed to a BOF along with a maximum of 30% scrap steel to be converted to raw steel. Oxygen is injected into the BOF to remove carbon from the pig iron through oxidation.

• **EAF steelmaking**: New steel produced via the EAF process is made from a feedstock of recycled steel and other iron unit feedstock. A combination of electrical and chemical energy is used to melt the recycled steel.

• **Casting**: From the electric arc furnace or BOF, molten steel is semi-finished through casting into various solid forms, including slabs, beams, billets, and blooms.

• **Rolling**: Rolling and finishing processes are used to produce the finished steel products.

### 1.3. The Role of Modeling, Simulation, and Visualization in Iron and Steelmaking

Modeling, simulation, and visualization (MSV) are the three discrete components that make up computer-generated representations of a real-world process or system. Simulation represents the operation of a system over time; a model must first be developed to represent the key characteristics or behaviors of the physical system or process. Visualization is the 2D or 3D depiction of the result of the simulation.

Simulation has been used in many applications. Simulation of technology performance, safety engineering, training, education, and video games are just a few examples. One useful application is to predict the effects of alternative conditions, solutions, or courses of action. Simulation can also be useful when it is too dangerous, expensive, or unacceptable to access the real system. As a design or planning tool, simulation is useful for looking at potential design scenarios before systems, facilities, or equipment are built.

Some of the major challenges for simulation include acquiring valid data for the key properties, characteristics, or behavior of the system to be modeled; developing approximations and assumptions that are credible; and assuring the robustness and accuracy of simulation results. Collaborative research centers or partnerships between industrial manufacturers and academic institutions can leverage the strengths of each to find optimal solutions to such challenges, benefiting both partners directly as well as indirectly (e.g., through academic/research reputation enhancement and enrollment, improved profit margins, stimulated local economy, etc.).

#### Visualizing Steelmaking

Computational fluid dynamics (CFD) has become widely accepted in many industries as a quick, economical way to solve process problems. CFD computer models can simulate real processes using fundamental equations for fluid flow, combustion, and heat transfer. Virtual reality (VR) imparts greater depth to the model, allowing engineers to ‘step inside’ the process. In 2011, a consortium at Purdue University Northwest collaborated with three integrated steel customers and Union Gas to maximize the benefits of co-injection of natural gas and pulverized coal into blast furnaces using CFD. Consortium research has resulted in **over $20 million in avoided costs** for member companies. (Union Gas 2012)
1.3.1. MSV in Manufacturing and the Steel Industry

Interest in MSV in the manufacturing sector has greatly increased in recent years. Many manufacturers are investing in advanced manufacturing technology including flexible manufacturing systems and various computer-aided manufacturing systems. The availability of a well-constructed and validated computer model allows system designers, users, engineers and managers to understand in advance the investments needed, and the detailed consequences of their decisions, prior to actually making commitments. Today simulations are being used in a broad spectrum of applications to overcome manufacturing and logistical challenges and improve efficiency and productivity.

Manufacturing represents one of the most important applications of MSV. It can be a valuable tool for evaluating the effect of capital investment in equipment and physical facilities, such as new factory space, warehouses, and distribution centers. Simulation can be effectively applied to predict the performance of a system and/or to compare alternative solutions (Benedettini 2008).

An important application of manufacturing simulations is quantifying the performance of systems, components, and overall operations. Some of the common performance measures well-suited for MSV techniques (Banks et al. 2005) include the following:

- Use of resources and labor (and staffing requirements)
- Machine utilization
- Manufacturing bottlenecks, choke points, and throughput
- Product cycle times
- Queuing at work locations, and delays caused by material-handling devices and systems
- Effectiveness of scheduling systems
- Performance of control systems

Implementation Example:
CFD Analysis of Secondary Cooling Process

A computational fluid dynamics (CFD) model of the steel slab secondary cooling process has been developed and validated against data from experiments and published literature. This model, which emerged from multiple, long-term collaborations between CIVS researchers and SMSVC/industry partners, is envisioned to help optimize cooling intensity in terms of both suitable cooling (avoiding slab cracking and deformation) and energy savings. Long-term research targets include optimizing the distance between spray cooling nozzles, developing more accurate and reliable heat transfer coefficient (HTC) correlation, and investigating slab thermal stress distribution. Expected outcomes include improved product quality and reduced rework and/or yield loss.

(Ma et al. 2018)
Three-dimensional (3D) graphical visualization techniques have been successfully used in manufacturing for facility layouts, visualization of process units, and design of products and equipment. There are many advantages to the use of 3D visualization. The use of 3D provides greater depth and context within which the operational environment is visualized — allowing users to view and understand more complex parameters more readily. For example, 2D drawings are difficult to produce, time consuming to analyze, and can provide inaccurate or ambiguous results. With a 3D simulation, more complete system designs and operations can be visualized. Object-level programming allows objects to be generated relative to items in the workplace, eliminating the need to perform complex positional calculations.

There is great potential for the use of MSV to generate operational and productivity improvements in iron and steelmaking. The advent of high-performance computing, advances in computational technology, and dramatic improvements in telecommunications are creating important new opportunities for MSV in steel and all manufacturing. While some of these are part of the trend toward “smart” manufacturing, others simply represent better, faster ways to manufacture products, conduct business planning, and perform important training and safety functions.

Research in MSV is a vital part of moving forward and taking advantage of the opportunities for manufacturing. Research and development (R&D) efforts are interdisciplinary in nature, often with collaborations occurring across many organizations and countries. Major research activities focus on:

- Integration of virtual reality with simulation technologies and high-performance computing
- Application of simulation and visualization technologies to industrial processes for process/product design, trouble-shooting and optimization to address issues of productivity, energy, environment, and quality
- Application of MSV technologies to business, healthcare, liberal arts, and science
- Development of advanced learning environments in virtual reality for training and education

**MSV benefits already in process:** Collaborative studies with industry partners/SMSVC members using CFD have yielded over $20M in savings/cost avoidances in a single (blast furnace) project, and studies targeting energy efficiency and product quality are identifying optimization areas for the ladle, reheat furnace, electric arc furnace, casting and primary cooling, and secondary cooling areas. MSV is also advancing safety and workforce development.
1.4. **Roadmap Scope and Objectives**

Purdue University Northwest and the American Iron and Steel Institute hosted two workshops on Advanced Simulation and Visualization for Steel Optimization in late 2014. The purpose was to explore the challenges and future needs for MSV in the steel industry, and to gain insights for the development of a technology roadmap for this important area. The event was made possible with support from the National Institute of Standards and Technology (NIST), through a grant from the AMTech Program. AMTech is a competitive grants program intended to establish new or strengthen existing industry-driven consortia that address high-priority research challenges impeding the growth of advanced manufacturing in the United States.

The combined events brought together over 65 interdisciplinary experts from industry, government, national laboratories, and academia with a dual interest in the steel industry and MSV. The objectives for these workshops included the following:

- Serve as a key building block for the creation of a technology roadmap for advanced simulation and visualization for steel optimization
- Evaluate implications for future R&D, within the context of these components:
  - Goals for the steel industry and the role of MSV
  - Future needs and capabilities for steel production and operations that can be enabled via MSV
  - Challenges, gaps, and barriers preventing the development and broad use of MSV in all aspects of the steel industry
  - R&D and other actions needed to address the priority challenges and create new capabilities, to aid in building a targeted technology roadmap
- Inform future technical programs and strategic planning with elements related to the steel industry
- Offer valuable information to government agencies and stakeholders focused on smart systems for steel and other manufacturing environments

This *Technology Roadmap for Advanced Simulation and Visualization for Steel Optimization* is based largely on workshop discussions as well as insights provided by speakers and panelists and contributions from the Steel Manufacturing Simulation and Visualization Consortium, which along with the Roadmap owes its genesis to the AMTech Program Grant. The *Roadmap* report is organized around eight significant topic areas:

- **Workplace Safety**
- **Energy Efficiency**
- **Production Efficiency**
- **Reliability and Maintenance**
- **Environmental Impacts**
- **Raw Materials**
- **Smart Steel Manufacturing**
- **Workforce Development**

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3 Industry-led steel-manufacturing consortium working across the value chain to develop simulation and visualization technologies in a pre-competitive environment.
This report details the findings that will be useful to both public and private decision-makers in furthering the capabilities of MSV and expanding their use in the steel industry. It is envisioned that the national research agenda for MSV and advanced manufacturing will incorporate some of the needs and challenges detailed in this report.

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Union Gas. Gasworks: Cutting-Edge Simulation Improves Industrial Processes. 2012. Available at:
2. **Broad Challenges for Simulation and Visualization in Steel Optimization**

The steel industry has faced many challenges over the last several decades and has re-emerged as a strong force in U.S. manufacturing. Modeling, simulation, and visualization offer many opportunities to continue improving the competitive position of the steel industry as well as accelerate improvements in production and operational efficiency, use of raw materials, environmental performance, reliability, and many other areas. While there are many benefits to MSV, a number of challenges impede their development and use for iron and steelmaking.

- **Limited resources**: Limited resources (people, time, money) are available for acquisition of computing software, hardware, and infrastructure as well as for training on sophisticated MSV tools. Sustained funding and commitment will be needed to support computational teams and reap the benefits of MSV. In times of constrained budgets there is substantial competition for resources for product development versus improvement projects.

- **Lack of proven value proposition**: It is hard for companies to justify and commit resources to advanced MSV without strong returns and a demonstrated value proposition. A strong return on investment (ROI) justification is especially needed for significant capital or operational investments, such as those needed to create and deploy new tools and systems.

- **Legacy cultural issues**: There is a lack of foresight, vision and buy-in, and awareness of computational tools and their effectiveness and utility. A perception persists that simulation/visualization is more useful as a training tool and to address a specific problem rather than to solve broad technological challenges.

- **Protection of intellectual property**: Real and perceived concerns exist about the release of proprietary information via MSV tools.

- **Access to practical knowledge and process environments**: Creating good MSV tools requires access to the people and equipment in steel facilities, as well as collection of real-time data. Without this access it is difficult to facilitate the development of accurate tools.

- **Advanced IT resources**: There is no pipeline of code developers familiar with high-performance computing (HPC) for steel industry problems.
3. **Workplace Safety**

3.1. **Overview**

Workplace injuries have a direct impact on production uptime in the iron and steel industry. Some of the most costly factors in industry are injuries and death resulting from workplace accidents (Waston et al. 2005). According to the Bureau of Labor Statistics, nearly 3 million nonfatal workplace injuries and illnesses were reported by private industry employers in 2012, along with about 4,400 workplace fatalities (Bureau of Labor Statistics 2013). Statistics from the National Safety Council place the average cost of a workplace death around $1.3 million, while an average “reasonable, serious non-disabling injury” was placed at around $22,500 (Reese 2017).

Although workplace incidents and injuries may impact a company’s reputation as well as its day-to-day operations, studies show many of these injuries are preventable by proper training. In one study of factors contributing to construction accidents, “70% of accidents were estimated to have involved failure associated with human error,” while use of improper equipment was the second most frequently cited factor at 56% (Albert et al. 2014). A number of researchers (Waehrer and Miller 2009, Dong et al. 2004) found that safety training appears to be effective in preventing occupational injuries and in reducing claims for workers compensation. In line with these findings, the North American steel industry is committed to the highest safety and health standards. Since 2005, U.S. steel producers have achieved reductions of nearly 78% percent in both the total OSHA recordable “injury and illness” and “lost workday” case rates (AISI 2017). In other words, safety training offers tangible benefits.

Safety training also offers less measurable but still valuable safety-awareness benefits. For instance, safety training interventions have been shown to lead to positive effects on safety knowledge, adoption of safe work behaviors and practices, and safety and health outcomes (Colligan and Cohen 2004). These outcomes affect day-to-day operations of companies in the steel industry and should eventually contribute to the success of their business.

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**Implementation Example:**

**Incident Visualization for Steel Safety Training**

Researchers at Purdue University Northwest in collaboration with SMSVC members are exploring the use of 3D visualization to **re-create real safety incidents**, as opposed to general or fictional incidents. The technique will tie safety concepts to an actual environment and circumstances, providing real-world relevance to training. With 3D visualization, viewers can see an incident as well as the events leading up to, and contributing to, the incident. 3D environments enable incident viewing from multiple locations to provide additional insights, such as conditions from the injured worker’s point of view, or from other key locations within the environment. The project will produce a video that can be merged with existing training materials or viewed online. The use of 3D visualization can provide unique insights into the circumstances and context of a safety incident, **creating more effective and realistic training**.

(Moreland et al. 2015)
Methods of safety training vary widely, ranging from passive means such as conventional lectures, videos, or pamphlets to moderately engaging means, such as programmed instruction or feedback interventions, to highly engaging training like behavioral modeling or hands-on training. Training that is more engaging is generally found to provide the most positive impacts, but all forms of safety training can be beneficial (Burke et al. 2006). Video training is widely used because of its scalability, ease of implementation, and low cost (Bosco and Wagner 1988). However, recent studies (Assfalg et al. 2002, Zhao et al. 2009) commonly agree on the superior benefits of virtual training, due mainly to interactive 3D environments that are more appealing to trainees and engage them with hands-on experience.

3D visualization technology has been used and evaluated for safety training in some industries to enhance the learning experience, and the use of 3D visualization implemented into construction industry safety training has been shown to improve safety awareness (Assfalg et al. 2002). The mining industry has also developed visualization training materials. These virtual environments simulate a number of hazardous conditions and replicate the results of neglected safety procedures and unsafe behaviors, resulting in virtual characters being injured or killed (Filigenzi et al. 2000, Moreland et al. 2015).

While these methods have proven benefits, their use in the steelmaking industry is not yet emphasized. In recent years, the use of high-quality, real-time rendering of equipment has increased the realism and accuracy of virtual reality (VR) simulations. Today, 3D interactive VR is considered one of the best aids for maintenance, safety, and operational training.

**MSV benefits already in process:** A 3D interactive training program developed collaboratively by CIVS & SMSVC is on track to provide interactive training based on real incidents that have occurred in the steel industry. Initial development scenarios/“risk areas” cover fall protection, lockout/tagout, confined space, and arc flash procedures; simulators for the first two areas are already deployed and/or in testing, and the latter two are in development. Other scenarios (e.g., heavy mobile equipment safety) will be added to include additional industrial environments. Users can engage these simulators to operate equipment, make choices based on the hazards they will encounter in the real world, and see the results of unsafe actions. This virtual training method is highly successful, efficient and cost-effective, immersing the user in a scenario and providing true-to-life experiences without placing the user in harm’s way.
3.2. Goals

A number of goals were identified for workplace safety in steel production and operations, and where simulation and visualization could play an important role.

- Reduce preventable workplace fatalities to zero while also minimizing non-fatal injuries and incidents
- Achieve continuous safety learning processes based on observations of what went wrong during incidents (i.e., translate historical knowledge into learning)
- Achieve an across-the-workforce ability to recognize hazards on the shop floor proactively
- Create and adopt MSV capabilities (tools, modules) to educate the workforce about dangerous or high-risk scenarios throughout the enterprise

3.3. Future Needs

MSV can provide numerous opportunities for increasing workplace safety in manufacturing. An overview of future needs is provided in Table 3.1 and summarized below.

**Safety Training**
Simulation and visualization can actively engage workers to experience the outcomes of commonly occurring accidents or mistakes without risk of personal injuries or mechanical failures. A top priority need is the development of training modules involving trainees with high-risk scenarios and incident recreation. The modules would train staff by engaging them in simulations of what could happen during incidents, the timing of events, and potential options for actions. This could enhance operator decision-making before, during, and after incidents.

**Design Improvements**
A top priority is to collect data about accidents in the steel industry, especially data that could provide critical information to generate visual representations of high-risk scenarios. The most common causes of safety incidents in the steel industry are slips, trips, and falls on the same level; falls from height; unguarded machinery; and falling objects (World Steel Association 2016). Accurate incident data will provide an opportunity to develop three-dimensional simulations of big platforms, lifelines, walkways, and how the different elements interact with each other. Ultimately, the data and representative simulations could help improve plant or process designs and prevent future incidents.

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<thead>
<tr>
<th>Table 3.1 Future Needs for MSV for Workplace Safety</th>
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<tr>
<td><strong>Safety Training</strong></td>
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<td><strong>High Priority</strong></td>
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<td>• MSV training modules to educate workforce about</td>
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<td>high-risk, dangerous scenarios; use of</td>
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<td>visualization in pre-job safety briefings on</td>
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<td>frequent incidents</td>
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<tr>
<td>• Visualization of safety incidents, including the</td>
</tr>
<tr>
<td>course of events in both safe and unsafe</td>
</tr>
<tr>
<td>versions</td>
</tr>
<tr>
<td><strong>Medium Priority</strong></td>
</tr>
<tr>
<td>• Recreating visual effect of incidents instead of</td>
</tr>
<tr>
<td>a safety flash (serious incidents)</td>
</tr>
<tr>
<td><strong>Lower Priority</strong></td>
</tr>
<tr>
<td>• Introduction of visual safety training for new</td>
</tr>
<tr>
<td>hires in the steel industry</td>
</tr>
<tr>
<td>• Virtual safety training with visualization/simulation of arc flash, failure rates of mobile equipment, and gas hazards</td>
</tr>
</tbody>
</table>
Table 3.1 Future Needs for MSV for Workplace Safety

<table>
<thead>
<tr>
<th>Design and Process Improvements</th>
<th></th>
</tr>
</thead>
</table>
| **High Priority**              | ● Incident recreation across industry – visual representation of what went wrong; ability to utilize accident history to improve design and procedures  
                                   ● Understanding of equipment settings and impact of changes  |
| **Medium Priority**            | ● 3D simulation of big platforms, lifelines, walkways – how they interact and possible failures |

3.4. Challenges

Two key challenges have been identified that hinder improvements in workplace safety via MSV.

**Operator Perceptions**
Experienced operators may reject modern concepts, such as MSV, because they do not see a need to learn new tools to understand their jobs.

**Safety Situational Awareness**
The workforce is not sufficiently prepared, or does not have sufficient tools for situational awareness, to recognize and understand how to react to a broad spectrum of dangerous scenarios in the plant.

