Development of Machine Connectivity Guidelines for Production Floor

by

Kenan Hayel Sehnawi

Bachelor of Science in Mechanical Engineering
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Authored by:	Kenan Hayel Sehnawi Department of Mechanical Engineering August 9, 2024
Certified by:	Brian W. Anthony Principal Research Scientist Thesis Supervisor
Accepted by:	Nicolas Hadjiconstantinou Professor of Mechanical Engineering, Graduate Officer, Department of Mechanical Engineering

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Abstract

This thesis introduces and uses a standardized method for assessing machine connectivity at manufacturing facilities and develops a roadmap for an organization looking to implement connectivity at its facilities. As technology rapidly advances and Industry 4.0 takes hold of manufacturing worldwide, it is essential for manufacturing companies to utilize the latest technology to maintain a competitive advantage by optimizing operations, improving productivity, and increasing throughput. In this work, an overview of machine connectivity and its benefits are presented, and technologies and security measures used for connectivity are explored. Upon compilation of this information, a comprehensive rubric was developed with six weighted connectivity criteria, each scored from 0 (no progress) to 4 (fully complete), from which a total connectivity score can be computed. The rubric serves as a guiding tool for gauging a manufacturing facility's level of maturity with regards to connectivity, and helps identify areas of need both within a facility and within an organization as a whole. The connectivity levels of six different manufacturing facilities were assessed using the rubric. The results were compiled to understand the development of connectivity at different facilities across the organization. The learnings from this analysis are used to develop guidelines as the organization continues its push towards full connectivity across all of its facilities. The next steps in this initiative are to: 1) utilize the developed rubric to assess connectivity at all of its manufacturing facilities, 2) identify facilities in need of the most resources in order to plan and execute connectivity, and 3) encourage collaboration between facilities to expedite the connectivity implementation process.

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Chapter 1 Introduction

As technology rapidly evolves, it is essential for companies to stay current in order to maximize productivity and maintain a competitive advantage. Specifically for manufacturing companies, it is crucial that their manufacturing processes utilize the latest technologies to enhance efficiency, optimize operations, and maximize profit. The purpose of this thesis is to introduce a standardized method of assessing machine connectivity at manufacturing facilities, demonstrate this method at several facilities, and use the results of these assessments to develop future guidelines for an organization on implementing connectivity in future facilities. This section details information on the company this project was done in collaboration with, introduces the problem motivation, and structures the work done in this thesis.

1.1 Company background information

Schlumberger Limited, doing business as SLB, is a world-leading oilfield services company providing technology to the energy industry worldwide. The company was founded in 1926 with a core business of testing geologic formations for the presence of oil (a process known as wireline logging). Since then, the company has greatly expanded its operations and acquired multiple companies, developing competency in all areas of the oilfield industry. The company operates through four key business segments: Digital & Integration, Reservoir Performance, Well Construction and Production Systems. Their services range from seismic data collection to well drilling, completion, and evaluation, along with reservoir monitoring and control, and data services and software. SLB's portfolio of products consists of, but is not limited to, wireline tools, drill bits, completion valves, blowout preventers (BOPs), artificial lifts, and well cementing technology. As a vertically integrated company, SLB operates over 60 production facilities spanning the globe, each dedicated to producing specific tools and services tailored for well operations.

1.2 Problem motivation and statement

The Fourth Industrial Revolution, also known as Industry 4.0, describes the current trend of automation and data exchange in manufacturing technologies. These include cyber-physical systems, Internet of Things (IoT), cloud computing, and cognitive processing. Industry 4.0

allows for the integration of digital and physical worlds to streamline manufacturing and better connect operators, engineers, and managers to the shop floor. It leverages smart technology to enhance efficiency and productivity, reduce costs, and improve customer satisfaction [1]. A critical component of Industry 4.0 is machine connectivity—the ability of different machines and systems within a factory to connect with each other, allowing for real-time data exchange, automation and control, predictive maintenance, and integration with systems such as supply chain management. Machine connectivity facilitates enhanced visibility and control over the entire production process, allowing production environments to self-optimize and make quick decisions based on real-time data [2]. For a company like SLB, investing in machine connectivity is critical to leverage the full potential of digital transformation to maintain a competitive edge in its respective industry.

The company's growth through strategic acquisitions has resulted in a diverse collection of manufacturing facilities, each with its own history of management and specialized product offerings. This introduces several challenges to machine connectivity at SLB, including:

1) Integration of diverse systems: Transitioning manufacturing operations to Industry 4.0 requires the standardization of disparate systems to communicate and operate seamlessly under industry standards. Each facility uses unique sets of machines, follows different operational protocols, and has varying levels of automation and digital maturity. Integrating and standardizing these diverse systems to achieve seamless machine connectivity can be complex and resource-intensive.
2) Data management: Robust infrastructure and expertise is required in order to effectively manage, process, and leverage the data to obtain useful insights.
3) Cybersecurity: As more machines are connected, there is a greater exposure to cyber threats that are potentially damaging to the company. Ensuring secure data exchange through continual monitoring and maintenance is required.
4) Cost: The financial investment required for upgrading equipment, software, and cybersecurity measures can be substantial for each plant. Determining the return on investment (ROI) and securing a budget for such an initiative can be a challenge.

This thesis aims to assess the state of machine connectivity at multiple SLB manufacturing facilities, and develop comprehensive guidelines for assessing, implementing, and advancing machine connectivity at existing and new manufacturing facilities. Six SLB manufacturing facilities (known as technology centers) were chosen for assessment due to their varied machine types, diverse product lines, and proximity to the company's base of operations in Houston, TX. These centers are listed and overviewed in section 2.3.2.

1.3 Approach

The broad scope of this project requires a high degree of research, collaboration, and adaptability. Early in the project, a thorough understanding of machine connectivity is garnered through research, time on the shop floor, and communication with connectivity vendors. Next, each of the facilities chosen for assessment was toured to obtain a better understanding of its operations and machine types. Existing connectivity implementations were noted and analyzed for maturity.

After thoroughly comprehending machine connectivity and the various elements required for its implementation, a standard rubric for assessing machine connectivity was established, tailored to SLB's needs. This rubric utilizes specific criteria to evaluate the current level of connectivity within an SLB technology center. Automation team leads from each center were asked to grade connectivity at their center using the rubric with assistance from the author. Feedback was then obtained to further refine the rubric. The rubric can be used to assess machine connectivity at other SLB technology centers, helping provide insight on areas that require attention for successful implementation.

In addition, the author organized and led a workshop at a center where the connectivity implementation was less mature. The goal was to gather expertise from the greater manufacturing community to advance the center's connectivity setup, and help develop an action plan for that center. The workshop further helped develop guidelines for implementing machine connectivity at existing and developing facilities.

1.4 Division of work

This project was done as part of a greater collaboration between SLB and MIT to implement and apply connectivity. The author worked with Mr. Kanishk Pal and Mr. Brandon Sun on different aspects of the collaboration. This thesis takes a high-level, general approach to assessing and implementing machine connectivity at multiple SLB facilities. Pal's work fully details the implementation process at one of these facilities (CHPC) [3], while Sun's work serves as a case study for machine connectivity usage by using data collected from machines to improve manufacturing capacity [4]. Their work is briefly summarized in this thesis, and more in-depth descriptions are found in their individual theses.

1.5 Thesis outline

This section briefly outlines and describes the content of each of the following chapters of this thesis. Chapter 2 introduces Industry 4.0 and machine connectivity and their applicability to manufacturing at SLB, and provides brief summaries of the SLB manufacturing facilities focused on in this thesis. Chapter 3 further details machine connectivity aspects including industry standards, networking, and cybersecurity. Chapter 4 overviews current technologies used in machine connectivity, including industry-standard communication protocols, machine controllers commonly found at SLB facilities, and current market connectivity ecosystem solutions that might be used to implement connectivity. Chapter 5 details the rubric used to assess machine connectivity at SLB facilities, and discusses the results of applying said rubric at the facilities focused on this thesis. Chapter 6 further analyzes the results of the connectivity assessments and develops guidelines for SLB moving forward as the organization attempts to push machine connectivity across all of its manufacturing facilities.

Chapter 2 Problem background

This chapter provides background information related to Industry 4.0 and its applicability to high-mix low-volume manufacturing (HMLV), discusses the value of adding machine connectivity to SLB's manufacturing operations, and overviews SLB's worldwide manufacturing operations with a focus on Houston-area facilities.

2.1 Industry 4.0 for low-volume flexible manufacturing

Industry 4.0 describes rapid technological advancement taking place in the 21st century. In practice, it refers to the increased merging of new technologies such as artificial intelligence (AI), Internet of Things (IoT), and robotics with human lives [5][6]. With regards to manufacturing, Industry 4.0 combines traditional existing manufacturing and industrial platforms and practices with modern smart technology, primarily using machine-to-machine connectivity, IoT, sensors to provide increased automation, data collection, real-time monitoring, and predictive maintenance. As smart factories adopt advanced technology, automating processes and incorporating self-tracking mechanisms, they can streamline operations and free up time for human workers to concentrate on other responsibilities [7]. Smart factories can be conceptualized as cyber-physical systems (CPSs), which encompass physical and engineering systems. These systems are monitored, coordinated, controlled, and integrated using a computing and communication core. Embedded sensors collect data, and actuators manipulate physical processes within digital networks. The key components—connectedness, smart machinery, decentralization, big data, and cybersecurity—contribute to enhanced intelligence, connectivity, and adaptability [8].

The ability to continually monitor and collect data allows for traceability and product identification, which are fundamental to Industry 4.0 flexibility. The ability to assign a unique ID to each component enables real-time control of the value chain throughout the product life cycle. These unique identifiers make individual components identifiable at every stage of the production process, facilitating dynamic and efficient production path planning down to the level of individual components. Additionally, information about each component—such as its origin, storage, state, and location—can be retrieved instantly, contributing to streamlined operations and improved decision-making [8].

2.2 Machine connectivity overview

This thesis will explore machine connectivity technology solutions (hardware and/or software), assess the current state of machine connectivity across SLB Houston-area technology centers (i.e. manufacturing facilities), and provide guidelines for future implementation of connectivity. Machine connectivity can be defined as the combination of hardware and software required for extracting data from shop floor machines, sensors, and other network-connected devices. Connecting shop and plant floor equipment to the network requires more than plugging ethernet cables. Machines need to be equipped with hardware (e.g. adapters, sensors) and software solutions need to be procured in order to enable automated data acquisition. Appropriate hardware and software solutions allow machines to be connected to a network, creating data flow that is the raw material of digitalization.