3.5. Priority Roadmap Projects

The integration of MSV into safety training has emerged as a priority for the steel industry. The priority roadmap developed for this area is shown in Figure 3.1 and summarized below.

- **Virtual Safety Training for Improved Workplace Safety** – Development of a comprehensive training library and tools for operators based on common failure scenarios, to fill the gaps in operator training (Figure 3.1). Scenarios that address hazards common to the steel industry include the following:
  - Fall protection
  - Lockout/tagout
  - Confined space
  - Arc flash
  - Mobile equipment

Implementation Example:

**Interactive Virtual Safety Training Simulator**

Virtual safety training reinforces the need for constant awareness and allows users to experience complex, multi-hazard environments. For example, an SMSVC-developed fall protection simulator guides workers through performing a task at height, focusing on aspects of fall protection such as harness inspection and determining what type and length of lanyard is needed. The scenario also includes mobile equipment and other hazards, requiring constant awareness while using the simulator. The simulator can be operated on multiple platforms and devices (e.g., mobile devices, Oculus Rift, HTC Vive, etc.), has already been tested and improved through extensive industry-partner use, and is receiving widespread positive feedback and requests for continued scenario development.

(Moreland et al. 2017)
**Figure 3.1: Roadmap Priority #15**

**Virtual Safety Training for Improved Workplace Safety**

**Challenge/Problem:** Safety is a paramount concern in steel production facilities but can be challenging. Simulations and visualization are not commonly used as safety training tools, so operators may be uncertain about their value. Cultural attitudes also present a challenge; operators can be resistant to new tools, believe accidents won’t happen on their watch, or feel additional training is unnecessary when they have long-term experience.

**Solution/Approach:** MSV can be a valuable tool for improving workforce safety through effective training. This project would develop visualization and simulation training modules for operators based on real safety scenarios taken from industry experiences. Pareto analysis of industry fatalities and events would provide the top “what if” scenarios for training.

### Action Plan

<table>
<thead>
<tr>
<th>1-2 years</th>
<th>3-5 years</th>
<th>5-10 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Choose a training scenario test case and implement</td>
<td>- Develop scenarios proactively based on serious near-misses, without operator risk</td>
<td>- Conduct conference with scenarios on safety issues, publish papers, provide video demonstrations</td>
</tr>
<tr>
<td>- Demonstrate tool at AIST safety conference</td>
<td>- Develop mechanisms for updating training based on emerging scenarios</td>
<td>- Develop/conduct online training using visualization</td>
</tr>
<tr>
<td>- Streamline structure of tool</td>
<td>- Choose experts for succession planning to ensure continuity and updating of training as industry changes</td>
<td></td>
</tr>
</tbody>
</table>

### Outcomes

- Annual Pareto analysis
- Focus areas in manufacturing established by consensus of sponsors
- Quick dissemination of knowledge
- Specific modules based on individual department areas in steel plants
- Training modules available to all steel companies

### Targets

- Comprehensive training library that simulates common failures in behavior and equipment
- Bridging the gap in operator training via virtualization
- Dramatic reduction in time it takes to share safety-related information

### Benefits

<table>
<thead>
<tr>
<th>Factor</th>
<th>Relative Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productivity</td>
<td>♦♦♦ Trained resources, less downtime</td>
</tr>
<tr>
<td>Environment</td>
<td>♦♦ Reduced effluent release, spills via training</td>
</tr>
<tr>
<td>Reliability and Maintenance</td>
<td>♦♦♦ Less downtime, safer trained employee</td>
</tr>
<tr>
<td>Operational Efficiency</td>
<td>♦♦♦ Same as productivity</td>
</tr>
<tr>
<td>Use of Raw Materials</td>
<td>♦♦ Less scrap and reworks</td>
</tr>
<tr>
<td>Competitiveness</td>
<td>♦♦♦ Same as productivity</td>
</tr>
<tr>
<td>Economic Growth</td>
<td>♦♦ Safer workforce, better trained, better recruiting, higher retention</td>
</tr>
<tr>
<td>Workplace Development</td>
<td>♦♦♦ Knowledge retention</td>
</tr>
<tr>
<td>Workplace Safety</td>
<td>♦♦♦ Better understanding of safety issues</td>
</tr>
</tbody>
</table>

### Steel Value Chain Impacts

- **Producers** – less downtime, safer work environment, greater throughput; relevant to every steel company
- **Suppliers** – trickle-down effect
- **Users** – less injuries/fatalities

### Stakeholders and Potential Roles

- **Industry/Producers:** Take the lead in driving short-term action items
- **Industry/Users:** Receive training
- **Academia:** Develop training based on input
- **National Laboratories:** Develop training based on input; train the trainers
- **Government:** Provide programmatic resources, review
3.6. Chapter References


4. ENERGY EFFICIENCY

4.1. Overview

Energy efficiency is an especially important factor for U.S. iron and steel producers, as it impacts both production and operational efficiency. Energy constitutes a significant portion of steel production costs, up to 40% in some countries (APP 2010). In the United States, energy represents about 20% of the total manufacturing cost of steel, a significantly high factor (AISI 2005). Overall the iron and steel industry is one of the largest energy-consuming industries in the United States, accounting for about 5.2% of total U.S. manufacturing energy (EIA MECS 2010). Figure 4.1 illustrates trends in energy costs in the iron and steel industry. While energy efficiency continues to improve, energy costs as a percentage of value added have decreased since 2001 (Figure 4.1).

Improving control of emissions from energy use (CO₂ and other emissions) is vitally important in iron and steel production as it also supports environmental compliance and reduces associated costs (Shieh et al. 2010, AISI 2010, Remus et al. 2013). Reducing energy consumption has the added benefit of reducing carbon emissions. Future climate policies may provide incentives to further decrease carbon emissions and emission intensities. Pollutants, waste, and carbon emissions are covered in more detail in Chapter 7, Environmental Impacts.

4.1.1. State of the Art

The U.S. iron and steel industry has dramatically reduced overall energy intensity for steel production since the 1950s. A large part of this decrease is due to the increasing proportion of steel recycled in EAFs since the 1970s, because the energy intensity of secondary steelmaking is much less than the integrated iron and steel process (EPA 2012).

Energy intensity has continued to decrease throughout the last few decades. Since 1990, technology advances in the steel industry, such as new process adoption and widespread adoption of advanced process controls, have reduced energy intensity by 30%. Contributors to the reduction in energy intensity include the widespread adoption of continuous casting, blast furnace coal injection, optimization of blast furnace operations, thin-slab casting, and the use of previously wasted process gases (blast furnace and coke oven gases) in furnaces and boilers (EPA 2012).

Several plants have installed cogeneration systems. The three newest U.S. coke plants recover the heat from the battery stack to produce steam and/or electricity. Integrated iron and steel plants use excess process fuel gases from blast furnace and coke ovens for cogeneration units. Many plants have implemented thin-slab casting, which uses slabs that are only 2 to 4 inches (5 to 10 cm) thick. Thin-slab casting integrates casting and hot rolling into one process, which reduces energy consumption (EPA 2012). A number of energy efficiency technologies and best practices have been identified, with...
many related to (or potentially enabled by) MSV. These include programmed heating in coke making, automated monitoring systems for cold rolling and finishing, energy monitoring and management, and improved (smarter) process control systems, to name just a few (EPA 2012, Worrell et al. 2010). Many steel plants have already implemented these technologies.

A recent international comparison of energy efficiency in different industries (power, steel, and cement) showed that the ratio of least/best specific energy consumption is 1.49 for the steelmaking BF-BOF route. This indicates that hot metal ratios and quality of raw materials have large effects on specific energy consumption in steel production (Oda et al. 2012).

Reusing process gases that have significant energy content can also improve efficiency and reduce fuel requirements in integrated iron and steel making (Wang et al. 2013, Li et al. 2009, Guo et al. 2015).

Management systems for whole-process monitoring and analysis of energy consumption and efficiency are another way to improve efficiency (i.e., managing plant-wide energy inputs/outputs) (Tang et al. 2014). While such systems exist in many forms today for use in the manufacturing sector, improvements and refinements/advances are needed for these to effectively target iron and steel processes and especially plant-wide energy sources and sinks.

Continued improvements in energy efficiency will require optimization of core processes, energy management practices, and in some cases development and adoption of revolutionary technologies and processes (AISI 2010, Worrell et al. 2010). MSV can play a key role by creating virtual environments that monitor and predict energy performance, both in existing environments and under scenarios involving new technology or practices (Zhou 2011).

A recent report by members of the U.S. steel industry illustrates some of the key gaps that should be addressed for optimizing energy efficiency (AISI 2010). Many of these can be realized and/or solutions accelerated through the use of advanced MSV, including systematic energy efficiency management systems oriented by quality and value of energy; highly energy-efficient process technologies and practices; efficient recovery of waste heat and energy; and rational matching of energy resources and requirements, among others.

**Implementation Example:** Simulation for Blast Furnace Efficiency

Improving blast furnace efficiency and lowering the consumption of metallurgical coke has become increasingly important for the iron making industry. Advanced in-house blast furnace shaft CFD code has been developed at Purdue University Northwest for the design and troubleshooting of the blast furnace. Development of a user-friendly interface is now underway in collaboration with SMSVC input to specify input conditions, geometry, and monitor the CFD simulation, to improve process optimization and energy efficiency.

**The Virtual Blast Furnace**
(CIVS 2015)

**MSV benefits already in process:** Beyond the $20M in blast furnace savings/cost avoidances already achieved, further SMSVC blast furnace studies using CFD have shown up to 30% improvement in pulverized coal burnout through optimized injection lance positioning, and have identified coke replacement/injected fuel optimization for significant potential energy efficiency gains. A 25% increase in coke replacement ratio for natural gas injection could save ~$8.2M annually for a generic North American blast furnace. Initial reheat furnace study results show a potential 12% reduction in fuel use with the use of elevated (450°F) slab charging temperature.
4.2. Goals

A number of goals were identified where advances in simulation and visualization can play a key role in improving the energy efficiency of steel production and operations. Goals also focus on utilization of waste and sensible heat. This approach reduces both overall energy requirements and related costs through the capture of heat that is now flared via stacks or simply wasted.

**Energy Efficiency**
Optimization of energy resources can occur through increased utilization of by-product fuels, optimization of incoming energy resources, and achieving more energy efficient equipment and process footprints. Specific goals include:

- Reduce energy intensity significantly in 10 years through new technologies (e.g., low fuel rate operation of blast furnace) and smart approaches that optimize energy resources (long-term goal)
- Optimize the electrical energy inputs to the overall plant; achieve maximum internal electricity generation
- Achieve dynamic optimization of fuel/gas usage across the entire plant in real-time
- Optimize energy recovery of process gases: coke oven gas (COG), blast furnace gas (BFG), and Linz-Donawitz converter gas (LDG)
- Improve productivity while reducing extra processing
- Increase product yields (reduce scrap generation)

**Waste Heat Utilization**
Waste heat exists in a number of forms throughout the steel production facility. While significant amounts of waste heat are currently recovered, additional opportunities remain for waste heat utilization that could be realized through advanced technology supported by MSV. Specific goals include:

- Achieve optimum usage of waste gas as energy resource, including blast furnace (BF) and other waste gases
- Recover sensible heat
- Use sensible reheat and optimize heat resources/rejects in an economical way (e.g., matching sources and sinks); this includes optimizing carbon monoxide (CO) and CO combustion for reheating
- Optimize the use of process gases (COG, BFG, and LDG)
- Minimize waste generation and material reprocessing to promote energy efficiency
- Minimize sensible heat loss in liquid metal and slabs through better scheduling including hot charge practices and more efficient containers to lower heat loss
4.3. Future Needs

Future technology and MSV needs for production and operational efficiency focus on improving energy use, optimizing equipment operations, and improving operational best practices throughout the manufacturing plant. An overview of future needs is provided in Table 4.1 and summarized below.

Energy Efficiency
Improving energy efficiency of production and greater utilization of waste heat resources are both top priorities. Future process and technology development is needed to reduce energy loss between core processes and optimize the efficiency of all major energy-consuming units (e.g., blast furnace, stove, etc.). Optimization of fuel injection, furnace linings, and combustion efficiency will also be needed.

Waste Heat Utilization
There are significant opportunities to better utilize waste heat and reduce primary fuel requirements. Future needs include ways to decrease heat losses from primary units, slabs, stacks, and other sources. Higher productivity and reduced costs might also be achievable by combining processes to improve efficiency (e.g., waste heat and products, optimal introduction of raw material [e.g., O₂], optimization of gas inputs to the BF, etc.).

Model Properties and Characterization/Data
A top priority is gaining knowledge to enable refinements of melting processes via simulation. Melting is a key process step, and optimization will impact energy and resource use as well as product quality. Another high priority is better understanding and simulation of the phase transformations occurring through iron and steelmaking and the ability to map and simulate all phases. This would enable production and energy optimization for some of the core processes.

Implementation Example:
Improving Blast Furnace Performance

Pulverized coal injection (PCI) is being widely adopted to reduce blast furnace coke consumption in the ironmaking industry. Computational simulations of co-injection of natural gas and pulverized coal in a working industry (and SMSVC member) blast furnace have demonstrated pathways for improving injected fuel combustion, thus enhancing furnace performance. CIVS researchers and industry partners found that utilizing natural gas as the carrier gas for PCI could increase coal burnout across the raceway region by up to 23%—without design alterations. A 27% improvement in coal burnout was observed in cases where a new dual lance design was used for natural gas injection as opposed to the original gas port design. The steelmaker has already begun to explore implementation of the dual lance design on the furnace, with potential for the inclusion of the new carrier gas technique in the future.

(Okosun et al. 2015, Okosun et al. 2017)
<table>
<thead>
<tr>
<th>Energy Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High Priority</strong></td>
</tr>
<tr>
<td>• Reduced energy loss between core processes (ironmaking, steelmaking, rolling, finishing)</td>
</tr>
<tr>
<td>• Optimized stove efficiency/operation for blast furnace</td>
</tr>
<tr>
<td>• Capability to combine processes to improve efficiency</td>
</tr>
<tr>
<td><strong>Medium Priority</strong></td>
</tr>
<tr>
<td>• Dynamic model for sinter plant heating optimization</td>
</tr>
<tr>
<td>• Optimized fuel injection in furnaces for greater efficiency</td>
</tr>
<tr>
<td>• Optimized BF and EAF linings (coolers, retrap, skill, etc.) to best protect shell, resist erosion, and minimize energy and waste</td>
</tr>
<tr>
<td>• Raceway simulation for optimized fuel injection in furnaces for greater efficiency and tuyere parameters</td>
</tr>
<tr>
<td>• Higher combustion efficiency in the EAF</td>
</tr>
<tr>
<td><strong>Lower Priority</strong></td>
</tr>
<tr>
<td>• Comparison of alternative energy sources (coal, solar, nuclear, wind) through energy balance analysis of steelmaking process (i.e., isolate parasitic energy in process)</td>
</tr>
<tr>
<td>• Greater combustion efficiency via solid fuel injection, and optimized to reduce NOx in coke making</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Waste Heat Utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High Priority</strong></td>
</tr>
<tr>
<td>• Decreased waste heat loss from slabs/stacks and BOF steelmaking</td>
</tr>
<tr>
<td>• Lower cost industrial gases (e.g., advanced membranes) and advanced separation of off-gases</td>
</tr>
<tr>
<td>• Recovery of sensible heat from coke and sinter</td>
</tr>
<tr>
<td><strong>Medium Priority</strong></td>
</tr>
<tr>
<td>• Capture of energy from low-temperature waste streams</td>
</tr>
<tr>
<td><strong>Lower Priority</strong></td>
</tr>
<tr>
<td>• Use of CO for injection and to reduce flare</td>
</tr>
<tr>
<td>• Pulverized plastic alternative fuels</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model Properties/Characterizations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High Priority</strong></td>
</tr>
<tr>
<td>• Refinement of physical and chemical knowledge of melting process for improved simulation</td>
</tr>
<tr>
<td>• Understanding of phase transformation through the entire process, mapping solids to liquid to solid</td>
</tr>
<tr>
<td><strong>Medium Priority</strong></td>
</tr>
<tr>
<td>• Simulation of hot blast penetration to tune wind velocity and temperature, angle, etc.</td>
</tr>
</tbody>
</table>

### 4.4. Challenges

A number of important challenges have been identified that inhibit improvements to production and operational efficiency.

**Energy Efficiency**

The low price of energy (mainly natural gas) is currently a disincentive for some efficiency improvements, whereas it may be a greater driver in other countries where energy is expensive and scarce. In addition, there is currently a greater focus on alternative energy sources (e.g., renewables, natural gas) versus energy efficiency. In many cases, using less energy can lead to a greater impact on cost and environment than pursuing different energy sources.

The ability to properly control the energy inputs into the steel in an efficient manner is another major challenge. Accurate simulations of the caster and reheating processes, for example, could potentially provide a better idea of how to control energy flows for optimized efficiency.
Many improvements to combustion efficiency have already been realized. However, less than optimal combustion efficiencies remain an issue for major process units in iron and steelmaking, including boilers and steam generators. Boiler efficiencies vary significantly depending on age and fuel type, ranging widely from 55 – 85%. These inefficiencies account for a large portion of heat losses, or about 44% of the steam energy lost in an integrated mill (Worrell et al. 2010, Shieh et al. 2010).

Waste Heat Utilization
A significant challenge is the availability of cost-effective technology for capturing low-quality waste heat (i.e., low heat content, contaminated waste heat, etc.). Reducing heat losses (or increasing recovery) from mature processes is challenging as it requires economically and technically feasible retrofits. Some solutions may also require significant capital investment.

4.5. Priority Roadmap Projects

Priorities for optimization of production and operational efficiency cover strategies targeting energy efficiency, process optimization, improved controls, and expert systems. These are summarized below and described in priority action plans in Figures 4.2 to 4.5.

- **Optimization of Steel Mill Energy Efficiency** – MSV tools to optimize energy efficiency, targeting core processes, powerhouse boilers, and gas recovery (Figure 4.2).