There are several benefits to implementing machine connectivity on the shop floor, including:

1) Monitoring of equipment performance: Real-time monitoring of equipment performance through the collection of sensor data for parameters like temperature and vibration can help detect anomalies, predict failure and optimize maintenance schedules.
2) Aggregation of data across different machines: Connected machines share data across a network. Aggregation of said data enables better insights, trend analysis, and predictive maintenance, and can reveal patterns and optimization opportunities.
3) Standardization of machine communication: Connectivity protocols (e.g. OPC-UA, MTConnect) standardize communication between machines. This consistency improves interoperability, making it easier to integrate new equipment into existing systems.
4) Elimination of downtime and extending asset life: Predictive maintenance based on real-time data minimizes unplanned downtime. By addressing issues before they escalate, companies can extend the lifespan of their assets.
5) Remote monitoring of machine operations: Operators are able to monitor machines remotely, enhancing efficiency, reducing travel costs, and allowing for timely interventions.
6) Enhanced safety: Connected machines can send alerts in the event of unsafe conditions. For example, machines might be able to automatically shut down to prevent accidents, or operators can log reasons for emergency stops to prevent future triggers.

7) Higher profits: Reduced downtime, optimized maintenance, and efficient operations lead to increased throughput and reduced costs. Moreover, data-driven insights help allocate resources effectively.

2.3 SLB manufacturing overview

SLB was initially founded as the Electric Prospecting Company in Paris, France in 1926, with a core business of testing rock and soil formation in a process called wireline logging. In the following 100 years, SLB expanded its operations and acquisitions, ultimately establishing a footprint in nearly all areas of the oil and gas industry's operations [9]. This expansive growth led to many of SLB's manufacturing facilities evolving differently, each with its own unique trajectory due to the varied management styles of the companies acquired. The result is a wide range of operational practices and technological development from facility to facility.

2.3.1 SLB .make program

SLB's .make initiative is dedicated to fostering cost-efficiency and elevating performance throughout its manufacturing operations. By aligning with the overarching corporate strategy and fortifying the fundamental aspects of manufacturing, the .make program seeks to drive a significant transformation in manufacturing efficacy. The program encompasses six essential elements:

1) Accelerate and guide SLB's modernization journey: This element is centered on expediting the company's shift towards contemporary practices and technologies. It entails navigating the organization through the intricacies of integrating new systems and methodologies that are in harmony with prevailing industry norms.
2) Evolve and anchor advanced planning solutions: The aim is to polish and advance the company's planning strategies. Through the evolution of these methodologies, the company intends to bolster its predictive capabilities, adaptability, and readiness to adapt to shifts in the marketplace.
3) Develop and launch manufacturing talent program covering all personnel: This component involves establishing an all-encompassing talent cultivation program for the manufacturing staff. The objective is to enhance the skill set of the workforce, equipping

them to adeptly manage the most recent advancements in manufacturing technology and practices.

4) Pivot to smart quality systems, creating a step change: This strategy marks a move towards sophisticated quality management systems that promise to substantially uplift the operational efficiency and productivity. This ‘step change’ signifies a considerable enhancement over existing procedures.
5) Reinvigorate passion and pride with innovation and technology programs: The final element strives to instill a spirit of innovation and a sense of pride among the company’s employees. By emphasizing state-of-the-art technology and inventive initiatives, the company aspires to motivate its team and instill a deep-rooted sense of dedication and passion for their roles.
6) Develop supply chain interconnects creating insightful real-time visibility and predictability: This strategic objective focuses on improving the synchronization and information flow throughout the supply chain network. By achieving this, the company anticipates more streamlined inventory management, shortened lead times, and heightened responsiveness of the supply chain to the demands of the market.

The .make program hopes to standardize and implement best practices across all manufacturing sites to ensure consistency in quality and efficiency regardless of the product being manufactured. It also encourages innovation and flexibility, allowing SLB to adapt to new processes quickly while maintaining a diverse product lineup. Machine connectivity plays a crucial role in the program by enabling real-time data collection and analysis, allowing engineers, managers, and executives to make quick decisions and optimizing operational efficiency.

2.3.2 SLB manufacturing facilities

SLB has over 60 manufacturing facilities in 19 countries across the world. As each facility produces its own unique product type, all the facilities vary in operations, throughput, machine types, etc. Each product a manufacturing facility produces follows one of three manufacturing models: 1) process—the creation of products by combining supplies or raw materials according to a predetermined formula or ‘recipe’; 2) precision machining—the use of computer numerical control (CNC) machines to cut, mill, and turn raw material stock into precise parts that meet exact specifications; and 3) assembly and testing—the integration of pre-manufactured components into a complete system, followed by rigorous testing to ensure functionality and performance. In the long term, the company aims to implement machine connectivity of some form at all of their manufacturing facilities. Due to the scope and timeline of the project, this thesis focuses on six of SLB's facilities, all in the Houston, TX metropolitan area. These facilities were chosen due to their diverse machine lineup and proximity to manufacturing headquarters. This section provides a summary for each of the six facilities chosen, with information including the products they produce and machine types on their shop floors.

2.3.2.1 KTC overview

The Katy Technology Center (KTC) is an SLB facility in Katy, TX that produces downhole motor equipment, including rotors, stators, and bearings. The facility was formerly owned by Dyna-Drill Technologies until it was acquired by SLB for their Well Construction division in 2010. The facility has various manufacturing technologies including CNC machining, a trepanning machine, a vacuum furnace for elastomer curing, a product testing lab, and an advanced elastomer and quality control measure laboratory. The elastomer laboratory develops stator rubber compounds and analyzes the impact of drilling fluids on power section stators to produce cutting-edge, efficient, and durable motor equipment [10]. The center utilizes both process and precision machining manufacturing for their product lineup.

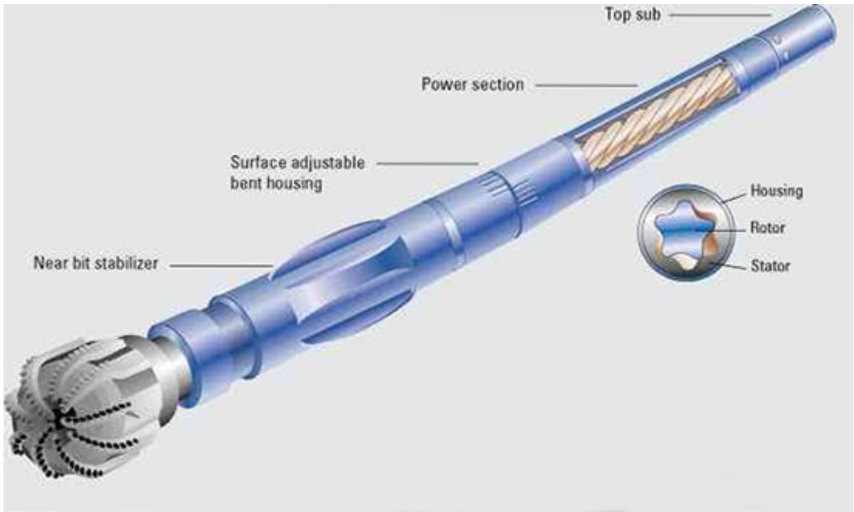

Figure 2.1: Mud motor diagram used for drilling wells

KTC produces the power section of mud motors, which includes the housing, rotor, stator, and bearings. [11]

2.3.2.2 RBTC overview

The Rankin Bits Technology Center (RBTC) is an SLB manufacturing facility that falls under the company's Well Construction division and produces drill bits. The fully integrated plant transforms raw material inputs, including round stock and powdered metal, into completed drill bits. Although the facility is equipped with extensive capabilities to support its comprehensive operations, its main production focuses on two machining cells and a metal foundry dedicated to crafting their drill bits. The center uses both process and precision machining manufacturing for drill bits.

At RBTC, the mainstay products are fixed cutter poly-diamond crystalline (PDC) drill bits, essential for oil and gas well construction. These drill bits are crucial for boring through the earth, and their design varies in size, shape, and composition to tailor-fit the specific requirements of each well construction project, optimizing the drilling process. Given the diverse geological conditions unique to each location, custom-designed drill bits are vital. Considering the high operational costs of well construction, custom drill bits are a strategic investment to expedite drilling and achieve cost-efficiency.

The PDC drill bits at RBTC feature synthetic diamond cutters, renowned for their superior hardness and longevity. These cutters are meticulously placed on durable steel or matrix bodies to endure the rigors of drilling while maintaining directional control and stability. The blades facilitate cutting by correctly positioning the cutters and help clear out debris. Specially designed nozzles channel the drilling fluid to cool, lubricate, and remove cuttings. Additionally, junk slots are incorporated to improve the removal of cuttings and the efficiency of mud circulation, thereby enhancing the drilling process's overall efficacy.

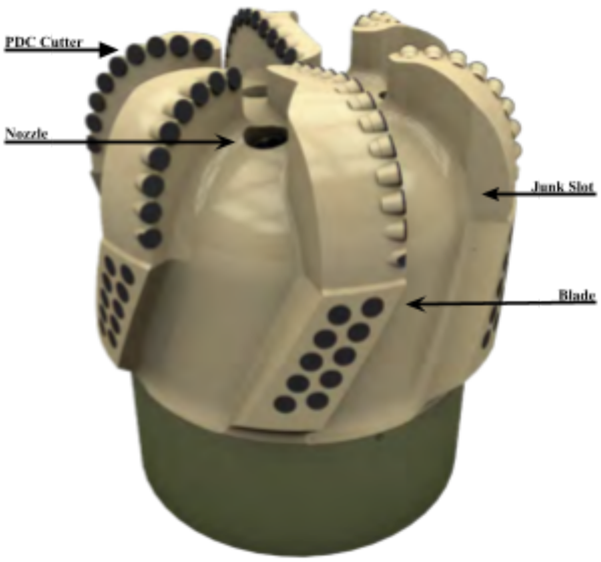

Figure 2.2: Generic drill bit produced at RBTC

Several important components of a drill bit for the oilfield are labeled. These features introduce various complications in the manufacturing process, especially with machining.