- **3D Integrated Blast Furnace MSV Capability** – Rapid, accurate 3D capability to improve fuel efficiency and enable quick-turnaround daily optimizations of furnace operations (Figure 4.3).

- **Optimized Blast Furnace Fuel Injection** – Raceway model that enables optimization of the fuel injection process via comparative analysis of injectants and process conditions (Figure 4.4).

- **Reduction in Energy Losses between Core Processes** – Simulations to enable analysis of energy and heat losses and prioritize optimization and improvement strategies (Figure 4.5).
**Figure 4.2: Roadmap Priority #1**

**Optimization of Steel Mill Energy Efficiency**

**Challenge/Problem:** The complexity and variability of the systems used in steel mills and the inputs/parameters driving these systems make it difficult to create plant-wide strategies for optimization of energy efficiency. Gaining buy-in for efficiency projects from management can be challenging, particularly if large capital investments are required. Benefits and returns must be clearly demonstrated.

**Solution/Approach:** Computational modeling tools can be developed to identify and evaluate opportunities to maximize energy efficiency and minimize emissions. This staged approach creates the capability to evaluate existing plants, make recommendations, and then implement improvements with the highest potential for greater efficiency and reduced emissions.

### Action Plan

<table>
<thead>
<tr>
<th>1-2 years</th>
<th>3-5 years</th>
<th>5-10 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Survey different steel plant powerhouse boilers for energy efficiency and identify low-hanging fruits</td>
<td>• Survey plants where further heat recovery from gases makes sense</td>
<td>• Predict emissions and model the effect of pollution control devices on efficiency</td>
</tr>
<tr>
<td>• Model and suggest improvements to achieve energy efficiency, both design and operational</td>
<td>• Model and suggest improvements, both design and operational</td>
<td>• Identify improvements to achieve zero discharge of water</td>
</tr>
<tr>
<td>• Implement recommendations and improvements</td>
<td>• Implement recommendations and improvements</td>
<td>• Identify improvements and technologies to achieve electricity self-sufficiency</td>
</tr>
</tbody>
</table>

### Outcomes

<table>
<thead>
<tr>
<th>1-2 years</th>
<th>3-5 years</th>
<th>5-10 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Survey report on steel powerhouse opportunities</td>
<td>• Survey report on heat recovery opportunities</td>
<td>• Modeling tools for emissions prediction and control</td>
</tr>
<tr>
<td></td>
<td>• Set of recommendations for energy efficiency changes</td>
<td>• Demonstration of zero discharge of water</td>
</tr>
<tr>
<td></td>
<td>• Plant implementation and performance testing</td>
<td>• Demonstration of electricity self-sufficiency</td>
</tr>
</tbody>
</table>

### Targets

- Units operating at highest potential efficiencies
- Zero discharge of water
- Reduced emissions to meet regulations
- 100% electricity self-sufficiency

### Benefits

<table>
<thead>
<tr>
<th>Factor</th>
<th>Relative Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productivity</td>
<td>♦♦ More heat/gases for processes</td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>♦♦♦ Direct reduction in energy use</td>
</tr>
<tr>
<td>Environment</td>
<td>♦♦♦ Direct reduction in combustion emissions</td>
</tr>
<tr>
<td>Operational Efficiency</td>
<td>♦♦♦ High throughput for given energy</td>
</tr>
<tr>
<td>Use of Raw Materials</td>
<td>♦♦ Indirect impact</td>
</tr>
<tr>
<td>Competitiveness</td>
<td>♦♦ Overall reduction in costs</td>
</tr>
<tr>
<td>Economic Growth</td>
<td>♦♦♦ Indirect impact</td>
</tr>
</tbody>
</table>

### Stakeholders and Potential Roles

**Industry/Producers:** Participate in surveys
**Industry/Users:** Conduct collaborative R&D
**Industry/Value Chain:** Conduct collaborative R&D
**Academia:** Conduct fundamental, collaborative R&D
**National Laboratories:** Conduct fundamental, collaborative R&D
**Government:** Provide programmatic interest/support as appropriate

### Steel Value Chain Impacts

Producers - lower energy use and costs
**Figure 4.3: Roadmap Priority #2**

**3D Integrated Blast Furnace MSV Capability**

**Challenge/Problem:** Simulation and visualization tools with high-performance computing (HPC) capability are currently lacking for the blast furnace. Existing software is single processor, steady-state only, and not integrated or designed for HPC. This limits the ability for rapid optimization of the blast furnace.

**Solution/Approach:** MSV tools with three-dimensional (3D) capabilities will be developed to enable rapid simulations and optimization of blast furnace design and operating parameters. The desired outcome would be a 3D tool that scales on an HPC platform, with multiple integrated elements and time-transient capabilities. The tool will facilitate better understanding of workflow and enable development of better guidelines to improve productivity and fuel efficiency.

### Action Plan

<table>
<thead>
<tr>
<th>Time Frame</th>
<th>Action Plan</th>
<th>Outcomes</th>
</tr>
</thead>
</table>
| 1-2 years  | • Parallelize individual components (e.g., shaft)  
• Research suitable HPC platforms  
• Conduct design study using HPC in 3D and 2D  
• Conduct full integrated demos using HPC  
• Develop user interface design  
• Design 3D time-transient code | • Faster code modules (100-fold)  
• Report and data that illustrate value of HPC  
• Understanding of important parameters and approach to quantifying error  
• Design document and plan |
| 3-5 years  | • Integration of additional models (burden distribution, stove, healthy furnace, skill)  
• Develop additional 3D capabilities  
• Develop integrated interface with user 3D code capability, both steady-state and transient | • Completion of missing model elements for the blast furnace  
• Integration of capabilities into code  
• User interface created/tested |
| 5-10 years | • Validate 3D code  
• Develop ROM for simulators  
• Optimize codes and simulation | • Testing of 3D code on realistic scenario  
• ROM and simulator tools using existing code infrastructure  
• Optimization tools integrated into system |

### Targets

- Achieving 3D simulation in 1 hour, and ultimately 15 minutes
- Optimization designs in one day
- Modeling designs with quantified validity and trust

### Benefits

<table>
<thead>
<tr>
<th>Factor</th>
<th>Relative Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productivity</td>
<td>♦♦ Process optimization</td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>♦♦♦ Optimized use of energy</td>
</tr>
<tr>
<td>Environment</td>
<td>♦ Direct reduction in combustion emissions</td>
</tr>
<tr>
<td>Operational Efficiency</td>
<td>♦♦♦ High throughput for given energy</td>
</tr>
<tr>
<td>Use of Raw Materials</td>
<td>♦♦♦ Optimized yield and use of raw materials</td>
</tr>
<tr>
<td>Competitiveness</td>
<td>♦♦ Overall reduction in costs</td>
</tr>
<tr>
<td>Economic Growth</td>
<td>♦♦♦ Lower costs</td>
</tr>
<tr>
<td>Workplace Safety</td>
<td>♦♦♦ Enables optimization of safety parameters</td>
</tr>
</tbody>
</table>

### Stakeholders and Potential Roles

**Industry/Producers:** Define problems, train user community operators, provide data

**Industry/Users:** Define problems, train user community operators, and provide data

**Academia:** Train students, develop software, and conduct foundational science

**National Laboratories:** Develop software, and provide HPC, libraries and tools

**Government:** Programmatic interest/resources

### Steel Value Chain Impacts

Producers – more efficient BF operations
Users – trickle down to product quality and cost
**Challenge/Problem:** Current thermokinetic models are inadequate for optimization of the blast furnace fuel injection system. Experimental data for supporting modeling of kinetics is lacking and difficult to obtain. Simulation of the fuel injection process requires characterization of multiphase heat transfer and complex reactions, which are difficult to model and validate. Incorporating the complex interactions of domain raceway/shift versus processing time is also challenging.

**Solution/Approach:** Reductions in hot metal cost can be realized through the development of a raceway model that takes into account different fuel injectants and considers chemical composition, cracking heat and size, and other tuyere parameters. The model would simulate temperatures, burnout rates, composition and volumes, and a permeability map.

### Action Plan

<table>
<thead>
<tr>
<th>1-2 years</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identify gap between desired optimization state and existing state of the art</td>
<td>Improved thermokinetic models</td>
</tr>
<tr>
<td>Identify experiments to provide thermokinetic parameters</td>
<td>Tuyere measurements, temperature, gas composition, pressure, 2D temperature and chemical composition</td>
</tr>
<tr>
<td>Develop methodology to validate simulation</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3-5 years</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrate shaft and raceway models and implement necessary improvements</td>
<td>New 3D blast furnace fuel injection model</td>
</tr>
<tr>
<td>Obtain thermokinetic data</td>
<td>Realization of high temperature data</td>
</tr>
<tr>
<td>Obtain necessary computer capacity and platforms</td>
<td>Upgraded computational resources, interface, and accessibility</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>5-10 years</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Validate the model</td>
<td>Improved, validated model with optimized capabilities</td>
</tr>
<tr>
<td>Study and incorporate interaction of char/fines, slag, and impact on permeability map</td>
<td></td>
</tr>
</tbody>
</table>

### Targets

- Accurate raceway model for fuel rate optimization, resulting in significantly lower hot metal cost

### Benefits

<table>
<thead>
<tr>
<th>Factor</th>
<th>Relative Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productivity</td>
<td>♦♦ Lower fuel rate, higher productivity</td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>♦♦ Overall reduction in furnace energy</td>
</tr>
<tr>
<td>Operational Efficiency</td>
<td>♦♦ Improved stability</td>
</tr>
<tr>
<td>Use of Raw Materials</td>
<td>♦♦♦ Less expensive, easier to process injectants, with less environmental impact</td>
</tr>
<tr>
<td>Competitiveness</td>
<td>♦♦♦ Lower overall costs</td>
</tr>
<tr>
<td>Workplace Development</td>
<td>♦♦ Development of high end skills/capabilities</td>
</tr>
</tbody>
</table>

### Stakeholders and Potential Roles

**Industry/Producers:** Supply input and validation data; provide guidance to modeling team

**Industry/Users:** N/A

**Academia:** Generate code; develop algorithms and thermokinetic models

**National Laboratories:** Generate thermokinetic data; provide high-performance computing

**Government:** Provide programmatic support/interest if appropriate

### Steel Value Chain Impacts

Producers – reduced energy requirements and lower costs
**Challenge/Problem:** There is limited understanding of the source and value of energy losses between the core steel production processes (iron producing, steelmaking, rolling), which impedes strategies to reduce heat losses.

**Solution/Approach:** The approach is to reduce heat losses between core processes and steelmaking/rolling by identifying the location and amount of losses, and using simulation to determine best ways to minimize losses. This will create predictive tools to achieve improvements, while providing a means for calculating return on investment (ROI)/cost of implementation for process infrastructure-improvements.

### Action Plan

<table>
<thead>
<tr>
<th>1-2 years</th>
<th>3-5 years</th>
<th>5-10 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Define location and amount of energy losses</td>
<td>- Develop solutions for reduction of energy losses</td>
<td>- Prioritize and implement continuous improvements over time</td>
</tr>
<tr>
<td>- Identify and define reasons why losses occur</td>
<td>- Simulate solutions using collected data, and estimate value</td>
<td>- Verify results of improvements (e.g., efficiency) against simulation recommendations</td>
</tr>
<tr>
<td>- Collect key data related to energy losses</td>
<td>- Create Go/No-Go decision framework for proposed solutions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Calculate ROI for project to support implementation</td>
<td></td>
</tr>
</tbody>
</table>

### Outcomes

- Identified location of losses (BF to iron ladle, to furnace, caster and reheat furnace)
- Collected data (temperature, time, delays, etc.)
- Identification/verification of factors contributing to energy losses
- Analyzed/verified alternatives
- Selection of potential improvements and projects
- Development of ROI best practices for energy loss reduction projects
- Identification of best practices and solutions
- Continuous monitoring for sustainability
- Understanding and refinement of model results

### Targets

- Reduced temperature difference between processes
- Increased productivity and efficiency
- Decrease in storage costs
- Decrease in operating costs

### Benefits

<table>
<thead>
<tr>
<th>Factor</th>
<th>Relative Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productivity</td>
<td>♦♦ More throughput; better process flow</td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>♦♦♦ Greater heat retention in product; better retention input</td>
</tr>
<tr>
<td>Environment</td>
<td>♦ Reduced CO2 emissions; good coordination of emissions</td>
</tr>
<tr>
<td>Operational Efficiency</td>
<td>♦♦ More throughput</td>
</tr>
<tr>
<td>Use of Raw Materials</td>
<td>♦♦ Lower material requirements</td>
</tr>
<tr>
<td>Increase of Steel Applications</td>
<td>♦♦ Hot charging improvements</td>
</tr>
<tr>
<td>Competitiveness</td>
<td>♦♦ Lower costs</td>
</tr>
</tbody>
</table>

### Stakeholders and Potential Roles

- **Industry/Producers:** Provide data and information for modeling/simulation (process knowledge)
- **Industry/Value Chain:** Integrate vendor solutions
- **Academia:** Provide expertise for simulation and tools
- **National Laboratories:** N/A
- **Government:** Provide energy saving credits

### Steel Value Chain Impacts

- **Producers** – lower energy use and costs
- **Users** – competitive product pricing
4.6. Chapter References


5. **PRODUCTION EFFICIENCY**

5.1. **Overview**

Production efficiency is used to describe the state at which a business produces the greatest number of units while utilizing the least amount of resources (e.g., raw materials, energy, etc.). The overarching objective for production is to achieve a balance between resource use and production output while optimizing cost and maintaining and/or improving product quality.

Operational efficiency is the ability to deliver products and services cost-effectively without sacrificing quality. Production and operational efficiency are synergistic and affected by many factors such as energy efficiency, environmental controls/strategies, the states of technologies and practices, raw material properties, materials flow, and so on.

Today’s volatile energy costs, increasing environmental awareness, and exacting product-quality demands are creating greater challenges for the iron and steel industry as producers strive to maintain competitive differentiators.

The projected growth in the use of advanced high-strength steel (AHSS) in the automotive industry, for instance, will continue to drive research into both the fundamentals of the thermomechanical processing needed to form various advanced high-strength steels, and into optimization of AHSS production processes.

Advanced high-strength steels are complex, sophisticated materials with targeted chemical compositions and microstructures resulting from precisely controlled thermomechanical processing. Their superior strength and better ductility, at lower weight, make them attractive components in a number of applications, particularly in automotive and light truck applications.
By replacing conventional steel with AHSS in some car bodies, it is possible to reduce weight by 25% and save 14% of the cost—as well as reduce fuel use and cost, and thus greenhouse gas emissions, throughout the vehicle’s life cycle (Zhao and Jiang 2018).

It is critical that steel producers continue to seek innovations that optimize factors that contribute to production efficiency and enhance competitiveness.

### 5.1.1. State of the Art

Technological advances in the iron and steel industry over the past two decades have helped to improve production efficiency. Today’s modern steel mills use a combination of new and legacy equipment and processes, and some are highly optimized. Many incorporate newer or best available technologies such as state-of-the-art power plants, coke dry quenching, and waste gas heat recovery (EU 2013).

Continued improvements in production efficiency will require greater efforts to enhance energy efficiency, optimize material flows, and develop new technologies and processes (AISI 2010). Achieving these goals involves greater understanding of the fundamental physical mechanisms of the complex processes involved in iron and steelmaking. This requires improved elemental data collection and process knowledge, as well as predictive models.

---

**Implementation Example:**

**Steel Ladle Mixing Efficiency and Inclusion Removal**

Molten steel temperature-control, cleanliness, and alloying characteristics can be improved through gas and/or electromagnetic (EMS) stirring in the steel ladle, and both EMS- and gas-stirred CFD ladle models have been developed in collaborative SMSVC and CIVS research projects. Multiple parametric studies have examined the effects of injection gas flow rate and other factors on mixing time and efficiency, in efforts to improve operational efficiency, reduce process failures (e.g., nozzle clogging), and improve steel quality. Future work and expected outcomes include inclusion removal (and thus improved steel cleanliness) based on the currently developed ladle models, and model refinement through addition of an inclusion generation model from effect studies on re-oxidation and chemical reactions.

(Lee et al. 2018, Data on file)
Computer simulation and virtual reality visualization have evolved to become critical emerging technologies in creating immersive virtual environments in the iron and steel industry. These computational technologies have already facilitated increased fundamental understanding while supporting development and implementation of advanced steel technologies, processes, and best operational practices (Gerber et al. 2006).

Most steels have primarily one microstructural phase, like ferrite. Advanced high-strength steels (AHSS) typically contain combinations of various phases (e.g., martensite, bainite, and ferrite) and exhibit high strength and high ductility due to their unique microstructures. The control of AHSS microstructures through precise thermomechanical technologies is one area where MSV tools can support fundamental knowledge acquisition as well as development and optimization of processes for AHSS production.

Advanced computer simulation and visualization technologies will play an ever-increasing role in addressing the issues of productivity, energy, environment, and quality. When combined with model-based process control systems and high performance computing, simulation and visualization techniques can potentially bring both production and operational efficiencies to dramatic new levels (Zhou 2011).

MSV benefits already in process: SMSVC studies on using hot charging with the reheat furnace revealed a potential 6% productivity increase with a slab charge temperature of 450°F. Optimization of spray parameters and cooling during the continuous casting process, while yielding savings on electricity and water costs, could drastically improve productivity through reducing slab yield losses (by breakage and/or cracking). Also not to be underestimated is downtime reduction through improved safety.
5.2. Goals

Goals for production efficiency are generally focused on achieving higher productivity via streamlined processes and better use of resources; more specific goals identified were to:

- Reduce cycle yield times significantly through start-to-finish visualization that enables streamlining of processes
- Visualize the streamlined, integrated “ideal” plant for purposes of comparison and evaluation of plant performance
- Maximize the use of inexpensive and newly abundant natural gas via new technology (energy or process) or by improvements to existing technology (e.g., exceed production design capacity of direct iron reduction [DRI] by 200%)
- Achieve improvements to processing and development of advanced high-strength steels (AHSS) (e.g., reduce the gap between actual and theoretical strength)
- Lower raw material costs through better utilization and recycling; maximize re-use of fines

5.3. Future Needs

Future needs for production efficiency focus on improving and optimizing core processes, and on delineating and improving processes for advanced materials. A top priority need is better understanding and control of alternative production processes, such as direct reduced iron (DRI) processing. MSV could play a role through good visualization of the shaft furnace, which could aid in understanding and controlling associated chemical and physical parameters. Improved processing techniques are also needed for advanced high-strength steels. This includes processing in the steel shop (at tap and at the Ladle Metallurgical Furnace [LMF]/Ruhrstahl Heraeus [RH] degasser), hot strip mill, and sheet mill. Other modeling needs include 3D simulations and visualizations for temperature/stress analysis of slabs and during hot band coil cooling.