2.3.2.3 CHPC overview

The Completions Houston Product Center (CHPC) in Houston, TX, is an SLB facility producing completion valves for production holes, and falls under their Production Systems division. The facility features a wide array of capabilities tailored to fulfill the complex needs of contemporary manufacturing. Within its quality control segment, the center provides optical Coordinate Measuring Machines (CMM), non-contact CMM analysis, and CNC machine inspections to ensure precision and quality in its products. The precision machining sector is outfitted with CNC turning & mill-turn, CNC milling, semi-manual lathes, and manual lathe and milling machines, enabling a wide range of accurate machining tasks. The facility's special processes section encompasses RAM & wire electrical discharge machining (EDM), both horizontal and vertical honing, gun drilling, and precision grinding, offering advanced manufacturing methods for intricate parts. The coating division manages treatments such as zinc phosphate, manganese phosphate, xylan, Ryton, and aluminum oxide blasting, providing protective and functional surface finishes. Finally, the assembly and testing area ensures product integrity of products with high-pressure testing bays, factory acceptance testing, torque machine operations, and a proprietary electrostatic discharge (ESD) laboratory, ensuring each product is rigorously tested and certified to withstand challenging operational conditions. The center uses precision machining and assembly and test manufacturing for completion valves.

2.3.2.4 HCS overview

The Houston Conveyance and Surface Equipment Center (HCS) in Sugar Land, TX produces wireline equipment for the oilfield, thus falling under the Reservoir Performance division. Wireline equipment is essential for acquiring petrophysical and geophysical data about the formation around a hole. HCS is the primary center for wireline cable production, requiring several complex processes to maintain precision and quality. Wireline cables at the facility intake copper conductive wire, polymer, and metal armoring and produce completed wireline cable spools. First, several spools of copper wire are twisted together to form the conductive core. Next, polymer coating is applied through an extrusion process, which requires precise control of temperature and nozzle diameter, among other parameters. An armoring process applies metal onto the polymer coating to shield the cable. The polymer extrusion and armoring process are then repeated, and finally, a polymer jacket is applied to the exterior of the cable. The completed wire is then spooled to be tested and delivered.

Figure 2.3: Example TuffLINE wireline cable produced at HCS

Wireline cables contain multiple layers of polymer coating and metal armoring surrounding the conductive core. [12]

2.3.2.5 Brookshire overview

The manufacturing site located in Brookshire, Texas, specializes in producing elastomers for BOPs. Initially managed by Cameron, the operations of this facility have transitioned to SLB after its acquisition of Cameron in 2016 [13]. The site falls under SLB's Well Construction division. Elastomers are important in BOPs in order to form tight seals and control wellbore pressure [14]. The site includes a research and development unit to develop and test proprietary compounds, ensuring they provide robust and consistent sealing across diverse temperatures, pressures, and environmental conditions, as well as compatibility with various drilling and completion fluids. Manufacturing of the elastomers starts with mixing the elastomer, while metal components are prepared. These elements are then combined in specialized presses for injection, compression, and transfer molding, designed to accommodate various sizes and types of seals. Quality control is a stringent part of the process, with elastomer samples undergoing thorough inspection. Additionally, the performance of the elastomers is rigorously tested in a laboratory capable of replicating any operational field environment [15].

Figure 2.4: Example elastomers manufactured at the Brookshire facility

These elastomers are ready to be inspected and tested for compliance with industry standards. [15]

2.3.2.6 SCMF overview

The Shaped Charge Manufacturing Facility (SCMF) in Rosharon, TX manufactures shaped charges used for well perforation in the oilfield. The facility belongs to the company's Reservoir Performance division. Shaped charges have four main components: the case, main explosive, primer explosive, and metal liner. SCMF is a highly automated facility with various processes that follow tightly controlled processes and parameters. The manufacturing process begins with powder blending using a new, automated mixer. Once powder has been produced, metal liners are fabricated using a fully automated liner press. The liners are then coated and transported to the explosive pressing bay for a final explosive pressing operation. The automated system eliminates operator exposure to explosives and allows for the monitoring, recording, and analysis of various parameters to ensure product quality.

Chapter 3 Machine connectivity overview

This chapter provides an overview of the framework, technologies, networking, and security qualifications involved with implementing machine connectivity.

3.1 Automation standard framework

In the manufacturing plant, the goal is to maximize production and profits. Part of achieving this goal is production optimization, which might involve designing efficient workflows, optimizing production line processes, and improving resource allocation. Industry 4.0 technologies offer numerous ways to enhance efficiency in manufacturing processes. By continuously monitoring and recording all aspects of a facility, sharing real-time data, and ensuring transparency, these technologies contribute to streamlined operations across the entire plant.

To allow for efficient sharing and coordination of information between various levels of a manufacturing system, the ISA-95 was created by the International Society of Automation as an international standard for integrating enterprise and control systems. The standard brings a holistic approach to system integration, focusing on defining and integrating activities that each part of the system is responsible for ranging from business-related activities to physical operations occurring on the shop floor [16]. The standard defines five levels of activity in a manufacturing organization, shown in figure 3.1 [17]:

- Level 0: the physical production processes on the shop floor; time frame of milliseconds to seconds
- Level 1: includes sensors and actuators that automatically sense and physically manipulate the production process; time frame of milliseconds to seconds
- Level 2: elements that directly monitor level 1 items and may include systems such as a supervisory control and data system (SCADA) or a human machine interface (HMI); time frame of seconds to minutes
- Level 3: encompasses several functions including maintenance, production management, and resource planning in a system collectively called a manufacturing execution system (MES); time frame of minutes to shifts (hours)

- Level 4: includes business planning and logistics and encompasses functions such as plant scheduling, inventory levels, delivery, and shipping in an enterprise resource planning (ERP) system; time frame of days to months

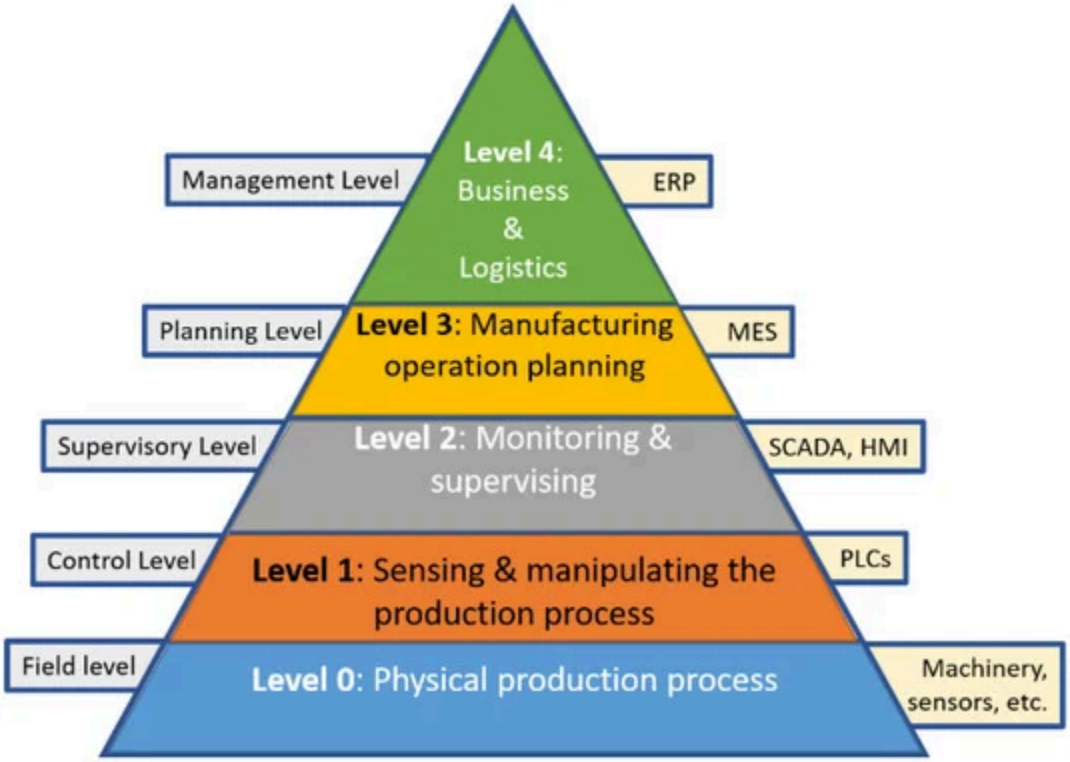

Figure 3.1: ISA-95 Automation Pyramid
The ISA-95 automation standards are often presented as a pyramid to demonstrate the hierarchy of activities in a manufacturing system. [17]

3.2 Network security enforcement

As technology in industrial control systems become more advanced and interconnected, the risk of cyber attack exposure becomes heightened. SLB has developed a comprehensive qualification process to ensure all connectivity related applications meet IT security standards.

3.2.1 SLB qualification processes

SLB employs multiple qualification processes to ensure that all risks associated with connecting systems together are properly captured, assessed, has mitigation plans, and is accepted by the business. Chief among them is the Security Assessment and Qualification Process (SAQP), which is a fundamental component to ensure the security of its software portfolio. The principal aim of SAQP is to bolster security measures across all applications, safeguarding them against threats that could undermine their confidentiality, integrity, and availability. This process is instrumental in maintaining a secure data environment and system operations. Additionally, SAQP is imperative for the protection of SINet and for maintaining conformity with the organization's stringent standards and operational procedures. The initiation of a cloud-based application for the administration of any licenses necessitates the approval of SAQP, which entails a comprehensive series of security assessments to affirm compliance. The purview of SAQP extends to six categories of applications: 1) On-premises Web Applications, 2) Mobile Applications, 3) Cloud Applications 4) Thick Client Applications (both on-premises and cloud-hosted), 5) Operational Technology/Industrial Internet of Things (OT/IIoT) Applications, and 6) Office 365 Applications.

Aside from the SAQP, the Network Analysis Qualification Process (NAQP) assesses and qualifies applications based on their performance and network impact before deployment at SLB. It ensures that the evaluated application affects the Schlumberger Internal Network (SINet) acceptably and operates at an optimal performance level. In addition, the Data Privacy Qualification Procedure (DPQP) assesses personal information data flows in a system, process, or application, and analyzes the possible privacy impact that those flows may have on the privacy of individuals. It provides a framework to ensure that privacy is considered in the design, development, and implementation of any system involving the use of personal information, and ensures that the system meets basic privacy requirements. These qualification processes act together to protect the company from external cyber attacks and employees from data breaches.