<table>
<thead>
<tr>
<th>Production Efficiency</th>
<th>High Priority</th>
<th>Medium Priority</th>
<th>Lower Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Simulation and visualization of DRI shaft furnace; chemistry control of DRI and process optimization</td>
<td>Investigation and visualization of skull formation mechanics</td>
<td>Crack behavior of slabs, including visualization and modeling of solidification, centerline, and slab</td>
</tr>
<tr>
<td></td>
<td>Modeling of steel cleanliness practices and casting for low temperature steel (LTS)</td>
<td>Processing of AHSS in steel shop (at tap and LMF/RH), hot strip mill, and sheet mill</td>
<td>Modeling of water flow through different cooling areas (BF shell caster bearing examples) – using water chemistry, heat transfer and chemical additives to minimize scaling</td>
</tr>
<tr>
<td></td>
<td>Simulation of hot rolling of advanced high-strength steels, including visual and numerical feedback on the impact of rolling parameters on AHSS</td>
<td></td>
<td>Optimized BF hot metal temperature and chemistries for given steel shop demands</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3D and temperature/stress analysis of slabs during cooling and reheating</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3D simulation of hot band coil cooling (temperature, stress, phase change)</td>
</tr>
</tbody>
</table>
5.4. Challenges

The important challenges for production efficiency center on the lack of process data in a number of areas. Knowledge is also lacking to support simulation for new processes such as those used for direct reduction of iron ore (DRI).

**Process Data**

Process data is critical for development and validation of MSV for iron and steelmaking. The lack of low-cost, reliable, real-time data that can be used for model validation is a major challenge. While some methods exist for real-time data collection, they lack the data quality or sophistication for accurate validation and can be expensive to implement. Better methods for measurement and collection of process data are needed, and technology is currently lacking. Multiple variables (e.g., operating parameters, raw materials, etc.) and complex processes and operations make it a challenge to simulate and/or integrate steel production processes in combined models. Non-intrusive characterization tools (both spatial and temporal) are lacking for good process measurements and data acquisition; there are also in-situ parameters that may be difficult (or impossible) to measure.

**Understanding of Alternative Technologies**

Knowledge and data needed for simulations may be in the nascent stage for a number of emerging technologies. For example, there is little fundamental study in North America for direct reduced iron (DRI), which has been gaining in use along with cheap, abundant supplies of natural gas extracted from shale. As the use of DRI expands and new technologies emerge, there will be a continuous need for data and fundamental process knowledge to support advanced MSV.

5.5. Priority Roadmap Projects

Four roadmap priorities for production efficiency were identified, summarized below and in Figures 5.1 through 5.4.

- **Improvement of Control Strategies for the Strip Steel Run-Out Table** – Hardware-in-the-loop simulator to improve the performance and resource efficiency of the run-out table cooling system (Figure 5.1).

- **Simulation and Optimization of Alternative Ironmaking Processes** – Models/tools to optimize alternative/emerging ironmaking processes to drive processes toward lowest possible resource requirements (Figure 5.2).

- **Modeling of Steel Cleanliness Practices for Low-Temperature Cast Steel** – Modeling/visualization to understand and improve steel cleanliness practices and efficiency of steel caster, and avoid inclusions leading to defects (Figure 5.3).

- **Simulation of Hot Rolling of Advanced High-Strength Steels** – Integrated multi-scale modeling to eliminate use of empirical methods for thermo-mechanical rolling simulations (Figure 5.4).
**Challenge/Problem:** The run-out table provides cooling for steel strip and is a key part of the hot rolling process. Controlling this process, which uses large amounts of water, is critical but challenging, and complex to simulate. Challenges include devising computational times that effectively simulate real-time conditions and events, and being able to effectively vary inputs to the process in real time (speed, temperature, composition, dimensions).

**Solution/Approach:** Developing new control strategies for the cooling run-out table will require better models and real-world simulations. A hardware-in-the-loop simulator and characterization of a laminar run-out table cooling system will enable development and testing of new models, control strategies and hardware to improve efficiency.

### Action Plan

<table>
<thead>
<tr>
<th>Period</th>
<th>Outcomes</th>
</tr>
</thead>
</table>
| 1-2 years | • Obtain all key physical dimensions, inputs, and flow rates  
• Develop the model for off-line analysis of run-out table operation and performance  
• Verify model results with historical operational information |
| 3-5 years | • Connect the system inputs and outputs to the model  
• Modify the old system to accept new control inputs and hardware  
• Develop data exchange interface between equipment and simulation  
• Build and test hardware-in-the-loop simulator and system performance |
| 5-10 years | • Create a scalable and configurable system hardware layout  
• Implement control strategies in operating environments |

### Outcomes

- Plant-specific model, verified by historical information  
- Off-line system optimization, with high level of confidence in results  
- Mechanism to exchange data between the real operating environment and model  
- Validated model/simulation ready for implementation  
- Scalable and configurable simulator

### Targets

- Hardware-in-the-loop simulator that can improve the performance of the current cooling system.

### Benefits

<table>
<thead>
<tr>
<th>Factor</th>
<th>Relative Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productivity</td>
<td>♦♦♦ Less scrap product</td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>♦♦♦ Fewer tons re-melted</td>
</tr>
<tr>
<td>Environment</td>
<td>♦♦ More efficient use of water</td>
</tr>
<tr>
<td>Use of Raw Materials</td>
<td>♦♦◆ Higher quality and minimal waste, e.g., hot rolling</td>
</tr>
<tr>
<td>Competitiveness</td>
<td>♦◆◆ Higher quality product</td>
</tr>
<tr>
<td>Workplace Development</td>
<td>♦ Better training tools</td>
</tr>
</tbody>
</table>

### Stakeholders and Potential Roles

**Industry/Producers:** Provide data and hardware implementation  
**Academia:** Develop model and simulator

### Steel Value Chain Impacts

- **Producers** - more consistent quality, reduced scrap  
- **End-users** - higher quality products
**Challenge/Problem:** Alternative ironmaking processes have the potential to increase production efficiency, but insufficient benchmarking and process data is available for modeling and comparing with conventional processes.

**Solution/Approach:** This project will define visualization of currently available alternative ironmaking process such as Midrex, Corex, HYL, HTC, Rotary Kiln, RHF, DRI, flash ironmaking, and others. The approach is to create a visualization similarity model to optimize hybrid technologies.

### Action Plan

<table>
<thead>
<tr>
<th>1-2 years</th>
<th>3-5 years</th>
<th>5-10 years</th>
</tr>
</thead>
</table>
| • Identify available alternative ironmaking technologies  
  • Benchmark key parameters for each process  
  • Develop preliminary model for visualization and fundamental understanding | • Select technologies for detailed process model, considering production, cost, and environmental issues  
  • Apply simulation and visualization to scale up new alternative ironmaking technology, such as flash ironmaking or other hybrid technologies | • Optimize existing processes  
  • Utilize simulation and visualization to develop new alternative ironmaking processes (e.g., hydrogen-based) |

### Outcomes

- Benchmarking report  
- Preliminary demonstration model  
- Sensitivity study and selection of alternative ironmaking processes  
- Models for selected alternative ironmaking processes

### Targets

- Drive ironmaking technology to reach theoretical cost/energy minimum  
- Comprehensive educational training and knowledge tool for alternative ironmaking processes

### Benefits

<table>
<thead>
<tr>
<th>Factor</th>
<th>Relative Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productivity</td>
<td>♦♦ Depends on process</td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>♦♦♦ Eliminate energy-intensive process steps</td>
</tr>
<tr>
<td>Environment</td>
<td>♦♦♦ Lower carbon dioxide, no coking</td>
</tr>
<tr>
<td>Reliability and Maintenance</td>
<td>♦♦ Indirect</td>
</tr>
<tr>
<td>Operational Efficiency</td>
<td>♦♦ Depends on process</td>
</tr>
<tr>
<td>Use of Raw Materials</td>
<td>♦♦❖ Eliminates coke</td>
</tr>
<tr>
<td>Increase in Steel Applications</td>
<td>♦♦ Depends on process</td>
</tr>
<tr>
<td>Competitiveness</td>
<td>♦♦❖ Competitive with BF</td>
</tr>
<tr>
<td>Economic Growth</td>
<td>♦❖ Indirect</td>
</tr>
<tr>
<td>Workforce Development</td>
<td>♦❖ Requires re-training</td>
</tr>
<tr>
<td>Workplace Safety</td>
<td>♦❖ Requires re-training</td>
</tr>
</tbody>
</table>

### Stakeholders and Potential Roles

**Industry/Producers:** Provide process data and design data  
**Industry/Users:** Provide demand and quality requirements  
**Industry/Value Chain:** Provide raw material, natural gas  
**Academia:** Conduct modeling  
**National Laboratories:** Provide computing resources  
**Government:** Provide programmatic interest/support

### Steel Value Chain Impacts

- **Producers** – lower cost, environmental impacts, and energy  
- **Suppliers** – Affects raw material producers, natural gas suppliers  
- **Users** – Higher quality products
FIGURE 5.3 ROADMAP PRIORITY #13
MODELING OF STEEL CLEANLINESS PRACTICES FOR LOW-TEMPERATURE CAST STEEL

Challenge/Problem: The presence of impurities in steel has implications from production, product quality, and safety standpoints. Equipment and steel parts have often been reported to fail prematurely and unexpectedly as a result of impurities. It is important to ensure tight control of steelmaking conditions in order to avoid reintroducing impurities with each progressive stage of processing.

Solution/Approach: There is a continual demand for cleaner steel by customers as steel is being used in more challenging environments. Models are needed to understand and improve steel cleanliness practices for low-temperature cast steel, and broadly to avoid inclusions that would lead to defects and rejects.

<table>
<thead>
<tr>
<th>Action Plan</th>
<th>Outcomes</th>
</tr>
</thead>
</table>
| 1-2 years   | • Identify set of best practices for steel cleanliness  
• Identify specifications for steel cleanliness  
• Identify required data sets and data collection methods and collect data  
• Develop algorithms and initial predictive models  
Phase I models for steel cleanliness  
Beta test/pilot demonstration of model in actual facility |
| 3-5 years   | • Select  
Phase II models |
| 5-10 years  | • Optimize  
Updated models |

Targets
• Predictive model for steel cleanliness and related parameters for low-temp. cast steel

Benefits

<table>
<thead>
<tr>
<th>Factor</th>
<th>Relative Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productivity</td>
<td>♦♦♦ Improved product yield</td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>♦♦ Less energy for reprocessing</td>
</tr>
<tr>
<td>Environment</td>
<td>♦ Indirect impacts</td>
</tr>
<tr>
<td>Reliability and Maintenance</td>
<td>♦♦ Indirect impacts</td>
</tr>
<tr>
<td>Operational Efficiency</td>
<td>♦♦♦ Less reprocessing, handling of rejects</td>
</tr>
<tr>
<td>Use of Raw Materials</td>
<td>♦♦♦ Higher materials utilization</td>
</tr>
<tr>
<td>Increase in Steel Applications</td>
<td>♦ Indirect impacts</td>
</tr>
<tr>
<td>Competitiveness</td>
<td>♦♦♦ Greater ability to compete in clean steels</td>
</tr>
<tr>
<td>Economic Growth</td>
<td>♦♦ Indirect impacts</td>
</tr>
</tbody>
</table>

Stakeholders and Potential Roles

Industry/Producers: Provide process data and pilot site
Industry/Users: Provide insights on quality and cleanliness requirements
Academia: Develop models
National Laboratories: Provide computing resources
Government: Provide programmatic interest/support if appropriate

Steel Value Chain Impacts

Producers – higher product yields
Suppliers – insights into raw material and other needs
End-Users – Meets high-quality product specifications
**Challenge/Problem:** Validated, accurate simulation and visualization models for thermo-mechanical rolling of high strength steels are currently lacking due to data and fundamental science impediments. A key challenge is the ability to choose the appropriate length and time scales for simulation without sacrificing the physics of the material and process.

**Solution/Approach:** Better thermo-chemical MSV tools combined with HPC platforms can support development and optimization of new high strength steels. The approach is to eliminate current empirical-based solutions through the use of integrated multi-scale modeling. A physically based thermo-mechanical rolling simulation and visualization model will be developed and demonstrated.

---

**FIGURE 5.4: ROADMAP PRIORITY #14 SIMULATION OF HOT ROLLING OF ADVANCED HIGH-STRENGTH STEELS**

**Action Plan**

<table>
<thead>
<tr>
<th>1-2 years</th>
<th>3-5 years</th>
<th>5-10 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Generate sufficient plant data for input as boundary conditions</td>
<td>• Conduct model validation using realistic boundary conditions from near-term work</td>
<td>• Develop inter-atom potentials for multi-component alloy systems</td>
</tr>
<tr>
<td>• Develop physically based constitutive models, including damage models</td>
<td>• Identify gaps, then conduct R&amp;D to generate a thermo-dynamic and kinetic database that includes missing data and parameters</td>
<td>• Develop design optimization methods and data for mill and product (work piece) properties</td>
</tr>
<tr>
<td>• Implement scalable parallel codes in the model at different length scales</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Outcomes**

- Demonstration of a multi-scale rolling simulation for a multi-component steel
- Demonstration of validation of the simulation for multi-component steel and rolling conditions
- Inverse modeling to predict optimized process conditions for a desired end product

**Targets**

- Simulation and visualization thermo-mechanical rolling model to support the development of advanced high strength steels
- High performance computing using GPUs

**Benefits**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Relative Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Efficiency</td>
<td>⬤⬤⬤ Downstream energy savings for end users</td>
</tr>
<tr>
<td>Environment</td>
<td>⬤⬤⬤ Indirect impacts</td>
</tr>
<tr>
<td>Reliability and Maintenance</td>
<td>⬤ Improved mill rolling performance</td>
</tr>
<tr>
<td>Operational Efficiency</td>
<td>⬤ Improved mill rolling performance</td>
</tr>
<tr>
<td>Increase in Steel Applications</td>
<td>⬤⬤⬤ Market retention, increase share of AHSS%</td>
</tr>
<tr>
<td>Competitiveness</td>
<td>⬤⬤⬤ Market retention, increase share of AHSS%</td>
</tr>
<tr>
<td>Economic Growth</td>
<td>⬤ Energy efficiency will lead to growth</td>
</tr>
</tbody>
</table>

**Stakeholders and Potential Roles**

**Industry/Producers:** Provide data and pilot demonstration sites; validate models

**Industry/Users:** Input on product specifications

**Academia:** Develop models and simulations; create databases

**National Laboratories:** Provide HPC platforms

**Government:** Provide programmatic support and interest

**Steel Value Chain Impacts**

- Producers – ability to optimize the process for a target material structure
- Supply Chain – Ability to meet fuel economy and safety targets
- Users – Energy efficient vehicles
5.6. Chapter References


Data on File, Center for Innovation through Visualization and Simulation (CIVS), Purdue University Northwest.


6. RELIABILITY AND MAINTENANCE

6.1. Overview

Proper maintenance is critical to the steelmaking industry to improve safety, product quality, and plant profitability. Equipment failure results in reduced productivity and high maintenance and operations costs, and modern equipment costs have increased the importance of life cycle optimization and limited downtime. The industry is moving from reactive to planned maintenance, seeking new tools and methods that can enhance safety, reduce costs, and improve reliability of machine performance.

Many in industry currently implement condition-based maintenance (CBM), in which decisions about replacement are made based on pre-determined criteria, i.e., the optimal control limit. While CBM results in more effective maintenance, fewer preventable replacements, and fewer equipment failures, the frequent inspections involved entail increased costs. Thus industry seeks the optimal control limit and the optimal inspection interval, as researchers have attempted to determine through mathematical formulations (Golmakani and Fattahipour 2011).

6.1.1. State of the Art

Reliability modeling is practiced throughout industry. However, repairable systems associated with steelmaking are large and complex, so researchers are investigating improvements to existing models and analytical systems. For example, preventive maintenance (PM) policies have been determined using linear consecutive k-out-of-n systems, which are the basis of many reliability models. A recent steelmaking model assumes that a component’s failure rate depends on the state of the adjacent components, and a failure sequence diagram is used to establish a reliability model. The model is then used to identify the optimal preventive maintenance strategy (Wang et al. 2015).

Another research team recently presented a heuristic approach for implementing a semi-parametric proportional-hazards model (PHM) that allows users to schedule PM based on the equipment’s full condition history (Kobbacy et al. 1997). A simulation framework incorporates two PHMs, one for the life of equipment following corrective work and one for the life of equipment following PM, to determine optimal PM schedules.

Another study has integrated computer simulation, design of experiment (DOE), and Tabu search to optimize performance of an Iranian steelmaking facility (Azadeh and Maghsoudi 2010). All facility operations and interacting systems were incorporated, and simulation outputs were integrated with DOE by defining decision-making parameters as numbers of machines, operators, etc. (k factors). While many studies have integrated simulation and DOE, the metaheuristic Tabu search allows for higher-level global optimization.

Some researchers are investigating intelligent maintenance systems, or E-maintenance tools, with real-time monitoring capabilities (Colace et al. 2013). For example, the electric furnace is an asset that presents particular safety and reliability concerns. Because the furnace runs continuously at high temperatures and in harsh environmental conditions, many elements and components cannot be visually inspected. An intelligent monitoring system can be integrated with a facility’s existing IT infrastructure to facilitate remote monitoring of asset health status.

**Implementation Example:**

**Modernizing Continuous Casting Design and Operations**

During the continuous casting process, issues with the flow of molten steel and other physical phenomena can create production and quality deficiencies as well as dangerous situations (e.g., when molten steel breakouts occur). Numerous collaborative studies with SMSVC partners have been undertaken to optimize submerged entry nozzle (SEN) and casting parameters, in order to eventually optimize fluid flow, reduce SEN clogging, and promote expulsion of particles and inclusions into casting slag. A molten steel fluid flow model has been extensively studied and validated, and expanded to include a multiphase model to account for the effects of argon gas injection from the upper tundish nozzle. Ongoing work continues to develop and refine the solidification model in long-term efforts to identify and mitigate conditions that may result in development of in-mold cracking and other quality, production, and safety issues. Expected outcomes include improved product quality, improved process and equipment reliability, cost reductions (through reduced caster shutdowns), and improved safety.

(Chen et al. 2018)
**MSV benefits already in process:** CIVS and industry collaborators have a long history of successfully using computational analysis & modeling tools, such as finite element analysis (FEA) and computational fluid dynamics (CFD), to predict and solve machine/system responses to various operating conditions. FEA was used to analyze stress and fatigue levels and help optimize maintenance scheduling for a vertical edger in a hot rolling mill, and was similarly employed in overhead crane operation. CFD and VR visualization technologies helped identify and troubleshoot flow restrictions in a boiler exhaust venting system—improving efficiency and saving the SMSVC partner an estimated $1.9 million annually.

### 6.2. Goals

A number of goals were identified for reliability and maintenance in steel production and operations. Simulation and visualization could play a role in all through optimization of process reliability and maintenance practices.

- Substantially reduce and minimize current nonconformance conditions, from safety to downtime and quality, with a priority of zero nonconformance from safety
- Increase mean time before failure
- Reduce unplanned breakdown days to near zero over the long term

### 6.3. Future Needs

Several opportunities were identified for MSV to improve reliability and maintenance of manufacturing equipment. The results are summarized below and listed in table 6.1.

**Failure Prediction and Design Improvements**

A top priority need is the development of simulation and visualization to identify weak spots in cranes to determine inspection needs before failure. Wireless sensors could help identify weak spots, fatigue, and repair needs, reducing operational downtime and capital costs.

The use of MSV to enable reliability maintenance, in real-time, for complex procedures is a top priority need. MSV could also be used to redesign motor working components, particularly for motor cooling. Another need is the ability to integrate vendor three-dimensional designs with MSV, to address technology integration issues and reduce costs.

**Reliability Maintenance Training**

Training tools are needed to assist operators in visualizing failure modes and methods for recovery. Virtual training tools that cover reliability and maintenance as well as operational needs and safety would provide comprehensive information for incoming employees.
### Table 6.1 Future Needs for MSV for Reliability and Maintenance

<table>
<thead>
<tr>
<th>Failure Prediction and Design Improvements</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High Priority</strong></td>
<td></td>
</tr>
<tr>
<td>• Failure prediction and lifecycle analysis for overhead crane components, including gearboxes and wheels.</td>
<td></td>
</tr>
<tr>
<td>• Reliability maintenance in real-time – visualization and simulation tools for line lock-out or other procedures</td>
<td></td>
</tr>
<tr>
<td><strong>Medium Priority</strong></td>
<td></td>
</tr>
<tr>
<td>• Use of visualization to safely reduce maintenance downtime and related capital costs</td>
<td></td>
</tr>
<tr>
<td>• Ability to exchange or use three-dimensional designs from vendors and apply them to MSV</td>
<td></td>
</tr>
<tr>
<td>• Use of MSV to redesign motor cooling, including blower optimization, windings, and insulation</td>
<td></td>
</tr>
<tr>
<td><strong>Lower Priority</strong></td>
<td></td>
</tr>
<tr>
<td>• Models incorporating robust furnace atmosphere effects with doors open/closed, water leaks, damper positions, refractory life</td>
<td></td>
</tr>
<tr>
<td>• Virtual welding for electrical / mechanical troubleshooting</td>
<td></td>
</tr>
<tr>
<td>• Hardware that is accessible at the operational level</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Reliability and Maintenance Training</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Medium Priority</strong></td>
<td></td>
</tr>
<tr>
<td>• Process automation and visualization training tools, developed with skilled maintenance craftsman, such as electricians and mechanics who understand the workings of the equipment</td>
<td></td>
</tr>
<tr>
<td><strong>Lower Priority</strong></td>
<td></td>
</tr>
<tr>
<td>• Visualization of what happens when the “wrong switch” is operated and simulation of recovery</td>
<td></td>
</tr>
<tr>
<td>• Consolidated reliability and maintenance training with operations and safety training</td>
<td></td>
</tr>
</tbody>
</table>
6.4. Challenges

Some of the major challenges to ensuring reliability and maintenance include:

**Standardized Ways to Predict/Respond to Events**
Too frequently, the process for responding to shutdowns or failure events is unclear, fragmented, and not standardized. The absence of a common approach can result in a wide range of methods being used for responding to and resolving equipment and other failures. Standard procedures and practices are also essential for effective use of maintenance resources.

**Maintenance Information Capture**
Capturing and analyzing information relevant to reliability and maintenance can be insufficient or inconsistently practiced. Lack of information on maintenance and breakdowns hinders the ability to understand and learn from the problems experienced.

**Extreme Operating Conditions**
In steel production plants, a number of extreme operational conditions (high temperatures and pressures, corrosive or hazardous environments, continuous high-speed production, etc.) create complex challenges for maintenance and reliability. For example, maintenance personnel in charge of continuous caster lines must control both reliability and maintenance costs for as many as 120 roll lines. This massive and complex production system is a harsh operating environment that places high stresses on equipment (e.g., highly abrasive scale, temperature extremes, very heavy loads, etc.) and daily maintenance challenges.

6.5. Priority Roadmap Projects

The top priority identified for reliability and maintenance where MSV can play a major role is the development of preventive maintenance tools. This is summarized below and in Figure 6.1.

- **Early Preventive Maintenance Tools for Breakdown Avoidance** – Combines the use of predictive models, visualization, sensors for additional data collection, and training to improve early preventive maintenance schemes and avoid breakdowns and downtime (Figure 6.1).
**FIGURE 6.1: ROADMAP PRIORITY #17**  
**EARLY PREVENTIVE MAINTENANCE TOOLS FOR BREAKDOWN AVOIDANCE**

**Challenge/Problem:** Preventive maintenance programs lack the sophistication now possible through new data analytics and MSV techniques. Key challenges to improving these programs include the inability to account for the condition and maintenance history of all parts, effective collection of the large quantities of valuable data needed to support real preventive maintenance, and management buy-in (e.g., understanding of the value proposition) and resource allocation for upgrading such programs.

**Solution/Approach:** Cost savings by early detection of imminent-breakdown conditions by using visualization to identify weak areas. Achieve by utilizing sensors to determine changes and early detection of problems.

### Action Plan

- **1-2 years**
  - Select proper equipment to monitor
  - Collect data for various operational processes
  - Model equipment (i.e., create prototype model) and validate models and data

- **3-5 years**
  - Purchase sensors and implement placement
  - Develop software to read sensors and interpret data
  - Develop and implement training programs for operators

- **5-10 years**
  - Continue to refine programs as technology emerges

### Outcomes

- Prototype validated models for select equipment
- Data collection, development of databases
- Sensor placement and real-time data collection
- Data analytics software and data interfaces implemented
- Training modules completed
- Refined maintenance programs

### Targets

- Lower downturn times
- Increased productivity
- Reduction in environmental impacts

### Benefits

<table>
<thead>
<tr>
<th>Factor</th>
<th>Relative Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productivity</td>
<td>♦♦♦ Lower downturn times</td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>♦ Higher efficiency via fewer breakdowns</td>
</tr>
<tr>
<td>Reliability and Maintenance</td>
<td>♦♦♦ Lower downturn times</td>
</tr>
<tr>
<td>Operational Efficiency</td>
<td>♦♦ Greater throughput and productivity</td>
</tr>
<tr>
<td>Increase in Steel Applications</td>
<td>♦ Greater flexibility/agility</td>
</tr>
<tr>
<td>Competitiveness</td>
<td>♦ Higher capacity use</td>
</tr>
<tr>
<td>Workforce Development</td>
<td>♦ Better trained operators</td>
</tr>
<tr>
<td>Workplace Safety</td>
<td>♦♦♦ Fewer failure events</td>
</tr>
</tbody>
</table>

### Stakeholders and Potential Roles

- **Industry/Producers:** Provide equipment data and process
- **Industry/Users:** Provide equipment data and process
- **Academia:** Provide knowledge for modeling of equipment with visualization
- **National Laboratories:**
- **Government:** Provide support/participation, discussion of requirements

### Value Chain Impacts

Producers – improved in-plant maintenance and equipment longevity
6.6. Chapter References


7. **ENVIRONMENTAL IMPACTS**

7.1. **Overview**

The manufacture of iron and steel is an extremely complex, multi-stage process, which in many cases is environmentally unfriendly. The industry needs to reduce emissions and pollutant flow throughout the manufacturing process.

Examining current efforts to minimize environmental impacts and improve process efficiencies can provide a good foundation for future research and improvements. Since the mid-1970s, there has remained a sustained focus on energy conservation and recycling in the iron and steel industry. Because of increasing government regulation on pollutants and emissions, there is a pressing need to minimize the environmental impact of existing processes and ensure that new designs are environmentally conscious.

Today, steel is the most recycled material in the world, and more steel is recycled yearly than aluminum, copper, paper, glass, and plastic combined. Over 80 million tons of steel are recycled or exported for recycling every year in North America. About 97% of steel by-products can be re-used; recent estimates show that the recycling rate for steel is around 86%. Recycling conserves raw materials as well as energy resources. Every year the steel industry saves enough energy through recycling to power 20 million homes (AISI 2014).

7.1.1. **State of the Art**

One of the simplest methods of reducing environmental impact is recycling scrap metal into new iron and steel. Because recycling scrap requires less energy than creating steel from ore, the use of electric arc furnaces (EAFs) has continued to increase. However, using scrap can lower the quality of steel created if buildup of unwanted elements (copper, tin, lead, etc.) occurs (UNEP 1984). In addition, a focus on reducing the environmental impact of steelmaking by-products such as slag, dust, and scale is often required to meet government restrictions. The Badische Stahlwerke EAF plant in Kehl, Germany, has adapted to extremely stringent government restrictions on environmental impact while maintaining high productivity (Doninger and Marz 2014).

Research to improve sustainability and environmental protection efforts has targeted specific processes within the iron and steel industry. Input-output models of manufacturing processes can be an efficient way of examining

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**Reducing Environmental Emissions**

In addition to carbon dioxide (CO₂) released by the combustion of fossil fuel, large steelworks can emit other pollutants that have environmental impacts. ArcelorMittal Gent, an integrated steelwork producing about $5 \times 10^6$ tons of steel per year, not only decreased its specific energy consumption and CO₂ emissions, but also reduced the environmental impact of its other emissions, through use of flue gas filters, desulfurization units, wet gas washing, and more efficient use of fuels in the production process.

(Van Caneghem et al. 2010)
resource and energy consumption, as well as pollutant flow (Tao 2011). For pollutant flow, carbon dioxide is one of the primary focus points, especially in the United States. While the removal of CO₂ from iron and steel production byproducts has not received the same amount of attention as in the power generation industry, there is some research on pollutant containment/removal. Gielen completed an appraisal of possibilities for CO₂ removal from blast furnace emissions (Gielen 2003). Additionally, Worrel et al. performed an analysis of energy efficiency and CO₂ emissions reduction for the U.S. iron and steel industry, examining 47 different energy efficient practices and technologies for possible implementation and ranking them by energy conservation (Worrell et al. 2001).

ArcelorMittal Gent, an integrated steel plant, which took steps to decrease its energy consumption, CO₂ emissions, and other emissions responsible for environmental impacts, such as acidification, fresh water eco-toxicity, and eutrophication, succeeded at decoupling its environmental impacts with steel production rates (Van Caneghem et al. 2010). Often the largest motivator for emissions reduction comes from legislative changes. New environmental standards that impose tighter restrictions are a powerful force for technological change (Lutz et al. 2005).

The European steel industry has had to respond to long-term targets set by the European Council in 2009. The goal of reducing greenhouse-gas emissions by 80-95% of the 1990 levels by 2050 is one of the most stringent in the world. In the European Union, emissions of CO₂ have decreased by roughly 25% from 1990 to 2010, primarily driven by lower total production and a shift towards recycling steel scrap in EAFs. In addition, methods for carbon capture, utilization, and storage (CCUS) have been examined for future implementation; however, the technological and economic feasibility of CCUS is uncertain at best (Wörtler et al. 2014).

The potential for improved operational efficiency can also motivate environmentally friendly changes due to economic advantages. For instance, many processes throughout the industry create large amounts of low-grade heat. Utilizing this heat could both save money and significantly reduce the amount of CO₂ released through combustion (Walsh and Thornley 2011). Examining how the industry can best adapt to and change environmentally unsustainable practices and material flows will help to ensure continued success (Yellishetty et al. 2010).

The increased focus on climate change by governments will lead to increasingly strict environmental regulations. Simulation and visualization can help to address emissions reductions by making the design and testing of new environmental management systems easier and less expensive. It can also help to predict which sectors may require modification to meet future regulations and standards so that necessary preparations can be made without additional difficulty.
7.2. Goals

The goals identified for environmental impacts focus on reduction of emissions (air, land, water) and waste mitigation and utilization, which includes recycling as well as material or resource optimization strategies.

Emissions

- Reduce CO2 emissions through more energy efficient processes, recuperation of process gases, and CO2 capture processes
- Minimize emissions through optimization studies of existing environmental protection equipment/facilities and study/implementation of new technologies for pollutant abatement
- Reduce carbon footprint through increases in process efficiency, heat recovery of different process streams, and use of less-carbon-intensive technologies and CO2 sequestration and capture
- Optimize energy sources and associated emissions through smart approaches and strategies

Waste Mitigation and Utilization

- Improve by-product utilization by reducing generation and improve by-product beneficiation to significantly reduce landfilling needs
- Develop CFD process models for emissions that could be based on raw materials composition and process parameters
- Reduce landfill waste significantly (e.g., by 50%) in 20 years
- Maximize utilization of steel plant wastes (e.g., slags, sludge) to avoid landfilling
- Develop cost-effective technologies to add value to wastes that are currently being landfilled
- Utilize significant amounts of waste stream and landfill materials for raw material inputs or fuel alternatives, where feasible

7.3. Future Needs

Future needs for environmental impacts focus on a diversity of opportunities to reduce waste and emissions in iron and steelmaking. MSV technologies and tools play a key role in accelerating the capabilities needed. The needs identified are outlined in Table 7.1 and summarized below.

Emissions Reduction/Mitigation

A top priority is the reduction and elimination of by-product fuel flaring from energy-intensive production units, including the blast furnace and coke oven. Fuel by-product flares account for a significant amount of emissions from steel plants. The blast furnace is also a source of particulates and other emissions; virtualization of the blast furnace with a focus on emissions mitigation is a major need.

Life cycle assessments that look at the environmental footprint of steel compared to other materials could also provide insights into where steel provides advantages or needs improvements to compete with these materials. Aluminum and carbon fiber are both priority candidates for life cycle assessment.

Waste Mitigation and Utilization

Reduction of waste streams has multiple benefits, including better environmental performance but also reduction in production costs related to waste handling. New methods are needed for mitigating and reducing waste streams overall. Recycling is a key strategy for reducing environmental impacts but will
require technology R&D for improved methods as well as better predictive models. The objective is to reduce the harmful components in waste while taking advantage of the valuable components via recovery.

### Table 7.1 Future Needs for Steel Environmental Impacts

<table>
<thead>
<tr>
<th>Emissions Reduction / Mitigation</th>
<th>High Priority</th>
<th>Medium Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Minimize flare of process gases</td>
<td>• Develop technologies or methods to minimize fugitive emissions as well as to identify and quantify them (use of smart cameras)</td>
</tr>
<tr>
<td></td>
<td>• Model processes and environmental protection equipment in order to improve environmental performance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Simulation of life cycle assessment compared to aluminum and carbon fiber</td>
<td></td>
</tr>
<tr>
<td>Waste Mitigation and Utilization</td>
<td>• Model/visualize flow of fuel gases to show flow and identify performance improvement areas</td>
<td>• Optimize location of emissions monitoring systems – study of plume dispersion</td>
</tr>
<tr>
<td></td>
<td>• Reduce waste material streams, including through new methods for dealing with waste streams, under both normal and upset conditions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Reduce environmental impacts through improved recycling of process gases and waste streams</td>
<td></td>
</tr>
</tbody>
</table>

### 7.4. Challenges

A number of challenges were identified for reducing environmental impacts, as outlined below.

**Emissions Reduction/Mitigation**

One of the key challenges to improving environmental performance is that monitoring is currently based primarily on visual observations and sample testing. These methods are highly subjective and can be open to interpretation and uncertainty.

**Waste Mitigation and Utilization**

In recovery and recycling, a major challenge is the separation of the valuable and useful elements in waste streams (e.g., Fe, Mn, C) from the hazardous ones (K, Na, Zn, P). For these separations to be useful they must be technically feasible, cost-effective, productive, and safe – a difficult balance to achieve in some cases. They may also require costly capital upgrades so ROI must be justified (and proven).

Permitting limitations can also limit progress in waste mitigation. When permitting of waste handling already exists, new proposed processes and operations that potentially change how waste is handled may need to undergo additional permitting processes or changes to what is considered best available technology (BAT). In some cases, existing permitting regulations may not facilitate (or even be adverse to) waste recovery, even if it is beneficial to the environment.

### 7.5. Priority Roadmap Projects

A priority identified for environmental impacts is to reduce the need for fuel flaring, as outlined below and in Figure 7.1.

- **Zero By-Product Fuel Flare** – Virtualization and modeling of flamed by-product gases to allow for better design of solutions for flare gas reduction (Figure 7.1).
**Challenge/Problem:** Flaring of byproduct fuel gases wastes energy and adds to production costs. However, implementing solutions to mitigate gas flaring can be expensive. In addition, accurate measurement of flare gas volumes and cost benefits that could result from mitigation is challenging. Understanding the best solutions for mitigation is also difficult without the capability to predict or simulate what the outcomes/benefits would be as well as the impacts on process performance.