3.2.2 IACS

Industrial Automation & Cyber Security (IACS) combines control components to achieve industrial objectives, encompassing various control systems and their associated instrumentation. These systems are crucial for field operations and manufacturing, but increased connectivity and digital adoption introduce risks to critical assets and systems. In the SLB environment, it's common to find machines integrating multiple IACS components—such as HMIs, PLCs, sensors, and actuators—into a single unit. These integrated systems enhance efficiency, ease of operation, and cost-effectiveness. Although IACS is currently developmental, adhering to IACS ensures compliance with the latest SLB connectivity and cybersecurity guidelines.

IACS primarily adheres to IEC 62443, an international series of standards designed to address cybersecurity for operational technology (OT) in automation and control systems. These standards cover both technical and process-related aspects of IACS cybersecurity, considering various roles within the field, such as operators managing and operating IACS, service providers involved in integration and maintenance, and component manufacturers. IEC 62443 provides guidelines for securing critical assets, implementing network segmentation, and prioritizing security measures to ensure comprehensive protection within an operational framework [18].

3.3 Network security measures

Network security measures are essential to protect sensitive data and maintain the integrity of digital systems. As cyber threats become increasingly sophisticated, organizations must implement robust security protocols to safeguard against unauthorized access, data breaches, and other malicious activities. Effective network security not only ensures the confidentiality, integrity, and availability of information but also helps maintain trust with clients and stakeholders. By proactively addressing potential vulnerabilities, organizations can prevent costly disruptions and enhance their overall cybersecurity posture.

3.3.1 Network segmentation

Network segmentation is an architectural approach that partitions a network into various segments or subnets, with each functioning as a separate mini-network. This segmentation enables network administrators to manage and direct traffic flow between these segments according to detailed policies. It is employed by organizations to enhance surveillance, increase network efficiency, confine technical problems, and strengthen security measures. Through the implementation of network segmentation, security teams can effectively block unauthorized access to critical data, such as customer details, company financials, and proprietary intellectual property [19].

In the SLB IACS environment, network segmentation is essential for protecting IACS systems based on their criticality and function. This segmentation aligns with the Purdue Enterprise Reference Architecture (PERA) and IEC 62443 standards. It involves layers such as the Internet demilitarized zone (DMZ), Corporate Network, Industrial DMZ (iDMZ), L3 (Manufacturing Operations and Control), L2 (Supervisory Control), L1 (Basic Control), and L0

(Process). Additionally, IACS network layers are further divided into segments based on criteria like business criticality, segregation of duties, geographical location, technical administration, and business purpose. Each zone should implement at least one segment (e.g., private virtual local area networks—VLANs), with traffic control facilitated through firewalls.

The PERA model is a widely adopted framework for segmenting industrial networks, particularly in the context of OT and IT integration. By dividing the network into distinct zones and levels, the PERA model enhances security by isolating critical assets and reducing the attack surface. This segmentation allows for better monitoring and control, ensuring that any potential threats are contained within specific zones, thereby preventing lateral movement across the network. Additionally, it facilitates the safe collection and analysis of data from OT environments without exposing sensitive systems to accidental or malicious interference.

Figure 3.2 illustrates a comprehensive industrial network architecture for a SCADA system, segmented into multiple levels to ensure secure communication and effective management. At the base, Level 0 includes field devices and I/O modules, which are fundamental for data acquisition and control. Moving up, Level 1 houses PLCs within VLAN H, crucial for executing control processes. Level 2 connects control devices to the enterprise network through a control DMZ, incorporating essential servers like OPC, database, and CMC servers. Level 3 is more complex, featuring various VLANs dedicated to services such as file services, remote access, MES operations, and network services & remote desktop protocols. These VLANs are connected to enterprise-level networks, with firewalls ensuring robust security. At the top, the Enterprise Zone links to external networks, including the Internet and office networks, highlighting the need for stringent cybersecurity measures. This structured approach underscores the importance of segregating OT from IT environments to enhance overall network security and efficiency [20].

The PERA model, widely adopted for segmenting industrial networks, plays a crucial role in enhancing security by isolating critical assets and reducing the attack surface. In accordance with IEC 62443 standards, which emphasize securing IACS through network segmentation, traffic originating from outside the IACS network, including the Internet and internal IT networks, must not directly communicate with lower levels of the Purdue model without passing through a jump host. This policy aligns with the PERA model's approach to network segmentation, ensuring that critical assets remain protected.

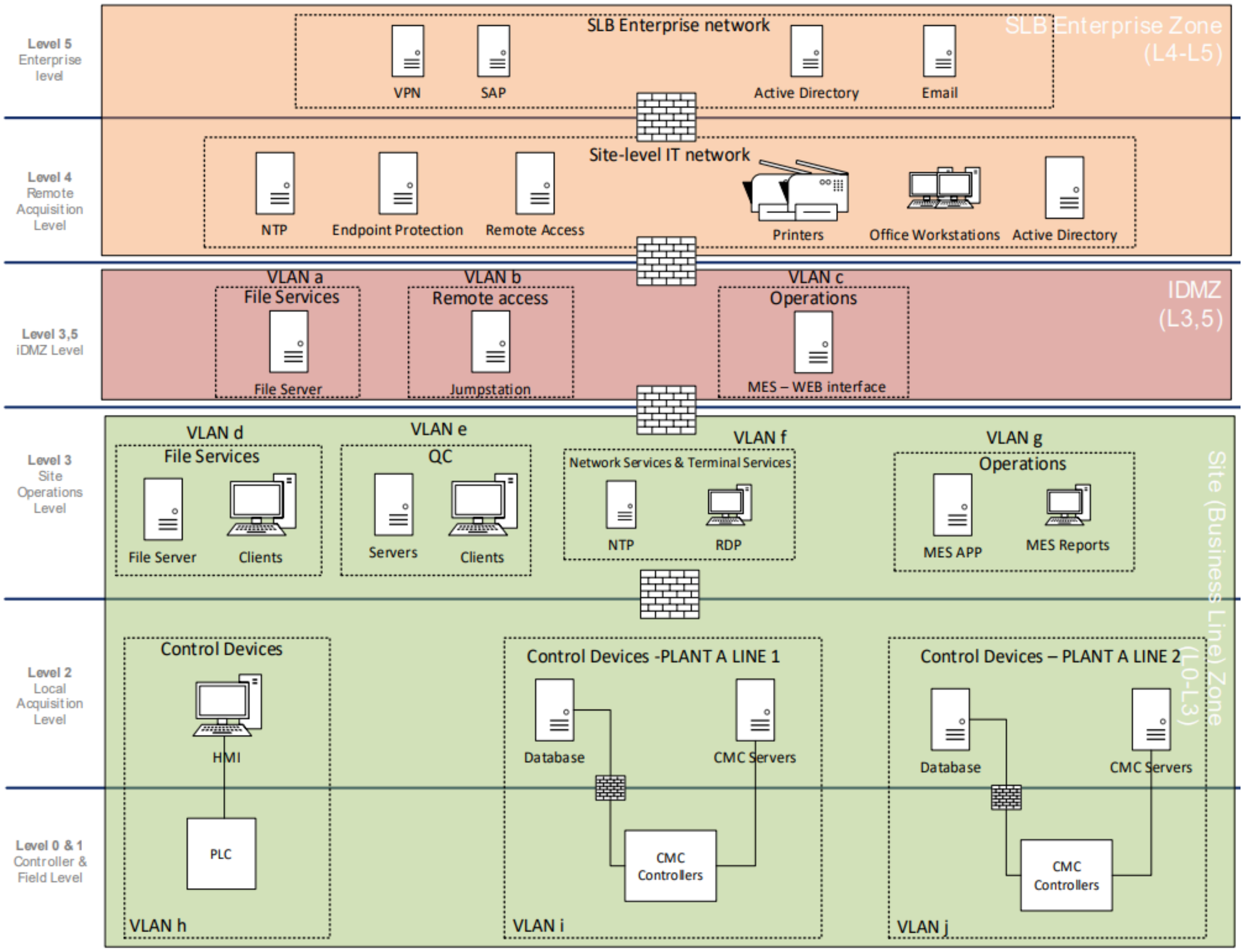

Figure 3.2: Diagram of PERA model framework

This diagram illustrates the hierarchical structure of a SCADA system network, segmented into levels for secure communication and management. Level 0 includes field devices and I/O modules. Level 1 contains PLCs within VLAN H. Level 2 connects control devices to the enterprise network through a control DMZ, incorporating servers like OPC and database servers. Level 3 features VLANs for services such as file services and remote access, with connections secured by firewalls. The Enterprise Zone links to external networks, emphasizing cybersecurity measures.

3.3.2 Network address translation

Network Address Translation (NAT) is a critical security feature that alters IP addresses as Ethernet packets are transmitted. It’s especially beneficial for hiding internal network addresses from the outside world. NAT works by changing an internal IP to a specific public address or by associating a set of internal IPs with a single public address, thereby increasing the security of industrial networks. A notable aspect of NAT is the N-1 or Port forwarding NAT, which effectively conceals the IP addresses of key networks or devices. Moreover, NAT aids in managing multiple Ethernet devices with identical configurations by giving them the same private IP, which eases the process of duplicating or extending production lines. NAT’s operational procedure includes a thorough examination of data packets against set policies, modifying addresses upon finding a match, and progressing through policies until the correct one is applied. This process ensures that only permitted traffic flows through the network, enhancing its protection against unauthorized access [21].

3.3.3 Air-gapping

Air gapping is a crucial security measure that involves physically separating sensitive computer systems from other networks, including the internet. This isolation is essential in environments like SLB, where there are many examples of integrated systems using industrial automation hardware. Such segregation protects these vital systems from cyber threats and unauthorized access, preserving the integrity of industrial operations. However, implementing air gapping presents challenges, particularly in system maintenance and updates, which may require physical intervention. To address these issues, organizations often establish separate LANs for different types of devices, enforce strict access controls, and maintain secure physical perimeters around air-gapped systems. While air gapping significantly enhances security, it must be part of a broader strategy that includes network segmentation and prioritization of critical assets to ensure comprehensive protection of integrated automation hardware systems within SLB’s operational framework [22].

Chapter 4 Technologies in Machine Connectivity

Machine connectivity involves integrating hardware and software to link machines to a network, enabling data extraction from these machines. This chapter overviews technologies that need to be considered when implementing machine connectivity. It covers commonly used machine communication protocols, discusses machine controllers typically found in SLB manufacturing facilities, and compares market connectivity ecosystem solutions.

4.1 Communication protocols

Most manufacturing facilities across SLB will have various types of machines with their own small ecosystem. Some machines use industry-standard communication protocols, but others use vendor-specific protocols that can make ecosystem integration difficult. In recent years, vendors have been adapting to open standard protocols, making it easier for the user to aggregate data from many machines to one central system. This section details the various types of communication protocols focused on in this thesis.