**Solution/Approach:** Cost-effectively capturing and utilizing flamed steelmaking by-product gases can be made possible through the accurate measurement of gases and selection of optimal solutions. The approach is to design and implement visual simulation modeling to assist with identification of solutions and then develop and utilize the best approaches for real-time control.

### Action Plan

<table>
<thead>
<tr>
<th>1-2 years</th>
<th>3-5 years</th>
<th>5-10 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Capture potential value through application of best practice measurement technology</td>
<td>• Identify alternative solutions</td>
<td>• Implement real-time dynamic control utilizing visual simulation modeling</td>
</tr>
<tr>
<td>• Identify all the reasons that gases are flamed</td>
<td>• Evaluate alternative solutions utilizing visual simulation modeling</td>
<td>• Develop lower cost solutions/technologies</td>
</tr>
<tr>
<td>• Identify impacts on other processes resulting from zero flame</td>
<td></td>
<td>• Evaluate alternative coke, iron and steelmaking processes to eliminate gas production</td>
</tr>
</tbody>
</table>

### Outcomes

- ROI calculations
- Selection of best available solutions
- Reduction in volume of flamed by-product gases by 90% of baseline measured flame

### Targets

- Accurately measure current volume flamed and reduce by 90% by 2025
- Design and implement visual simulation models for selection of best solutions as well as real-time process control

### Benefits

<table>
<thead>
<tr>
<th>Factor</th>
<th>Relative Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Efficiency</td>
<td>♦♦ Utilize wasted energy</td>
</tr>
<tr>
<td>Environment</td>
<td>♦♦♦ Reduce air emissions</td>
</tr>
<tr>
<td>Operational Efficiency</td>
<td>♦ Lower cost and higher efficiency operations</td>
</tr>
</tbody>
</table>

### Stakeholders and Potential Roles

**Industry/Producers:** Identify data process constraints, provide power information, and collaborate with model developers.

**Industry/Users:** Identify process constraints, provide process information, and collaborate with model developers.

**Academia:** Analyze data and information and develop models; assist with best solution identification and development.

**Government:** Support model development and cost-effective technology development.

### Steel Value Chain Impacts

- **Producers** – Efficient blast furnaces, coke oven, BOF furnaces
- **Suppliers** – Energy supplier solutions
- **Users** – Replicate in blast furnace stoves, boilers, furnaces, other fuel combustion processes
7.6. Chapter References


8. Raw Materials

8.1. Overview

The key raw materials in the ironmaking and steelmaking processes are iron ore, coke, limestone, and recycled steel. Generally, the raw material section in an ironmaking plant consists of an iron ore handling system, coal and coke handling system, lime handling system, and sinter plant.

The quality of the raw materials greatly affects process efficiency, the amount of by-product produced, recycling potential, emissions, and energy use. The World Steel Association reported that increased demand for high-quality raw materials, combined with limited immediate sources for those materials, will eventually force the industry to use lower-grade raw materials (Reimink 2014). The use of beneficiation and blending processes of raw materials will become more important to ensure the industry can meet the demand for steel.

8.1.1. State of the Art

Some steel producers, anticipating the eventuality of lower-quality resource use, invested in fundamental research, first on the normative characteristics of some lower-quality resources, and second on process research and development in ways to control or use those characteristics to “reform” the resources—and make their use more efficient and profitable. For instance, it was found that by rapidly heating coal to a certain temperature range, the caking properties of the coal could be improved, thus increasing the coke strength. In order to translate initial lab results to a commercial scale, many numerical simulations were carried out, until “the range of optimum pre-heating conditions” could be found. The “Super Coke Oven for Productivity and Environmental enhancement toward the 21st Century,” or SCOPE21 project, was commercially enacted at Nippon Steel’s Oita Works plant in 2008 (Haga et al. 2012).

Also in the area of MSV, researchers have developed numerical models for optimizing the sintering process of iron ore (Castro 2010) and coke ovens (Zhang et al. 2013). These provide a means for improving process and operational efficiency, productivity, and capability for recycling of valuable byproducts.

The raw material handling process involves receiving, unloading, stocking, handling, and supplying different raw materials. Coelho et al. (2001) developed a deterministic model to help in the project team’s decision-making when controlling the iron ore inventory at an integrated steel mill.

Optimizing Raw Material Processing via CFD

In the integrated steel industries the sintering process plays an important role furnishing raw material to the blast furnace. A computational simulation of the sinter process has been developed to predict the most important phenomena within the sintering bed. This comprehensive tool will aide in making good decisions on the kind of raw materials and blending needed to meet the sinter quality requirements for use in the blast furnace or other reducing process. The simulation can be used to indicate the most promising operational conditions, resulting in higher productivity, lower fuel consumption, and high recycling.

(Castro 2012)
MSV benefits already in process: Collaborative research between SMSVC and CIVS has resulted in a comprehensive CFD model for examining conditions inside the electric arc furnace (EAF), with potential impacts and areas of process improvement including reducing electrical power consumption while increasing natural gas input; scrap preheating; scrap blending; and oxygen enrichment.

8.2. Goals

A number of goals have been identified where MSV can play a key role in optimizing raw materials processing:

**Raw Materials**

- Minimize the generation and need for beneficiation of by-products through improved process efficiency (e.g., improved skimming operation, better separation of scale/oil)
- Develop advanced by-product beneficiation technologies to increase recycling rates and value of by-products
- Optimize the use of more abundant/lesser quality raw materials without adversely impacting product quality, operations or the environment
- Develop process models that could relate raw material characteristics like size, strength, and chemistry to process performance including productivity, quality, and environmental aspects

**Materials Processing**

- Develop techniques to reduce degradation during handling, and improve sizing of raw materials
- Develop optimization tools to optimize the use and flow of raw materials plant-wide
- Develop optoelectronic sensing (sensing of optical properties) of raw materials, to achieve a significant reduction in impurities (e.g., 50% in 5 years) (long-term goal)
- Reduce generation of fines during steel and hot metal production, and develop cost-effective technologies to process fines generated during raw materials processing

8.3. Future Needs

Future technology and process needs for raw materials processing range from optimizing of materials input to materials handling and processing of advanced materials. The complete list of needs identified is illustrated in Table 8.1, with major priorities outlined below.

**Raw Material Inputs**

Optimization of raw materials is a top priority for reducing costs and achieving higher productivity, particularly for the basic oxygen furnace (BOF) and electric arc furnaces (EAFs). This would also help to optimize energy requirements for BOF and EAF processes, which are highly dependent on material inputs and yields. Simulations and visualizations that enable accurate modeling of performance and other parameters based on material inputs would be highly valuable. A closely related priority is the need to optimize plant-wide material flows, especially for high-level (macro view) and logistical parameters. This would encompass more than just primary material inputs and cover waste, rejects, and other material processing parameters. Increasing process efficiencies to reduce the generation of by-products and
developing ways to beneficiate by-products so that they can be reused are both critical for overall raw material performance in terms of yield.

**Materials Processing/Handling**
A top priority is the optimization of raw material handling practices, particularly the most cost- and energy-intensive. Reducing fines during handling of coke, sinter, and other lump raw materials could bring significant savings. Another area of potential benefit is screening/sizing efficiency, since size consistency plays an important role in blast furnace operation and sintering. Good stirring in steelmaking could also contribute to lower use of raw materials (fluxes and other alloy additions). Modelling and especially visualization techniques could be valuable for optimization of material mixing in the refining ladle including mixing and stirring processes, time required, etc.

**Raw Materials Optimization**
The use of optimization models that could relate raw material chemistries and/or metallurgical properties with process performance could generate significant savings through optimized operations for blast furnace and ladle metallurgy.

**Implementation Example:**
**Modeling of Steel Refining Process in the EAF**

Collaborative, ongoing studies with SMSVC partners have yielded four different 3D CFD models that simulate the electric arc furnace (EAF) physical processes of scrap melting above the bath (1), in the bath (2), freeboard combustion (3), and multiphase flow in the bath (4); in addition, a fifth sub-model was developed to compute heat flux from the electric arc. Model integration has resulted in a generic EAF CFD model that encompasses scrap melting, heat transfer, combustion, turbulent flows, and dynamic operating conditions. Long-term/future work and expected outcomes include parametric studies on energy inputs and scrap (raw materials) blending, aimed toward improving steel quality and energy efficiency and reducing costs.

(Tang et al. 2017 [1], Tang et al. 2017 [2], Data on file)
8.1. Table 8.1 Future Needs for MSV for Raw Materials

<table>
<thead>
<tr>
<th>Raw Material Inputs</th>
<th>High Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Optimization of raw materials (input) for BOF, EAF, blast furnace, coke plant, and sinter</td>
</tr>
<tr>
<td></td>
<td>• Technologies to incorporate lower-cost raw materials into the raw material mix</td>
</tr>
<tr>
<td>Medium Priority</td>
<td>• Modeling of processes to connect impact of raw material qualities with process performance and/or product quality</td>
</tr>
<tr>
<td></td>
<td>• Study/Model Steering and addition time on process performance in steelmaking (desulfurization, BOF and Ladle met)</td>
</tr>
<tr>
<td></td>
<td>• Scrap/DRI/Metlink type simulation</td>
</tr>
<tr>
<td>Lower Priority</td>
<td>• Tungsten replacement</td>
</tr>
<tr>
<td></td>
<td>• High toughness steel</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Materials Processing/Handling</th>
<th>High Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Optimization of raw material handling practices</td>
</tr>
<tr>
<td>Medium Priority</td>
<td>• Density/sizing techniques versus mechanical handling of raw materials</td>
</tr>
<tr>
<td></td>
<td>• Model for material mixing in the refining ladle</td>
</tr>
<tr>
<td>Lower Priority</td>
<td>• Dynamic optimization of the BF/BOF hot metal interface and BOP charge model</td>
</tr>
</tbody>
</table>

8.4. Challenges

The supply of raw materials is a key issue for the global steel industry, which is heavily reliant on iron, coal, refractories, and other materials. A major challenge for steel worldwide is the decreasing quality of raw materials. This carries through into challenges in materials processing. Optimization of materials use via new processing techniques or best practices that increase yields, reduce waste, or enable waste recovery can have a significant impact on material requirements. MSV in many cases can enable simulation and comparison of approaches and opportunities for raw materials optimization and the potential benefits or advantages. Some of the major challenges to be addressed are summarized below.

Degradation of Raw Materials
There is a general lack of good data on raw materials degradation as well as knowledge and understanding of the impacts on productivity. Validated models and simulations with the capability to demonstrate how degradation and losses of raw materials occur are currently lacking. The lack of adequate process knowledge is a contributing factor.

Processing and Recycling
Another challenge is optimizing the ability to recycle and recover byproducts and scrap materials effectively. While significant recycling occurs, a number of factors related to the type of raw materials input continue to create challenges. Examples are keeping pace with the decreasing quality of raw materials, and ever-changing steel grades and residual specifications, which tend to impact raw material and processing requirements.
8.5. Priority Roadmap Projects

Priorities for raw material processing cover strategies targeting primarily advanced raw material handling practices and simulations for material flows and processing. These are summarized below and described in priority action plans in Figures 8.1 and 8.2.

- **Optimized Raw Material Handling Designs and Practices** – MSV methods and tools to enable better material handling/equipment designs and management of materials in the field, with the objective of reducing yield losses (Figure 8.1).

- **Optimization of Raw Material Inputs into EAF for Reduced Cost and Higher Productivity** – Technologies, methods, and models to enable optimization of raw materials for EAFs, including improved materials consistency and optimal composition as well as ways to reduce energy requirements (Figure 8.2).
**Challenge/Problem:** Lack of data on raw materials handling is a barrier. Knowledge and understanding of the impacts of handling on material losses are needed. Analysis and tools are also lacking to predict/demonstrate how losses occur. The use of obsolete equipment for handling raw materials is a growing concern.

**Solution/Approach:** Modeling of material handling equipment designs and field management best practices are needed to minimize raw materials yield loss. A combination of data collection and development of process flow and degradation models will be used to create new simulation and visualization tools to aid in efficient material handling designs.

**Action Plan**

<table>
<thead>
<tr>
<th>1-2 years</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Identify current process flows (baseline)</td>
<td>• Current process flow map finalized</td>
</tr>
<tr>
<td>• Collect samples throughout handling process</td>
<td>• Data analysis review/report</td>
</tr>
<tr>
<td>• Develop material degradation model for each material type</td>
<td>• Working model established and validated</td>
</tr>
<tr>
<td>• Test and validate models in practical operating environment</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3-5 years</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Refine and update degradation models as needed</td>
<td>• Current degradation model updated</td>
</tr>
<tr>
<td>• Develop virtual simulation and visualization of the raw material handling process</td>
<td>• Virtual raw material handling simulator model ready for use</td>
</tr>
<tr>
<td>• Use virtual model to optimize the raw material handling process</td>
<td>• Optimized future raw material handling processes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>5-10 years</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Continue to update design tools</td>
<td>• Updated model and flexible tools incorporated in design</td>
</tr>
</tbody>
</table>

**Targets**

- Advanced simulation and visualization models of the current raw material handling processes with the ability to demonstrate the degradation of raw material losses
- Quantified, validated material losses
- Application of simulation and visualization models to develop improved equipment capability, best practices

**Benefits**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Relative Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productivity</td>
<td>♦♦ Improved BF operation, e.g., coke/iron</td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>♦♦ Improved coke quality, e.g., coke/iron</td>
</tr>
<tr>
<td>Environment</td>
<td>♦♦ Less dust/BF upsets, e.g., coke/iron</td>
</tr>
<tr>
<td>Reliability and Maintenance</td>
<td>♦♦ Streamlined handling system, e.g., coke/iron</td>
</tr>
<tr>
<td>Operational Efficiency</td>
<td>♦♦ Improved material yield/BF operation, e.g., coke/iron</td>
</tr>
<tr>
<td>Use of Raw Materials</td>
<td>$$$ Improved material yield/loss</td>
</tr>
<tr>
<td>Competitiveness</td>
<td>♦♦ Increased productivity, e.g., coke/iron</td>
</tr>
<tr>
<td>Economic Growth</td>
<td>♦♦ Increased productivity, e.g., coke/iron</td>
</tr>
<tr>
<td>Workplace Safety</td>
<td>♦♦ Less dust/improved BF stability</td>
</tr>
</tbody>
</table>

**Stakeholders and Potential Roles**

- **Industry/Producers:** Provide current design; conduct R&D to develop optimal material handling
- **Industry/Users:** Provide impact to improved raw materials
- **Industry Value/Chain:** Contribute to design and validation
- **Academia:** Provide the advanced simulation and visualization models
- **National Laboratories:** Assist with model development
- **Government:** Support collaborative R&D

**Steel Value Chain Impacts**

- **Producers –** improved raw material yield
- **Suppliers –** design of handling and transport equipment
- **Users –** Improved raw material quality that improves BF efficiency and throughput
Figure 8.2: Roadmap Priority #10
Optimization of Raw Material Inputs into EAF for Reduced Cost and Higher Productivity

Challenge/Problem: Challenges include a dynamic marketplace, resistance to change within the industry, scarce capital for improvements, lack of process knowledge, variability of recycled raw materials, increasing government regulations, and continuously changing steel grades and residual specifications.

Solution/Approach: The approach is to develop a comprehensive strategy for optimizing EAF production. New models, tools, and best practices will be used to refine raw materials usage and chemistry, conserve energy, train operators, and reduce costs.

Action Plan | Outcomes | Targets | Benefits
--- | --- | --- | ---
1-2 years | • Create closer relationship with raw material suppliers to optimize quality of inputs | • Greater consistency of raw materials | • Optimize raw material input (2.5% over five years)
• Develop tools, models, and training methods to optimize raw material charging practices | • Training of furnace operators | • Minimize the use of all energy sources → productivity increase (5% over 10 years)
• Optimize inputs to minimize downstream processing (e.g., sulfur and other impurities) | • Tools to provide greater throughput/higher productivity | • Lower operational costs/competitive edge
3-5 years | • Develop methods to maximize residual potential while staying within specifications | • Strategies for reducing power requirements | • Lower carbon footprint/costs
• Optimize power consumption (e.g., electricity and gas) via comprehensive simulations and predictive models | • Predictive methods for residuals and foamy slag | • Demonstrating increased furnace life
• Develop model for foamy slag practices | • Demonstration of increased furnace life | • Tools to provide greater throughput/higher productivity
5-10 years | • Develop technology to better analyze and process raw materials | • Proven optimization of raw materials for better composition of products | • Proven optimization of raw materials for better composition of products
• Develop model of charging and flux practices | • Demonstration of energy recovery methods and optimization strategies | • Demonstrating energy recovery methods and optimization strategies
• Devise and implement strategies for optimizing energy recovery from post-combustion

Stakeholders and Potential

Industry/Producers: Define problems with raw materials, train user community operators, and provide data
Industry/Users: Define problems with raw materials, train user community operators, and provide data
Academia: Train students, develop software, and conduct foundational science
National Laboratories: Develop software and provide HPC, libraries and tools
Government: Provide programmatic resources

Steel Value Chain Impacts
Integrated Steel Producers – optimized raw materials use
Suppliers – Higher quality material inputs
Workforce – better trained and qualified workforce
8.6. Chapter References

American Iron and Steel Institute, www.steel.org


9. **Smart Steel Manufacturing**

9.1. **Overview**

Smart manufacturing (SM) is the application of information and manufacturing intelligence to integrate process, operational, and business intelligence throughout the entire manufacturing supply chain. The result is a more coordinated, agile, and performance-oriented manufacturing enterprise that minimizes resource use while maximizing environmental sustainability, health and safety, and economic competitiveness.