4.1.1 OPC-UA

Open Platform Communications-Unified Architecture (OPC-UA) an industry-standard machine-to-machine communication specification framework used for industrial automation and developed by the OPC Foundation [23]. OPC-UA runs on a client-server protocol. The OPC server is a software that serves as the basis of communication, implementing the OPC standard and providing standardized OPC interfaces to the user. OPC servers can be provided by either: 1) the hardware vendor as stand-alone software or embedded on the device or machine controller, or 2) independent OPC server providers such as Kepware and Softing. The OPC client connects to the OPC server and reads out data provided by the server. Examples of OPC clients include SCADA and MES systems. The communication architecture of OPC-UA is shown in figure 4.1 [24][25].

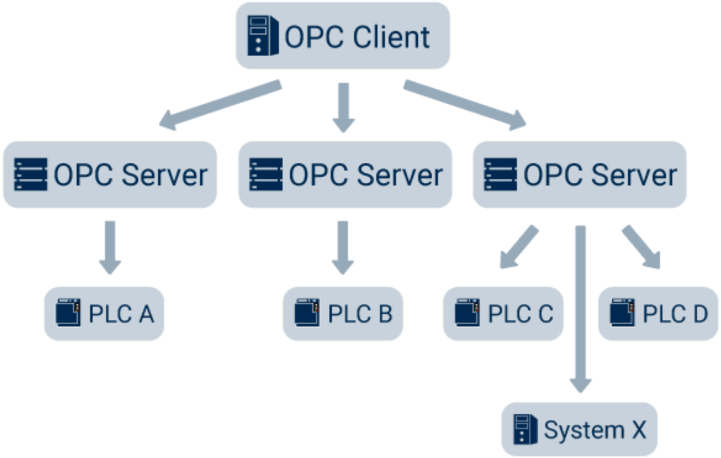

Figure 4.1: OPC-UA example network architecture diagram

This diagram outlines the relationships between the OPC client, server, and machines. A client is able to communicate with multiple servers, each of which is able to communicate with multiple machines at once. [24]

OPC-UA provides numerous advantages in flexibility and security. It is able to function on various platforms including traditional PC hardware, cloud-based servers, PLCs, and CNC controllers, and supports almost all common computer operating systems used in manufacturing (i.e. Windows and Linux). It also provides a suite of controls for security and was developed as "firewall-friendly", meaning that it can be controlled via standard network techniques. Messages are securely transmitted using various encryption levels and support digital signatures, allowing recipients to verify the origin and integrity of the received messages. Applications using OPC-UA can also utilize user control to restrict and enhance capabilities through access rights. OPC-UA is also extensible in that it can integrate new technologies such as new transport protocols and security algorithms while maintaining backwards compatibility [25].

4.1.2 MTConnect

MTConnect is a technical standard used in manufacturing to retrieve process information from CNC machines. This open-source, royalty-free communication protocol is based on XML and HTTP, enabling real-time data sharing between shop floor machines and SCADA systems. MTConnect is designed as a read-only standard, focusing on data reading from the control device rather than writing. The standard comprises three parts: 1) details about the protocol and XML document structure via XML schemas, 2), descriptions of machine tool components and available data, and 3) the organization of data streams that can be provided by a manufacturing device.

When connecting a device to an application via the MTConnect protocol, there are two intermediate components. The MTConnect adapter converts low-level data sent by a machine or sensor into the MTConnect data definition, a plain-text, pipe-delimited string format. MTConnect adapters may be provided by the device maker, built by an end-user, or purchased from third party software providers. Some equipment use MTConnect as their native language, for which an adapter is not necessary. This connects to the MTConnect agent—a piece of software that collects and organizes the data from the adapter or machine. The agent will also receive and process requests for data made from an application [23]. The MTConnect protocol building blocks are shown in figure 4.2.

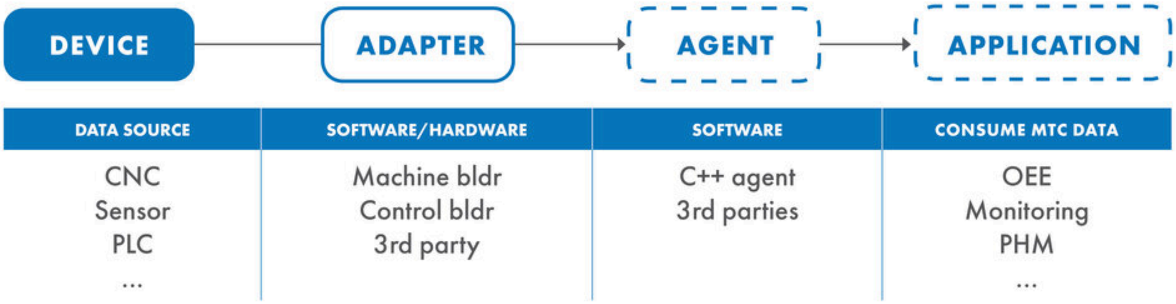

Figure 4.2: MTConnect protocol building blocks
This diagram shows the flow of information through the MTConnect protocol. A device such as a CNC controller or sensor will send information in its own language to an (optional) MTConnect adapter, which will translate the information into MTConnect. An agent will receive the data in MTConnect form and process requests from applications. [26]

4.1.3 FANUC FOCAS

FANUC FOCAS is a software interface library developed by FANUC allowing developers to access, monitor, and manage data from FANUC CNC controllers. The industrial communication protocol has become widely adopted by several machine tool builders, who incorporate FANUC CNC controllers into their machine products. Its core functionality lies in a collection of library files (.dll), accessible by various applications to extract critical information stored within the CNC. By acting as a conduit for direct communication via Ethernet, FOCAS provides comprehensive access to CNC state, part count details, program information, tool offsets, alarm data, and more [27]. FOCAS libraries can access CNC using either Ethernet or HSSB (high-speed serial bus).

4.1.4 MQTT

MQTT is a standards-based messaging protocol that facilitates machine-to-machine communication. It is particularly suited for smart sensors, wearable technology, and IoT devices that operate on networks with limited bandwidth and resources. The protocol enables bidirectional communication between devices and cloud services. It is designed with security in mind, simplifying the encryption of messages and the authentication of devices and users through modern authentication methods.

The protocol operates on a publish-subscribe basis, distinguishing between clients and brokers. An MQTT client can be any device, from a large server to a small microcontroller, equipped with the MQTT library. Clients publishing messages are known as publishers, while those receiving messages are subscribers. Essentially, any networked device can function as an MQTT client. The MQTT broker is the central system that orchestrates the flow of messages among clients. It is tasked with the reception and sorting of messages, determining which clients are subscribed to specific messages, and ensuring the authorization and authentication of clients, in addition to relaying messages to appropriate systems [28].

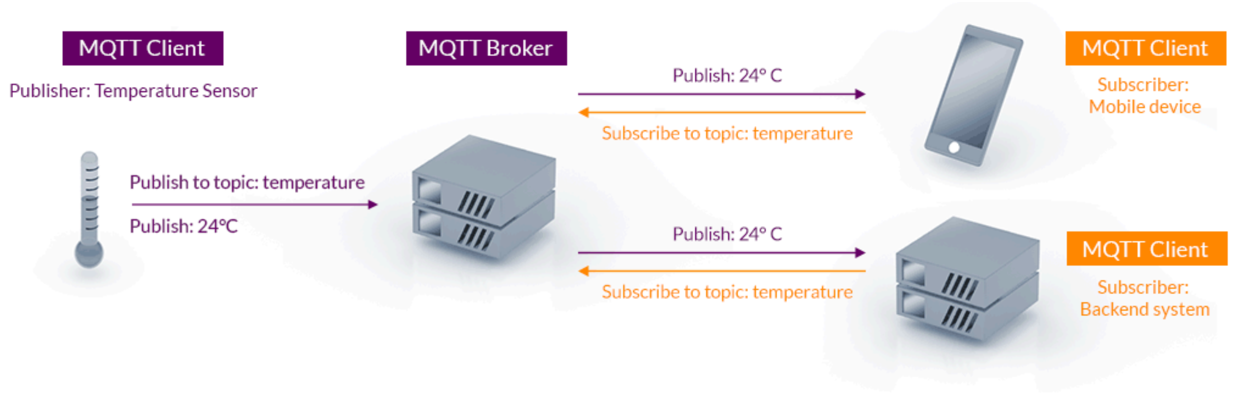

Figure 4.3: MQTT Architecture

This diagram outlines the MQTT publish/subscribe architecture. Any device communicating over the network can be considered a client, while a central broker handles all messages between clients. [28]

4.1.5 Modbus

Modbus is an application-layer messaging protocol providing client/server communication between devices connected on various types of buses or networks [29]. Modbus protocol can use a variety of modes for communication as a transport layer, including serial communication lines and Ethernet. The Modbus Serial protocol is a master-slave protocol that includes one master node that issues explicit commands to slave nodes and processes responses. Slave nodes do not typically transmit data without request from the master node, and do not communicate with other slaves. At the physical level, Modbus Serial can use different interfaces such as RS-485 and RS-232 cables. An adaptation of the Modbus protocol, Modbus TCP/IP, can be communicated over Ethernet, allowing for more reliable and efficient data exchange compared to traditional serial communication. Overall, Modbus is a popular method of communication in industrial environments. because of its simplicity, ease of deployment, and minimal restrictions on data format. It is commonly used in SCADA systems to connect supervisory computers with remote terminal units and other devices [30].

4.2 Common machine controllers in SLB manufacturing

The majority of SLB’s manufacturing facilities date back to the mid-20th century and were managed by various companies before being acquired by SLB, making a wide array of products. As a result, the facilities have evolved independently over time and now operate machines from different generations and different manufacturers, both within individual facilities and across the company. However, all machines across the company can be categorized as: 1) having network capabilities, including modern PLCs and commercial off-the-shelf CNC machines with built-in/add-on communication port/card and drivers, and 2) lacking network capabilities, including legacy PLCs and CNC machines with no communication interface. Combining machine data from multiple manufacturing centers across SLB, this section lists the most common types of machine controllers found company-wide.

4.2.1 CNC controllers

A computerized numerical control (CNC) machine is an automated machining system operated by a computer. It utilizes integrated software to execute pre-programmed sequences of control commands. In the process, it replaces traditional machines that were manually controlled by levers, handwheels, or cam systems.