The ability for multiple and disparate machines and equipment to communicate seamlessly is creating new opportunities for broader use of system simulation and optimization software in the operation and control of advanced manufacturing systems. Today, smart tools and systems are increasingly used to design, build, operate, and maintain manufacturing facilities – creating competitive advantages while providing environmental and safety benefits. The economic and other benefits of smart systems (and the need to accelerate developments in this area) are receiving broad attention from government and other decision-makers, as noted in numerous reports (McKinsey 2012, PCAST 2011, PCAST 2012, PCAST 2014).

Substantial progress has been made in SM systems and infrastructure in the industrial sector. However, new capabilities are needed to make knowledge-based manufacturing a widespread reality. These range from new wireless and communication devices, sensors, and other systems to computational platforms and tools. The interoperability of these systems is a major challenge; once developed and adopted, multiple systems and equipment must be interconnected and be able to seamlessly communicate to exchange information (SMLC 2011).

SM concepts have been slow to migrate to the basic material industries, such as iron and steelmaking. While the discrete manufacturing industries (e.g., aerospace, automotive) have in recent years begun to integrate sensors with IT infrastructure, these advances have been slower to migrate to the more mature material industries. This is partially due to the harsh operating environments and lower turnover rate of capital assets.

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**Smart Manufacturing Logistics and Planning**

Researchers at Purdue University Northwest have been studying ways to improve factory operational flows and decrease traffic jams via a broad application logistics system simulation. Statistical analysis was applied to create a model to identify bottlenecks and potential solutions. Using the simulation and optimization techniques, clear planning scenarios were predicted for the growth of a simulated factory. For example, for a proposed growth optimization scenario, it was found that significantly increasing the loading efficiencies of storage could in turn increase the shipping capability of the overall logistics system. Simulations like this can be applied to improve operational efficiency in many different types of plant environments, and potentially for multiple plants operating in sync.

(Purdue University Northwest 2014)
9.1.1. State of the Art

Modeling, simulation, and visualization will play a key role in the development of smart steel manufacturing environments. For example, MSV can enable process optimization without the need for “trial and error” in the manufacturing environment. Multi-scale modeling can be used to solve some of the larger process efficiency, safety, and other problems facing the steel industry. Computational and software platforms are also the key underpinnings of all smart systems.

The use of MSV to enable smart steel production has made some inroads to date. Research on optimizing material flow via simulations has been conducted in iron and steel and other industries. Research has shown that mixed-integer linear programming models for plant-wide byproduct gas scheduling in the iron and steel industry can reduce operational costs by about 6.2% (Kong et al. 2010).

Optimizing the iron flow via simulations can also improve iron resource efficiency in the steel manufacturing process (Shieh et al. 2010, Yu et al. 2007). MSV further provides valuable information on energy and material consumption (Zschieschang et al. 2014).

As noted in a recent report (SMLC 2011), greater adoption of smart platforms in production and operations in general will require models and computing platforms that are easily accessible to the community, but have good methods for security and protection of intellectual property.

Advanced computational capability will also be required to support higher levels of analysis and to enable actionable decision-making in a plant environment. A new generation of software tools will also be needed to extract useful information from large volumes of data, and then present it in user-friendly ways.

Implementation Example:
3D Visualization of Steelmaking Processes

The complexity of steelmaking processes and the many factors that engineers and equipment operators must take into account are largely unknown to the general public—and to many would-be steel industry workers. To serve as an overall “guided tour” through these processes, an AIST-produced “Steel Wheel,” developed in collaboration with CIVS, uses 3D models and animations in a series of HD videos to demonstrate more than two dozen processes, the equipment used, and reactions inside the equipment. In addition to the Steel Wheel videos, an interactive web interface was created to help guide viewers through iron- and steelmaking processes. The AIST Steel Wheel can be found on the AIST website at: https://www.aist.org/resources/the-msts-steel-wheel.

(AIST website)
MSV benefits already in process: CIVS researchers have developed a caster scheduling model/software that integrates customer order selection with planning and scheduling of the continuous casters, and reports on five items balanced in the found optimal schedule (slab quantity cost, downgrade penalty, inventory cost, tundish fly cost, and additional slab benefit). While “rigorous testing to evaluate the performance and cost savings is ongoing,” the software is another useful tool in tracking and analyzing how efficiently materials flow and are used through the steel production process. (Silaen et al. 2017)

9.2. Goals

Smart systems that utilize modeling, simulation, and visualization can help to streamline operations and create a more efficient operational environment, with positive impacts on yield, cost-effectiveness, and productivity. MSV can also provide new opportunities for better product quality. Specific goals include:

- Achieve high-speed simulations and visualizations that allow for iterative design and operational insights (1-hour to 1-day turnaround in 5 years) (long-term goal)
- Improve and optimize product quality through effective modeling and simulation, including integrated processing, improved structure-property, and multi-scale models
- Achieve a comprehensive hot strip finishing mill with broad capabilities for simulation (e.g., work roll bending, work roll crown, etc.) to improve and optimize product quality
- Optimize plant and value chain enterprise via MSV to significantly improve time from raw material to customer

9.3. Future Needs

Future needs for steel applications center around development of new models and simulations that will help improve performance and provide overall optimization of product manufacturing and quality. The future needs identified are illustrated in Table 9.1, and summarized below.

Application-Specific
Simulations can aid in evaluation and comparison of damage and other performance scenarios for steel products in both the lab and the field. Effective damage- or failure-predictive models could improve both design and use of steel applications. Specific needs for MSV include the design of puncture-resistant tank cars, to demonstrate impacts of damage situations, and to aid in the design of burst-resistant pipeline steel.

<table>
<thead>
<tr>
<th>Table 9.1 Future Needs for MSV for Smart Manufacturing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Smart Operating Systems</strong></td>
</tr>
<tr>
<td><strong>High Priority</strong></td>
</tr>
<tr>
<td>● Richer integration of sensors and data with process control / production planning</td>
</tr>
<tr>
<td>● Optimization of material flows through facility using logistical models of inputs/outputs</td>
</tr>
<tr>
<td>● Operational efficiency visualization tools to help production planning/sales department track changes in yield, throughput, inventory, etc. as new products/processes are introduced; integrated planning of enterprise production scheduling/process material flows</td>
</tr>
<tr>
<td>● Increased facility capability to reduce un-needed assets and increase working ratio (to improve efficiency and lower costs)</td>
</tr>
<tr>
<td><strong>Medium Priority</strong></td>
</tr>
<tr>
<td>● Faster interactions and knowledge integration between metallurgists and modelers/IT experts</td>
</tr>
<tr>
<td>● Continuous processes from raw material to finished product (no batch processes) via smart systems</td>
</tr>
</tbody>
</table>
## Table 9.1 Future Needs for MSV for Smart Manufacturing

<table>
<thead>
<tr>
<th>Priority</th>
<th>Needs</th>
</tr>
</thead>
</table>
| **Lower Priority**| • General decisions built into models based on certain selections – reduced order modeling (rather than detailed models)  
• Optimize gas usage and find new applications to improve operational efficiency |
| **Low Priority**  | • Dynamic model of blast furnace daily operations with real-time data  
• Whole-plant gas distribution analysis (dynamic, real-time)  
• Operational efficiency and scheduling of the mill under upset conditions, and recovery in real time  
• Ladle refining optimization – inclusion flotation, degassing |
| **Application-Specific** | • Design of a puncture-resistant tank car to avoid release of hazardous materials – minimize car weight to maintain payload  
• Models/simulations to demonstrate impacts of materials damage situations (e.g., tank car is derailed and coupler punctures the broadside of a tank car) and recommendations for mitigation of damage  
• Design of burst-resistant pipeline steel – e.g., spiral and straight seam welded pipes |
| **High Priority** | • 3D simulation of product transition in a continuous anneal line (dynamic) |
| **Medium Priority** | • High-performance gears and bearings to increase reliability of wind turbines  
• Corrosion resistance in sour gas environments |
| **Lower Priority** | • Integration of 3D with existing models for the hot strip mill  
• Uncertainty quantification for modeling – tools and methodology  
• Structure-property micro-mechanical damage/failure models, integrated with process models  
• Improved thermodynamic database to support models/simulations  
• Faster turnaround time for simulations  
• Multi-objective optimization (e.g., process flows, properties)  
• Integration of ‘Big Data’ and machine learning in models |

### Smart Operating Systems

Models and simulations can be important tools for optimizing operational efficiencies plant-wide. In many cases, improving operational efficiencies also improves energy efficiency (and can be overlapping). A top priority is the optimization of material flows and associated logistics throughout the production and plant environment. This would feed into an expert system for integrated planning of enterprise production scheduling/process material flows, including process mapping and Just in Time (JIT) lead-time reduction for operational efficiency.

Another priority is richer integration of sensors and data with process control as well as enterprise production planning to enable smart optimization of inputs and outputs. Data analytics and sensor/data collection infrastructure would be integrated to support greater operational and production efficiency across plants and business units.

The implementation of smart systems that would enable the facility to identify and reduce the use of unneeded or underutilized assets and increase working ratios was identified as a high priority. The end result would be improved efficiency and lower costs. Scheduling/logistics models are closely related. These models are needed to integrate and improve the movement of products from process lines. Optimizing steel inventory control practice and logistics is important to reducing costs. This would include integration of systems that lack common communication, timing, and measurement methods. There is a specific need for an operational efficiency visualization tool to help production planning/sales departments track changes in yield, throughput, inventory, etc., as new products/processes are introduced.
Improving the operational efficiency of equipment is another priority. Steel cleanliness practices for low-temperature cast steel are one priority—and a current source of inefficiencies. Gas distribution and use (including waste gas streams) could be improved by optimization models, improving operation efficiency.

**Models and Simulations**
Future needs for MSV include application-specific simulations as well as fundamental physical models and data. A top priority is the development of simulations for hot rolling of advanced high-strength steels, which are seeing increasing use in structural applications, especially in automotive use. Property data will be needed to support new models and simulations. Structural and micro-mechanical damage/failure models are also needed to aid in evaluation of the performance of steel products. Ideally these could be integrated with process models. Models for flow optimization and improved properties analysis are needed to achieve multi-objective optimization of products as well as manufacturing processes.

### 9.4. Challenges

The challenges identified for smart steel manufacturing range from data requirements to scalability.

**Real-Time Capabilities**
A major challenge is the lack of real-time process optimization and control strategies, methods, and systems for data collection. Non-intrusive characterization tools, both spatial and temporal, are currently lacking. This contributes to data acquisition challenges, as does the complexity of process equipment. In situ parameters that cannot be measured may lead to model errors. Knowledge and technology for effectively measuring these parameters is currently limited. In addition, many operators rely on (and are comfortable with) rules of thumb for decision-making rather than real-time data.

**Issues of Scale**
Creating a smart manufacturing enterprise is a “large” problem with many complex elements. The challenge can be so large it is difficult to target the phases and starting points. For example, while creating a “streamlined integrated plant model” is highly desirable, it represents an enormous undertaking with many components and uncertainties. In many cases, processes are still treated as individual systems that do not lend well to integration. For example, understanding and controlling the stability of material flows, from raw material inputs to various processes and finally in finished materials, is an important but daunting technical problem as it spans multiple parts of the production process.

Scaling is another issue for advanced MSV using high-performance computing. For example, scalable HPC multi-physics models and simulation codes are lacking and could be used for a number of process units. An example is using scalable HPC to model the entire blast furnace, which would allow for effective start-up diagnostics and modeling of other important operating parameters.

**Risk of Adoption**
There is inherent risk (i.e., issues of trust and reliability) involved in the adoption of model-based systems, especially if large operational changes and capital investment are required. In addition, adoption of smart manufacturing techniques may require installation of high technology equipment which can be problematic in a plant setting where harsh environments require very robust systems.
9.5. Priority Roadmap Projects

The priority research topics for smart steel manufacturing are summarized below and described in Figures 9.1 to 9.3. These emphasize the capabilities that MSV can provide to optimize operational and production efficiencies.

- **Expert System for Integration of Scheduling, Production, and Material Flow** – Integrated inventory, schedule, price, and control management tool to improve operational efficiency (Figure 9.1).

- **Integration of Sensors and Data with Process Control Systems for Production Planning** – Automated, sensor-driven smart manufacturing system to enable optimization of materials, manpower, downtime, and product quality (Figure 9.2).

- **Optimized Material Flows through a Constrained Facility** – Production planning execution model that enables operation of the constrained facility at a world-class utilization rate (Figure 9.3).
**Challenge/Problem:** Integration of systems that lack common communications, timing and measurement methods is a major challenge due to issues of interoperability. Commitment is also lacking for allocating the needed resources and expertise for developing expert systems, in spite of the potential benefits.

**Solution/Approach:** An expert system is proposed that would predict production time, cost, inventory, and price. This would enable prediction of the influence of new products on all these factors; allow for the rapid estimation of new outputs as a result of unplanned disruptions; and provide a system to ensure long term optimization of operations.

### Action Plan

**1-2 years**
- Develop case study of both an integrated and mini-mill steel operation
- Benchmark non-proprietary and non-price sensitive data
- Initiate development of a visualization tool for an expert system
- Initiate beta testing of system in practical environment

**Outcomes**
- Set of good case studies as foundation for expert system
- Collection of base data
- Expert system platform structure and beta version
- Validation of foundational system

**3-5 years**
- Collect additional data and case studies to expand expert system in real plant and enterprise environment
- Add new variables/parameters to visualization modules
- Adjust platform and algorithms based on beta testing

**Outcomes**
- Refined and expanded expert system

**5-10 years**
- Continue implementation and upgrade of systems as logistics and production parameters change

**Outcomes**
- Refined and expanded expert system

### Targets
- Improve company bottom line
- Achieve higher production efficiency
- Quick feedback on mill capability
- Better planning tools

### Benefits

<table>
<thead>
<tr>
<th>Factor</th>
<th>Relative Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productivity</td>
<td>♦♦♦ Optimizes production variables</td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>♦♦ Indirect; optimizes operations</td>
</tr>
<tr>
<td>Environment</td>
<td>♦♦ Indirect; optimizes operations</td>
</tr>
<tr>
<td>Operational Efficiency</td>
<td>♦♦♦ Optimizes major operational variables</td>
</tr>
<tr>
<td>Use of Raw Materials</td>
<td>♦♦♦ Optimizes inventory/materials use</td>
</tr>
<tr>
<td>Competitiveness</td>
<td>♦♦♦ Reduces operational costs</td>
</tr>
</tbody>
</table>

### Stakeholders and Potential Roles

- **Industry/Producers:** Provide data and case studies; test systems
- **Industry/OEMs:** Provide data for equipment and pricing
- **Academia:** Develop algorithms and platforms
- **National Laboratories:** Develop algorithms and platforms
- **Government:** Review systems, provide programmatic supports as appropriate

### Steel Value Chain Impacts

- **Integrated Steel Producers – lower cost, higher productivity**
- **Users – timely delivery of quality products**
- **Suppliers – better logistics**
Challenge/Problem: Large amounts of data are generated from processes, equipment, and planning functions. These exist in multiple formats and taxonomies, are of variable quality, and lack standardization. In some cases good real-time data is not available.

Solution/Approach: The objective of this effort is to improve the productivity of plant operations through better, more robust integration of sensors, data, and analysis. This will be achieved through modeling and simulation tools that connect and integrate data from both processes with production planning and logistics.

Action Plan

<table>
<thead>
<tr>
<th>1-2 years</th>
<th>3-5 years</th>
<th>5-10 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Identify application for case study and site for testing/validation</td>
<td>• Develop logistical models and initial platforms</td>
<td>• Develop fully modular modeling platform</td>
</tr>
<tr>
<td>• Survey sensor resources, data storage, and other requirements</td>
<td>• Develop process models to optimize unit processes</td>
<td>• Extend to other plants/facilities</td>
</tr>
<tr>
<td>• Develop consistent methods to handle missing data, multiple formats, and bad data</td>
<td>• Collect and input data for models; integrate process and logistics functions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Validate model outputs versus real-time data</td>
<td></td>
</tr>
</tbody>
</table>

Outcomes

<table>
<thead>
<tr>
<th></th>
<th>• Working plant model based on historical data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Demonstration of optimization via model outputs</td>
</tr>
<tr>
<td></td>
<td>• Validated integrated process-planning models</td>
</tr>
<tr>
<td></td>
<td>• Roll out of generalized, modular platform</td>
</tr>
</tbody>
</table>

Targets

- Heavily automated system to optimize material flow, manpower utilization, product quality, and maintenance/downtime

Benefits

<table>
<thead>
<tr>
<th>Factor</th>
<th>Relative Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productivity</td>
<td>*** Optimizing plant utilization</td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>** Better unit process utilization</td>
</tr>
<tr>
<td>Environment</td>
<td>** More efficient operations leading to reduced effluents</td>
</tr>
<tr>
<td>Operational Efficiency</td>
<td>*** Optimized fully</td>
</tr>
<tr>
<td>Use of Raw Materials</td>
<td>** Indirect; optimization of processes overall</td>
</tr>
<tr>
<td>Competitiveness</td>
<td>*** Optimized/increased utilization</td>
</tr>
<tr>
<td>Economic Growth</td>
<td>** Resulting from improved competitiveness</td>
</tr>
<tr>
<td>Workplace Safety</td>
<td>** Higher knowledge level</td>
</tr>
</tbody>
</table>

Stakeholders and Potential Roles

**Industry/Producers:** Gather resources; purchase sensors, organize existing data, standardize formats, work with developers

**Industry/Users:** Plant managers, production planning to specify system requirements, work with sensor/data team

**Industry/Value Chain:** Contribute to discussion of process optimization criteria

**Academia:** Support model R&D, analysis technical talent pool (future employees)

**National Laboratories:** Provide HPC for physics-based process modeling and optimization

**Government:** Support pre-competitive innovation, collaboration

Steel Value Chain Impacts

**Producers** – improved productivity, operations

**Suppliers** – vendors tied in for raw material management

**Users** – Better-informed customers gain improved planning for operations
**Challenge/Problem:** Facility layouts are constrained, and material handling flow is assumed to be constant over the planning horizon. In today’s market-based, dynamic environment, this assumption may not suffice and layout rearrangement may be required. In addition, multiple facilities and market complexities pose additional challenges. Facilities need to operate with changing demands but face constraints on the resources and parameters for layout rearrangement.