Modern CNC machines rely on a programming language called G-code, directing the cutting tool to achieve precise measurements, including tool location, feed rate, and spindle speed. This allows CNC machines to perform various machining tasks with greater accuracy, increased productivity, and reduced production waste [31]. CNC machines can also be controlled through direct numerical control (DNC), which allows operators to send G-code line by line or by file directly to machines instead of via USB drive, allowing for quick edits and version control. The vast majority of CNC machines used across SLB are for machining operations, and include mills, lathes, and electric discharge machining (EDM) machines.

4.2.1.1 Mazak

Mazak is a Japanese company that produces industrial metal cutting machine tools [32]. Mazak CNC machines are commonly found in completions centers such as CHPC, and most cases use MAZATROL controllers. It is highly recommended to communicate with Mazak controllers using MTConnect protocol, due to adapter and agent availability at many CNC machine tool manufacturers. All new Mazak CNC machines are MTConnect compliant, meaning that the MTConnect protocol and agent are either pre-installed on the machine controller or can be obtained from the Mazak parts department.

4.2.1.2 FANUC

FANUC is a Japanese company providing automation products and services including robotics and CNC systems [33]. FANUC controllers output data in FOCAS protocol using either Ethernet or HSSB. However, they can also be made to output data via MTConnect or an OPC-UA protocol, making them highly flexible with various connectivity software.

4.2.2 PLC controllers

A programmable logic control (PLC) is an electronic computing device deployed to manage the operation of a machine. PLCs use ladder logic programming language, empowering engineers to construct virtual circuits for controlling electromechanical systems. Renowned for their rugged design, PLCs withstand harsh industrial environments and demanding applications.

Their real-time capabilities allow rapid scanning of inputs and execution of programming. Additionally, PLCs establish input/output (I/O) connections, facilitating data exchange with connected equipment and enabling precise output instructions [34].

4.2.2.1 Allen Bradley

Allen Bradley is among the most popular PLC brands in North America and widely found in manufacturing centers across the US. They provide PLCs ranging from small applications (e.g. MicroLogix) to very large-scale applications (e.g. ControlLogix). Older Allen Bradley PLCs use fieldbus solutions such as DeviceNet and ControlNet, whereas new ones use Ethernet. Regardless, they are easily connectable to an OPC server to send data through an OPC-UA protocol.

4.2.2.2 Siemens

Siemens is another popular PLC controller and commonly found in SLB manufacturing centers. Siemens has a diverse lineup of controllers that are renowned for fast execution times and reliability of safety circuits. They are also easily connected to an OPC-UA through Ethernet.

4.2.2.3 Omron

Omron PLCs can be found in SLB manufacturing centers in two types: 1) older models (CJ2) that use user datagram protocol (UDP), and 2) newer models (NJ/NX). Using older models is not recommended with new machines because they require the use of UDP to connect to an OPC server, requiring management of a separate UDP network. On the other hand, newer models are able to connect to an OPC server through Ethernet.

4.3 Machine connectivity ecosystem solutions on the market

Before implementing machine connectivity at a facility, it is important to examine connectivity solutions on the market in order to ensure that the best one for that facility is selected. This section discusses existing connectivity solutions in use at various SLB sites and on the market and the types of shop floors they are best fit for.

4.3.1 Ignition

Ignition by Inductive Automation is a comprehensive software system designed for industrial organizations. It provides a comprehensive suite of tools for creating, managing, and deploying industrial applications such as SCADA systems, and offers seamless integration with a range of manufacturing technologies, such as machines with various communication protocols, SQL databases, and ERP systems. The platform is recognized for its ability to bridge the gap between different technologies, facilitating a cohesive manufacturing environment.

Ignition has several features that make it an extremely customizable and flexible platform. It runs on a web-based architecture, so it is capable of running on any operating system. Ignition is a modular platform, with available modules including connectivity protocols (e.g. OPC-UA, MQTT, and Modbus) along with advanced functionalities such as alarm reporting, machine learning integration, and recipe management. This allows for a custom-fit solution for any industrial application. The platform is also able to provide real-time data visualization and controls, offering a variety of components for creating dynamic user interfaces that display live data, trends, and analytics.

4.3.1.1 Kepware integration

PTC Kepware is a portfolio of industrial connectivity solutions providing access to data from virtually any sensor, device, or machine. It enables the secure sharing of data among various IT and OT systems through a scalable and unified architecture that allows for the combination of drivers and consumption of multiple protocols in a single server. This facilitates a streamlined interface for remote visualization and connectivity configuration at scale.

Kepware utilizes a client-server architecture. As a server, KEPServerEX connects to more than 150 different drivers (e.g. various types of PLCs, sensors, databases), and on the client side, it connects to various applications. These applications are typically in the upper levels of the ISA-95 model such as SCADA, MES, and ERP systems, custom-built applications, and enterprise databases. The server offers many advanced plugins and drivers for network management. It also supports legacy systems with OPC-UA.

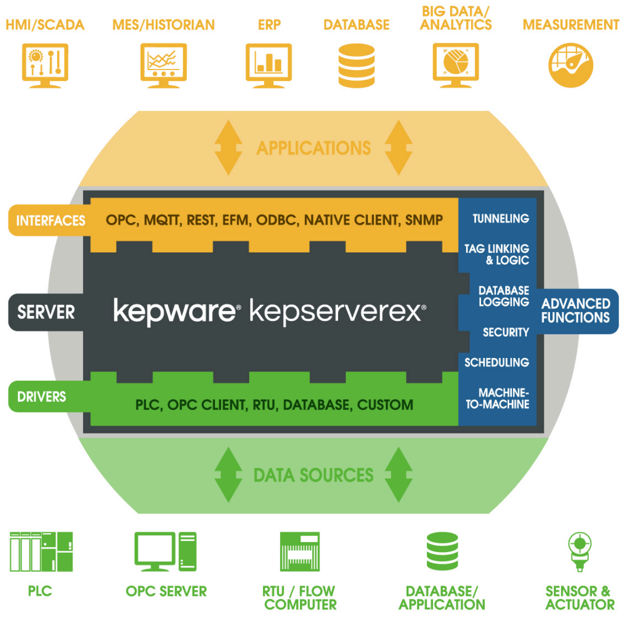

Figure 4.4: Kepware building blocks

This diagram shows how KEPServerEX fits in when connecting various data sources (e.g. PLCs, sensors) with applications such as SCADA systems. [35]

Although machines are able to connect to SCADA systems such as Ignition directly, there are multiple advantages of Kepware. These include:

1) Security: Connecting a single machine to a SCADA directly opens a port of the industrial network. When there is a large number of machines, connecting each machine individually creates greater exposure. Having Kepware as a middleware mitigates this risk by connecting all incoming machines and exposing the data to only one port, reducing the number of failure points in the industrial network.
2) Encryption: Kepware offers different levels of encryptions for machine data. For example, individual tags can be set to "read only" to prevent accidental writing of data to PLCs or machine tags.
3) User management: Kepware is able to integrate with lightweight direct access protocol (LDAP) or Active Directory to grant administrator access to server configuration for authorized users. It is also possible to give users a range of permissions (e.g. read-only access).

4) Enterprise level connectivity: With Kepware being available at each manufacturing center, it is possible to have one standard access point to machine data at the organizational level.

4.3.2 CIMCO suite

CIMCO is a Denmark-based company that develops software solutions for computer-integrated manufacturing. Their software package includes software for CNC editing, simulation, DNC communications, machine data collection, and production data management [36]. This section describes the network architecture of the CIMCO ecosystem, details the various software it offers, and evaluates the kinds of facilities and machines it works best with.

4.3.2.1 Network architecture

CIMCO software is an on-premise solution able to run on a virtual machine. This means that the network architecture is entirely contained within the shop floor, without the need for external connections to the cloud. The CIMCO network ecosystem runs on a server/client architecture. The core of the ecosystem is the DNC-Max server, responsible for managing communication with machine tools and serving as the central hub for collecting messages from various clients. Various software clients and machines are connected to the server. The DNC-Max server is linked to the CIMCO Database Server (also known as the NC-Base Server), which runs in the background as a Windows service. Its primary function is to manage one or multiple SQL databases and to store, process, and retrieve data from these databases. The database itself can be local to the shop or in a different location, but the server will run on the virtual machine with all other software. This is linked to a “software manager” - a CIMCO network license server carrying a company’s license for the software package.

To establish the CIMCO ecosystem, DNC-Max software is installed as a server on a virtual machine within the company environment. If a company has multiple sites, it is preferred to install one server per site to reduce latency in information transfer. The server is able to support up to 4,000 simultaneous ports of various communication protocols via Ethernet and/or RS-232, eliminating the need for multiple servers. Thus, the system is compatible with various types of CNC controllers and PLCs. The DNC-Max server is then connected to various machine controllers and clients, including the DNC-Max client, MDC-Max, and web clients to display information. The file management system client, either NC-Base or MDM, links to the CIMCO Database Server to facilitate user interaction with the file directory.

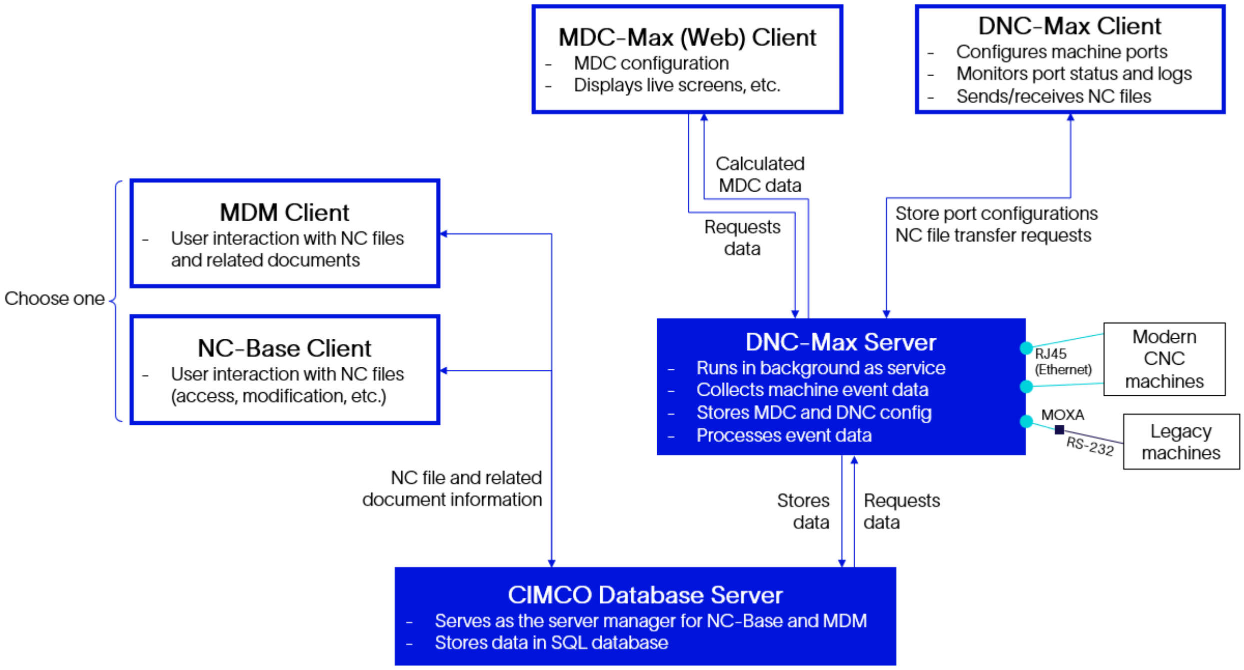

Figure 4.5: CIMCO product suite network architecture diagram

This diagram outlines the relationships between the various servers and clients offered in the CIMCO product suite. The CIMCO Database Server serves as the foundation for the entire ecosystem and is required.