**Solution/Approach:** This effort will develop an order entry and planning execution model to optimize the material flow (tons/hr) through the constrained facility operating under dynamic market and demand conditions. The boundary is hot metal at start and hot band at finish. The objective is to optimize inventories and waste while minimizing production changes while meeting on-time delivery targets.

### Action Plan

<table>
<thead>
<tr>
<th>Timeframe</th>
<th>Outcomes</th>
</tr>
</thead>
</table>
| 1-2 years | - Identify the constrained facility  
- Define world-class performance level for constrained unit  
- Identify root causes of performance gaps  
- Identify waste associated with intermixes  
- Performance gap between current and world class is identified  
- Cost effective balance achieved between waste and production of the constrained facility |
| 3-5 years | - Develop an order entry and planning execution model  
- Test and validate model with actual order entries and measured performance  
- Production planning employees enter customer orders and they are scheduled through hat band  
- Achievement of world class performance |
| 5-10 years | - Continue to refine and adapt models as markets and products change  
- Incorporate appropriate changes in IT and other technologies/infrastructure  
- Continuity of performance, more refined models, widespread adoption of planning models |

### Outcomes

- **Productivity**
- **Energy Efficiency**
- **Reliability and Maintenance**
- **Operational Efficiency**
- **Use of Raw Materials**
- **Increase in Steel Applications**
- **Competitiveness**
- **Economic Growth**

### Targets

- Operating constrained facility at a world class utilization rate  
- Optimized in-process inventories and waste associated with intermixes  
- Minimized production changes at BF  
- Meeting on-time delivery performance targets

### Benefits

<table>
<thead>
<tr>
<th>Factor</th>
<th>Relative Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productivity</td>
<td>Maximized production stream and time flows</td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>Optimization impacts</td>
</tr>
<tr>
<td>Reliability and Maintenance</td>
<td>Optimization impacts</td>
</tr>
<tr>
<td>Operational Efficiency</td>
<td>Optimization impacts</td>
</tr>
<tr>
<td>Use of Raw Materials</td>
<td>Optimization impacts</td>
</tr>
<tr>
<td>Increase in Steel Applications</td>
<td>Agile facilities</td>
</tr>
<tr>
<td>Competitiveness</td>
<td>On-time delivery to customer</td>
</tr>
<tr>
<td>Economic Growth</td>
<td>Higher capacity utilization opportunities</td>
</tr>
</tbody>
</table>

### Stakeholders and Potential Roles

**Industry/Producers:** Use model and determine variables

**Industry/Users:** Business planning and sales to place orders and schedule

**Industry Value Chain:** Customer on-time delivery

**Academia:** Develop model

**National Laboratories:** Computing platforms as appropriate

**Government:** Support for collaborative efforts

### Steel Value Chain Impacts

- Producers – improved material balance
- Suppliers – more customers/sales
- Users – effective production
9.6. Chapter References


10. WORKFORCE DEVELOPMENT

10.1. Overview

There is a critical need for skilled workers in manufacturing, especially the steel industry. A survey by the Manufacturing Institute and Deloitte, titled “The Skills Gap in U.S. Manufacturing,” revealed that 82 percent of manufacturers reported moderate to serious shortages in skilled production workers, and over 600,000 U.S. manufacturing jobs remain unfilled (Morrison et al. 2011). Further evidence of the shortages is provided by recent surveys conducted by the Steel Manufacturing Association (SMA) and the Association for Iron and Steel Technology (AIST) Foundation’s Board of Trustees, which has prompted the formation of a task force to address the technical skills gap (AIST 2013).

The inability to fill skilled production jobs—machinists, operators, craft workers, distributors, technicians, and more—is taking a toll on manufacturing industries. Seventy-four percent of respondents surveyed in the Deloitte and Manufacturing Institute report indicated that workforce shortages and/or skill deficiencies in skilled production roles are having significant negative impacts on manufacturers’ ability to expand operations and improve productivity (Morrison et al. 2011). Unfortunately, these jobs require the most training and are traditionally among the hardest manufacturing jobs to fill with existing talent.

In spite of workforce challenges, productivity for the U.S. steel industry has improved five-fold since the early 1980s. The 2014 average for steel mills was 1.9 worker-hours per finished ton of steel in 2014, compared to the much higher 10.1 worker-hours per ton in the 1980s. Today many facilities, such as highly efficient mini-mills, can produce a ton of steel in less than one worker-hour.

Advanced manufacturing, information technologies, and workforce development complement each other and can lead to even greater productivity gains than ever thought possible (Waldeck 2014). Recent research in manufacturing suggests that an internally consistent “bundle” or system of human resource practices may promote productivity and quality (MacDuffie 1995). Large-scale corporate survey research has demonstrated the relationships between employer-sponsored training and enhanced firm productivity (Bartel 1994, Bassi 1995, Bishop 1994), and increased individual worker performance (Bartel 1995).
10.1.1. State of the Art

The integration of virtual reality (VR) visualization and simulation provides an efficient tool to enhance communication and understanding (Rohrer et al. 2000). Yet to date, the steel industry has used VR as a training tool on a very limited scale (Fillatreau et al. 2013). As simulation technology evolves, more engineers in the industrial sector believe VR can help them better understand phenomena in complex environments, many of which are difficult to access directly (Jimoyiannis 2011).

In recent years, VR has been improved by using high-quality real-time rendering of the equipment to increase simulation realism and accuracy. Today, three-dimensional (3D) interactive VR is viewed as one of the best aids for maintenance, safety, and operational training. VR technology is used mainly in industrial training applications such as gas refining and mining, where achieving “Zero Harm” (no injuries) is of paramount importance. VR provides the capability to simulate dangerous situations in a safe, visual, and interactive way (Rovaglio and Scheele 2011).

10.2. Goals

The following goals were identified for workforce development, for which simulation and visualization could play an important role:

- Achieve full connection and awareness of the workforce opportunities in the steel industry, beginning with education and carrying through to workforce
- Achieve across-the-board occupational competence throughout the entire organization
- Optimize/enhance intellectual capital and company success via knowledge, training, and understanding of new technology
- Create a lean manufacturing work force via application of targeted simulation and visualization
- Improve employee retention
- Develop training modules for processes used to make current products

10.3. Future Needs

In addition to workforce training such as safety training, MSV can enable many improvements in the workplace. Table 10.1 lists the needs for MSV in workplace development.
Workforce Training
Simulation and visualization can promote the ongoing development of skilled maintenance technicians, such as mechanics and electricians, who understand the technology of today and tomorrow. Also a priority is the need to develop computerized, technical training that is specific to the steel industry, in-house, to enhance core capabilities. MSV can also help train employees to understand plant logistics, such as shop and material flows.

Industry Image and Workforce Retention
Changing the image of manufacturing is a top priority need. This can be achieved by obtaining data that demonstrate improvements in health and safety of employees in the workplace, and highlight satisfaction with modernized jobs. MSV can help retain and attract a younger workforce with attractive videos and simulations of what a shop floor looks like as well as the various steel processes, and help students and young professionals see how working in the modern steel industry can be safe, rewarding, and innovative.

<table>
<thead>
<tr>
<th>Table 10.1 Future Needs for MSV for Workplace Development</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Workforce Training</strong></td>
</tr>
<tr>
<td><strong>High Priority</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Medium Priority</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Lower Priority</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Industry Image</strong></td>
</tr>
<tr>
<td><strong>High Priority</strong></td>
</tr>
<tr>
<td><strong>Lower Priority</strong></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

10.4. Challenges
Three key challenges have been identified that hinder improvements in workplace development.

Training
Operators often lack an understanding of material flows through mill, including areas such as the blast furnace, basic oxygen furnace, and strip mill. However, it is challenging to find time and resources for front-line trainers to educate operators. Another challenge is that the new workforce has a short time to learn from the experienced workforce before the latter retires. Additional barriers related to training include the scarcity of trained people to do research and improvement and the fact that technology is constantly changing.

MSV Challenges
Challenges related to MSV include the availability and use of the software, and training the trainers once the software is onsite.
Workforce Retention
A key challenge is the difficulty of attracting and retaining undergraduate and graduate students in materials science to the steel industry, instead of losing them to competing industries. In addition, retention can be difficult in companies where there is limited opportunity for promotion and growth.

Industry Image
The industry is often perceived as being unsafe, dirty, and plagued by antiquated technology. For this reason, top-performing students and young talent may not initially seek jobs in a steel mill.

10.5. Priority Roadmap Projects
Priorities identified for workforce development will enhance awareness of steel industry opportunities for the incoming workforce, and provide training to optimize use of modern MSV tools. Priorities are summarized below and in Figures 10.1 and 10.2.

- **Interactive Student – Steel Industry Program and Tools** – Comprehensive training, outreach, and curriculum program to introduce students to the steel industry (Figure 10.1).
- **Virtual Simulation and Visualization Training** – Virtual training tools to enhance operator performance and productivity (Figure 10.2).
Challenge/Problem: The current workforce in the steel industry is aging and will need a fresh influx of operators, engineers, and scientists. Students often have limited understanding of the steel industry and the many types of opportunities it provides. College curricula and technical training may not necessarily target the skills needed for working in the industry or prepare students for steel industry careers.

Solution/Approach: A comprehensive training, curriculum, and outreach program is needed to build a new steel industry workforce. The approach is to develop real-world interactive problem scenarios to introduce students to and instruct students in the skills and concepts of the steel industry. This will involve identifying appropriate mentors, identifying a few key problems/projects, and then bringing these together to develop a simulation that is engaging and demands critical thinking.

### Action Plan

<table>
<thead>
<tr>
<th>1-2 years</th>
<th>Outcomes</th>
<th>Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Network with people in the industry and CIVS and identify mentors and champions at universities/colleges, technical schools, post-secondary institutions, CIVS and industry</td>
<td>- Strong, productive relationship with key partners</td>
<td>- Comprehensive training library that simulates common failures in behavior and equipment</td>
</tr>
<tr>
<td>- Identify problems/projects for scenarios</td>
<td>- Developed pathway and curriculum</td>
<td>- Curriculum and training that encourages new steel workforce via modern and effective techniques, such as virtualization</td>
</tr>
<tr>
<td>- Identify a curriculum pathway and begin development</td>
<td>- Simulated projects developed</td>
<td>- Operator training via virtualization</td>
</tr>
<tr>
<td>3-5 years</td>
<td>- Graduates seeking employment in engineering, advanced manufacturing, or steel industry</td>
<td>- Continued dissemination of knowledge and skill-building</td>
</tr>
<tr>
<td>- Refine, fine-tune, update, modify, and collect data</td>
<td>- Implemented curriculum and simulations</td>
<td>- Graduates seeking employment in engineering, advanced manufacturing, or steel industry</td>
</tr>
<tr>
<td>- Provide a suite of solutions (small, diverse, large, targeted, broad) to gain buy-in</td>
<td>- Earning of certifications and degrees, dual college credits</td>
<td>- Comprehensive training library that simulates common failures in behavior and equipment</td>
</tr>
<tr>
<td>- Interact with CIVS and steel industry to identify internships and collaborative projects and partners</td>
<td>- Students engaged in internships</td>
<td>- Curriculum and training that encourages new steel workforce via modern and effective techniques, such as virtualization</td>
</tr>
<tr>
<td>5-10 years</td>
<td>- Continue development – sustain and refine</td>
<td>- Operator training via virtualization</td>
</tr>
<tr>
<td>- Replicate with other districts and other industries</td>
<td>- Students engaged in internships</td>
<td>- Particularly workforce advantage</td>
</tr>
</tbody>
</table>

### Stakeholders and Potential Roles

**Industry/Producers:** Steel makers

**Academia:** Develop curriculum, implement training, confer associate and/or bachelor’s degrees

**National Laboratories:** Support graduate and post-doctoral students with research grants

**Government:** Federal grant opportunities

### Benefits

<table>
<thead>
<tr>
<th>Factor</th>
<th>Relative Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliability and Maintenance</td>
<td>** All levels</td>
</tr>
<tr>
<td>Operational Efficiency</td>
<td>** All levels</td>
</tr>
<tr>
<td>Competitiveness</td>
<td>** Highly skilled workforce for competitive advantage</td>
</tr>
<tr>
<td>Economic Growth</td>
<td>** Increased worker employability, creates jobs</td>
</tr>
<tr>
<td>Workforce Development</td>
<td>*** Foster new workforce</td>
</tr>
<tr>
<td>Workplace Safety</td>
<td>** Highly trained workforce</td>
</tr>
</tbody>
</table>

### Steel Value Chain Impacts

Producers – skilled future workforce
**Figure 10.2: Roadmap Priority #18**

**VIRTUAL SIMULATION AND VISUALIZATION TRAINING**

**Challenge/Problem:** Operators not familiar with MSV tools may be resistant to innovative training. Management initiative will be needed to incorporate MSV training into routine activities. Another challenge will be obtaining buy-in from senior leadership; successful implementation of MSV training will require strong drive by senior leadership.

**Solution/Approach:** Virtual training tools are one way to enhance operator maintenance and overall industry performance. New training tools would combine all aspects of operations (i.e., safety, maintenance, reliability) and contribute to workforce development. Such tools are also cross-cutting and could be applied across steel companies to replicate benefits.

### Action Plan

<table>
<thead>
<tr>
<th>1-2 years</th>
<th>3-5 years</th>
<th>N-10 years</th>
</tr>
</thead>
</table>
| - Identify top priority job functions for training  
- Survey industry for best training practices  
- Collaborate with SMEs to develop curriculum and tools  
- Develop and initiate testing of training tools | - Implement programs within work environment  
- Review content for accuracy as programs are implemented and used  
- Establish host server/document sharing platform point to share and exchange materials from class | - Review and update as needed |

### Outcomes

| - Compilation of rules/best practices gathered from industry  
- Completed training materials for key job functions  
- Program pilot implemented | - Operating version in working environment  
- Content review and update  
- Materials available on-line | - Content review and update |

### Targets

- Training program that provides reproducible results  
- Steel industry-wide training materials  
- Potential training materials for supply chain

### Benefits

<table>
<thead>
<tr>
<th>Factor</th>
<th>Relative Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productivity</td>
<td>♦♦ Skilled operator performance</td>
</tr>
<tr>
<td>Environment</td>
<td>♦♦ Increased operator knowledge</td>
</tr>
<tr>
<td>Reliability and Maintenance</td>
<td>♦ Higher skill levels</td>
</tr>
<tr>
<td>Operational Efficiency</td>
<td>♦♦♦ Higher operational performance</td>
</tr>
<tr>
<td>Use of Raw Materials</td>
<td>♦ ♦ Indirect impacts</td>
</tr>
<tr>
<td>Competitiveness</td>
<td>♦ ♦ Reduces costs overall</td>
</tr>
<tr>
<td>Workplace Development</td>
<td>♦♦♦ Higher skilled workforce</td>
</tr>
<tr>
<td>Workplace Safety</td>
<td>♦♦♦ Increased situational awareness</td>
</tr>
</tbody>
</table>

### Stakeholders and Potential Roles

- **Industry/Producers:** Provide best practices for job process; potential to develop best practices.
- **Industry/Users:** Utilize program and supply feedback
- **Industry/Value Chain:** Provide best practices for job process
- **Academia:** Conduct and collaborate to create each process
- **National Laboratories:** Provide support for consensus standards
- **Government:** Provide regulatory standards

### Steel Value Chain Impacts

- **Producers – skilled workforce**
- **Suppliers – best practices for vendors**
- **Users – reliable product supply**
10.6. Chapter References


Association for Iron and Steel Technology (AIST) Foundation, University-Industry Relations Roundtable, May 2013.


11. APPENDICES

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## Appendix B. Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D</td>
<td>Two-dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>Three-dimensional</td>
</tr>
<tr>
<td>AHSS</td>
<td>Advanced high-strength steel</td>
</tr>
<tr>
<td>AISI</td>
<td>American Iron and Steel Institute</td>
</tr>
<tr>
<td>AIST</td>
<td>Association for Iron and Steel Technology</td>
</tr>
<tr>
<td>BAT</td>
<td>Best available technology</td>
</tr>
<tr>
<td>BF</td>
<td>Blast furnace</td>
</tr>
<tr>
<td>BOF</td>
<td>Basic oxygen furnace</td>
</tr>
<tr>
<td>CBM</td>
<td>Condition-based maintenance</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational fluid dynamics</td>
</tr>
<tr>
<td>CIVS</td>
<td>Center for Innovation through Visualization and Simulation</td>
</tr>
<tr>
<td>CO</td>
<td>Carbon monoxide</td>
</tr>
<tr>
<td>CO2</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>DOE</td>
<td>U.S. Department of Energy</td>
</tr>
<tr>
<td>DRI</td>
<td>Direct reduced iron</td>
</tr>
<tr>
<td>EAF</td>
<td>Electric arc furnace</td>
</tr>
<tr>
<td>EPA</td>
<td>U.S. Environmental Protection Agency</td>
</tr>
<tr>
<td>HPC</td>
<td>High-performance computing</td>
</tr>
<tr>
<td>IT</td>
<td>Information technology</td>
</tr>
<tr>
<td>JIT</td>
<td>Just-in-time (production)</td>
</tr>
<tr>
<td>LMF</td>
<td>Ladle metallurgical furnace</td>
</tr>
<tr>
<td>LTS</td>
<td>Low-temperature steel</td>
</tr>
<tr>
<td>MSV</td>
<td>Modeling, simulation, and visualization</td>
</tr>
<tr>
<td>NIST</td>
<td>National Institute of Standards and Technology</td>
</tr>
<tr>
<td>OSHA</td>
<td>Occupational Safety and Health Administration</td>
</tr>
<tr>
<td>PHM</td>
<td>Proportional hazards model</td>
</tr>
<tr>
<td>PM</td>
<td>Preventive maintenance</td>
</tr>
<tr>
<td>R&amp;D</td>
<td>Research and development</td>
</tr>
<tr>
<td>ROI</td>
<td>Return on investment</td>
</tr>
<tr>
<td>ROM</td>
<td>Read-only memory</td>
</tr>
<tr>
<td>VR</td>
<td>Virtual reality</td>
</tr>
</tbody>
</table>