4.3.2.2 DNC-Max

DNC-Max is CIMCO's software solution for CNC communication, handling all NC program file transfer, monitoring, and system administration. DNC-Max enables program management at the CNC controller level or through a web client using an edge device. Controllers equipped with Ethernet capabilities can directly browse, select, and download programs to local storage from the server. Additionally, DNC-Max provides version and revision control, allowing users to track edits made by operators and programmers and revert to previous versions when needed.

The package is a client-server solution consisting of a DNC-Max server and a DNC-Max client (or web client). The server runs as an application or a background service on the virtual machine, and handles all communication with machine tools and is the central data collection source for various client messages, including the DNC-Max client. The server is connected to the CIMCO database server, where it will store all messages and calculated data. The DNC-Max client allows for the configuration of machine ports, monitors port status and logs, and sends and receives NC files.

The DNC-Max server is compatible with various types of machines through serial or Ethernet. The majority of newer machines (PLC or CNC controllers) are able to be connected through an Ethernet RJ45 connector and usually do not require any additional hardware. The server is able to accept various common communication protocols, including MTConnect, Fanuc FOCAS, and OPC-UA. Older machines that do not have a data interface require the hardware signals to be wired from the machine's PLC relays using a serial cable such as an RS-232 cable. To connect to the server, a MOXA serial-to-Ethernet device (e.g. MOXA NPort 5110) is used to connect to the LAN via Ethernet.

4.3.2.3 NC-Base

NC-Base is the CIMCO program management tool that allows for the organization and management of CNC programs and related production documents through the use of a reliable and fast SQL relational database, either MariaDB or MySQL. NC-Base consists of two applications: NC-Base Server (no user interface, runs in the background as a service) and NC-Base Client (NC-Base Explorer). The server's primary function is data storage and processing (e.g. search for specific programs). The client serves as the user interface for the service provided by the server, allowing for inputting search criteria, displaying results, executing programs, and providing options for modifying program data.

NC-Base allows the user to organize and manage NC files with related documents, including simple tool lists, sets of sheets, and photos associated with particular programs. However, the related documents do not have version control as they do in MDM, as discussed further in section 4.3.2.5. NC-Base does provide the ability to backup or restore NC files.

4.3.2.4 MDC-Max

MDC-Max is a CIMCO software solution for real-time manufacturing data collection and machine monitoring. It enables automatic data collection from both machines and operators, providing live and historic insights into shop floor productivity, performance, and quality. Data can be used for a variety of purposes such as real-time monitoring with Andon boards, planning and analysis, or export to ERP, MES, or other systems. When events occur (such as a machine starting or stopping), MDC-Max generates messages and stores them in its database. The MDC-Max client is used to configure the MDC system and display timelines, live screens, operator screens, reports and so forth. The configuration is stored in the DNC-Max server.

Data collected from machines can be analyzed through MDC-Max to obtain calculations including OEE (overall equipment effectiveness), time tracking (e.g. cycle time, setup time, downtime) and scrap rates. The data can also be analyzed for predictive maintenance purposes (e.g. tool wear). In addition, the software provides data visualization features, including time-series charts and tables, which users can utilize for further analysis. It is important to note that the software does not have direct machine control capabilities.

4.3.2.5 MDM

MDM is CIMCO's manufacturing document management system and supersedes NC-Base. The software manages, controls, and archives production documentation, including CAD, CAM, and NC files. MDM enables users to monitor document changes, implement paperless manufacturing, and centralize production-related files. It incorporates automated file handling, simplifying the categorization of new additions without manual input. Additionally, it supports version control for not only NC files, but all related documents, allowing for greater control over NC-Base. Similar to NC-Base, MDM runs on a client-server architecture. It is important to note that NC-Base and MDM use the same CIMCO Database Server for data storage and processing. However, when a company selects to use the CIMCO product suite, they choose one of MDM or NC-Base; they cannot use both.

MDM operates alongside CIMCO DNC-Max, supporting a variety of controllers including Mazak MAZATROL, FANUC, and Heidenhain CNC controllers, and can utilize either a CIMCO or MSSQL database for flexible data storage. Additionally, web clients can be integrated for handling requests via hypertext transfer protocol (HTTP).

4.3.2.6 Edit

CIMCO Edit is a CNC program editing, simulation, and communication tool that allows a user to work with NC programs from a computer in a Windows-based application. Edit features include NC-specific functions, math, transforms, drag/drop editing, file comparison, mill/turn simulation, and tool management. Edit integrates well with NC-Base and MDM, but can be run in isolation should a shop choose to utilize another file management system.

4.3.2.7 CIMCO suite summary

Based on CIMCO's product offerings and their capabilities, the CIMCO product suite is best suited for shop floors focused on CNC operations. Its built-in capabilities, including NC program simulation, DNC communication, and manufacturing data management, allow it to work well with CNC environments with various types of CNC machines. In addition, its MDC-Max software allows for real-time data collection and machine monitoring for both CNC and PLC machines. However, the lack of direct machine control for PLC machines might necessitate looking for a more low-level SCADA system, depending on the use case for the connectivity ecosystem.

4.3.3 FANUC MT-Link*i*

MT-Link*i* is an operational management software developed by FANUC, designed to connect and manage machines in a factory setting through Ethernet. It is able to collect, manage, and visualize various types of information from machines. The software is best suited for FANUC CNC controllers and robots, which it can communicate with via FOCAS and Robot Interface, respectively. However, it is also able to monitor and collect data from third-party machines via other protocols including OPC-UA and MTConnect. It can also connect to machines without Ethernet via an Ethernet I/O connector.

MT-Link*i* has an architecture that can scale with a shop floor's needs. Data collection is done by specialized collector PC software, while storage and management of the data are handled by server PC software. This server also provides a web interface for accessing and visualizing data, which is available to any network-connected PC or tablet via a web browser. In setups with a limited number of devices, both the collector and server software can operate on a single conventional PC. A single MT-Link*i* server can manage up to 100 devices efficiently. For expansive systems exceeding 100 devices, the MT-Link*i* Integration Server can be employed to accumulate the production data [37].

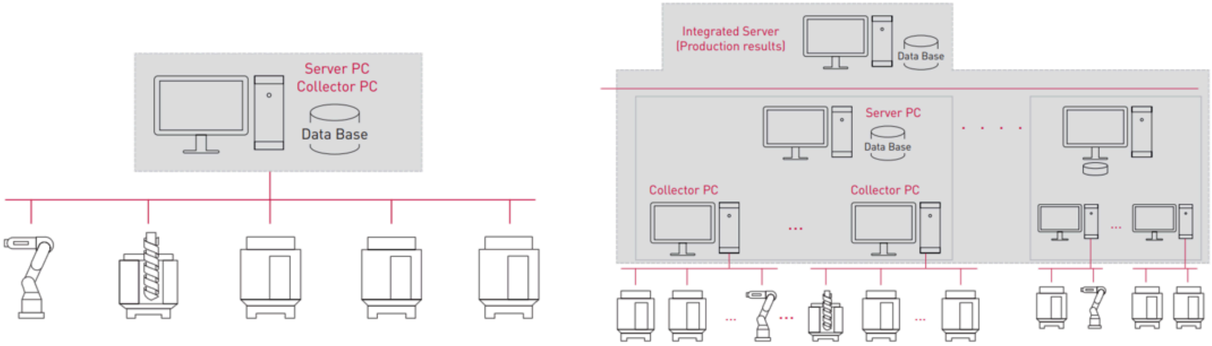

Figure 4.6: MT-Link*i* Network Architecture

The left diagram shows the network architecture for smaller systems with few devices. The right diagram shows that for larger systems with over 100 devices. Larger systems require multiple server and collector PCs that integrate with the MT-Linki Integration Server. [37]

MT-Link*i* is a web-based software product meaning it can work on any device, and has comprehensive functionalities to monitor shop floor status, results, and diagnoses. These features include shop floor overlook (seen in figure 4.6) to view the statuses of all machines at once, alarm monitoring, signal monitoring for signals such as feed rates, spindle loads, etc., operational and production results, and histories for alarms, programs, and signals. It is also able to perform NC file transfer between CNC machines and the server PC, allowing for efficient management of NC programs with backup capabilities [37]. It is important to note that the software can only transfer entire files at once; it cannot do line-by-line DNC control like some other softwares. Thus, depending on machine memory capabilities and the size of NC files at the site, an additional DNC solution might be needed.

There are messages (Number of messages: 2).

Auto layout feed: OFF

Machine_Shop

DISCONNECT	1	20.00%
ALARM	0	0.00%
EMERGENCY	0	0.00%
SUSPEND	0	0.00%
STOP	1	20.00%
MANUAL	1	20.00%
WARMUP	0	0.00%
ALL (UNITS)	5	100.00%

Figure 4.7: MT-Link*i* Overview screen

The Overview screen allows for a high-level view of the statuses of all machines on the shop floor.

4.3.4 Predator DNC

Predator DNC is a comprehensive software solution designed to streamline and enhance the connectivity and management of CNC machines and other manufacturing equipment. The system proves an industrial networking solution that allows for the seamless transfer of CNC programs, variables, offsets, parameters, and other production data between manufacturing equipment and the network. It supports drip-feeding (line-by-line feeding of NC programs), downloading, and uploading of files, ensuring efficient and reliable communication with CNC machines.

Predator DNC boasts a wide range of features designed to enhance manufacturing efficiency. It supports over 50 industrial communication protocols, including RS-232, RS-422, Ethernet, and wireless Ethernet, and handles various file formats such as ISO, conversational, and binary. The software integrates seamlessly with ERP, MES, and PLM systems, and supports remote requests via RFID chips, bar codes, or QR codes. Customization is possible through

VBScripting, JScripting, and DLL plugins, and it can run as a Windows Service for headless operation. The software also includes a CNC editor for intelligent editing, 3D backplotting, and animation. In terms of compatibility, Predator DNC works with a wide array of equipment, including CNC machines, robots, CMMs, PLCs, 3D printers, laser markers, dot peen markers, tool presetters, and test stands. It supports both Windows Server and client operating systems, and is compatible with virtual environments such as VMWare. Additionally, it supports both wired and wireless Ethernet connections, ensuring flexible and reliable networking options [38].

4.4 Miscellaneous connectivity hardware

In most cases, the equipment needed to connect machines is straightforward. Post-2000 CNC controllers generally offer ethernet IP and serial ports, necessitating the use of readily-available RJ45 and RS-232 cables, respectively. Similarly, ethernet cables can be used to connect shop-floor edge devices. The cables from both the machines and edge computers can be directed to a network switch, facilitating the interlinking and data exchange among various sources. However, various considerations may need to be made depending on the security requirements of particular facilities, or for older legacy machines without the appropriate ports. This section overviews miscellaneous connection hardware that can be used to facilitate connectivity with older machines and/or help achieve cybersecurity standard compliance.

4.4.1 MOXA devices

Moxa is a provider of industrial automation technology to help manufacturing shop floors achieve machine connectivity and achieve Industry 4.0 goals. They have multiple devices that help connect older legacy machines along with providing additional security in the connectivity implementation. Their NPort device servers help make serial devices network-ready by connecting older legacy machines using serial ports to an IP-based Ethernet LAN. Specifically, the NPort 5100 series helps provide PC software direct access to serial devices. This is done by connecting to older legacy machines using various serial protocols (RS-232, RS-422, and RS-485) and to servers or networks through Ethernet IP. In addition, NPort devices can operate in various modes to ensure compatibility with different network setups. Once configured, the device servers convert serial data into TCP IP packets and vice versa, allowing for communication between the serial device and networked system. The devices can be managed and monitored over the network for network management or through alerts and email notifications for troubleshooting [39].

In addition to the NPort series, Moxa also provides the NAT-102 device, a specialized industrial NAT device crafted to streamline the IP setup process for machinery within the existing network frameworks of factory automation settings. Equipped with dual ethernet RJ45 ports, the NAT-102 facilitates network partitioning, enabling one port to link with external networks (like the internet or different subnets) and the other to interface with internal equipment. This segregation bolsters security by barring direct contact with critical devices. Offering full NAT capabilities, it allows for the adaptation of machinery to distinct network environments minus the intricacy of elaborate setups. Moreover, the device safeguards internal networks against unsanctioned external ingress, a key factor in adhering to SLB cybersecurity standards [3].

Chapter 5 Connectivity assessments and roadmaps

In order to provide informed recommendations for implementing machine connectivity at each manufacturing facility, it is essential to analyze specific details related to machine connectivity. This analysis should encompass factors such as the list of machines, efforts made towards connectivity implementation, and the readiness of the network. This chapter provides a method towards assessing the state of connectivity at a manufacturing facility, then applies this method to each SLB Houston-area technology center focused on in this thesis.

5.1 Rubric for facility machine connectivity

A standardized method for evaluating the current status of machine connectivity at a facility is important to identify next steps for that facility and determine its priority within other facilities. A machine connectivity rubric is developed to evaluate and compare connectivity statuses across different facilities. The rubric provides an efficient method for assessing connectivity, while also identifying certain facets of connectivity that a facility needs to work on. It can be used both for existing facilities that are in the process of implementing machine connectivity and for new facilities seeking a structured framework and prioritization strategy for the adoption of connectivity.

To create the rubric, six evaluation criteria were determined to obtain a full understanding of machine connectivity status. For each criterion, there are five possible scores ranging from 0 (no progress/not applicable) to 4 (fully complete). Each criterion is assigned a weight reflecting its importance and impact on the overall assessment. The weights are based on factors including ease of completion and the time and logistics required for fulfillment. The criteria and weights are further detailed in table 5.1. It is important to note that the determined time frames are theoretical, and only somewhat account for administrative delays inherent to large organizations. Once all the criteria are scored, each score is normalized by the maximum possible score (4) and multiplied by its respective weight. The weighted scores are then summed to obtain a total connectivity score out of 100, representing the percentage of connectivity achieved. The full rubric is shown in table 5.2, showing the evaluation criteria and explanations for each score.

Table 5.1: Connectivity rubric criteria descriptions

This table contains a list of the six criteria (column a) and descriptions (column b) used to evaluate the machine connectivity status at each manufacturing facility. The weights used in evaluating the total score and theoretical time frame needed for completion are listed in columns c and d, respectively.

(a) Criteria	(b) Brief Description	(c) Weight	(d) Time Frame
Resources available	Describes availability of staff and budget to dedicate towards connectivity implementation. Assesses whether a dedicated full-time automation team is in place at the facility and if there is a budget allocated towards machine connectivity.	25%	Months
Hardware	Indicator of whether the machine list to be connected has been fully defined and if all the hardware (including servers, wires, and adapters) necessary to connect the machines has been identified and procured.	20%	Weeks to months
Software	Indicator of whether a connectivity software ecosystem solution (e.g. MTLink*i*, Ignition) has been researched, identified, and procured. Also indicates if software has been implemented on appropriate devices, and whether operators and engineers are trained to use it.	15%	Weeks to months
Cybersecurity	Assesses whether the planned connectivity solution fully meets SLB IT security standards and qualification processes (SAQP and IACS), or whether there is a plan for ensuring compliance.	15%	Weeks to months
Connectivity level	Estimates proportion of machines at a facility that have been connected and fully integrated into the ecosystem and network. Places emphasis on high-priority machines (e.g. CNCs, bottlenecks). Assesses accessibility of machine data.	12.5%	Days to weeks
Usage level	Evaluates whether the facility has the connectivity solution it has implemented to its full extent, including analysis of machine data and use of DNC capabilities, and whether connectivity solution has had identifiable impacts on operations.	12.5%	Days to weeks

Table 5.2: Rubric used for facility machine connectivity assessment

This rubric was used to evaluate the status of machine connectivity across multiple SLB technology centers. Each of the criteria are scored within a range of 0 (no progress/not applicable) to 4 (fully complete). The justification for each score for a criterion is written in the corresponding cell.

Criteria *Weight*	**4 - Fully complete**	**3 - Near completion**	**2 - In progress**	**1 - Preliminary steps**	**0 - No progress/not applicable**
Resources available *25%*	Fully staffed automation team working on implementing and maintaining a machine connectivity solution. Regular budget allocated towards machine connectivity implementation and maintenance.	Full-time automation team being assembled to research, implement and maintain a machine connectivity solution. Some budget is allocated towards connectivity.	Managers and other stakeholders are on board with machine connectivity, looking into resource allocations.	Managers and other stakeholders informed about the potential of connectivity, looking into the benefits and determining it will work for the facility.	Managers and other stakeholders are not concerned with connectivity, do not see value in implementing it at their facility.
Hardware *20%*	All hardware (e.g. servers, wires, adapters) necessary to connect most machines has been procured and available.	Machine list fully defined, necessary hardware has been selected and is in the process of being procured.	Machine list is being defined, investigating necessary hardware to connect machines and exploring availability.	Machine list and priorities are beginning to be identified. Hardware requirements not yet defined.	No information on machine lists/priorities. No hardware requirements have been identified.
Software *15%*	Connectivity ecosystem has been acquired and is in place. Connected/ready to be connected to machines. Staff are fully trained on using it.	Connectivity ecosystem has been selected and licenses acquired, but needs to be implemented. Staff needs some additional training. Not ready to be connected.	Connectivity ecosystem selection is (nearly) finalized, inquiring about license availability/pricing from vendor.	Preliminary research into connectivity ecosystems being done.	No exploration of connectivity ecosystems.

TABLE 5.2 CONTINUED ON NEXT PAGE

TABLE 5.2 CONTINUED

Cybersecurity *15%*	Security measures have been fully implemented. SLB IT security standards are fully met. All security qualification processes and standards (e.g. SAQP) have been complied with.	(Planned) measures nearly meet IT security standards, some adjustments are needed. Current solution is SAQP compliant, some other (new) standards such as ones from IACS have not been complied with yet.	Plans for cybersecurity measures are complete and need to be qualified by IT. Current solution was previously compliant but now needs changing, potentially preventing connectivity.	Plans for cybersecurity measures in progress, IT has been informed of connectivity plans. Current solution is SAQP non-compliant.	No cybersecurity measures being considered. Current solution non-compliant with IT standards.
Connectivity level *12.5%*	All connectable machines have been connected and fully integrated into the ecosystem. Machine data is readily accessible remotely.	High-priority machines (e.g. CNCs, bottlenecks) have been connected and integrated into the ecosystem. Machine data is accessible for most machines.	High-priority machines are in the process of being connected. Connectivity plan and timeline is in place for the facility. Little to no machine data has been accessed yet.	Little to no machines being connected, but a plan is in progress for the facility. Data cannot be accessed.	No machines are connected, machines are not ready/do not have hardware/software necessary, no plan in place for implementing a solution.
Usage level *12.5%*	Connectivity ecosystem functionality is being fully utilized. Important data is being collected and fully utilized to gain important insight and improve operations. DNC (if applicable) is being used to its maximum extent.	Connectivity ecosystem functionality is being utilized. Data is being collected with analysis having some impact on operations. DNC (if applicable) being used irregularly.	Connectivity ecosystem is connected to the machines. Raw data is being collected, little analysis, no clear impact on operations. DNC (if applicable) capabilities not being used.	Some machines are connected, but no data has been accessed or recorded. No clear use case has been established. DNC not being used.	Machines are not connected. No data can be collected.

5.2 Connectivity assessment case study

Although it is simple for engineers at a facility to self-evaluate the status of machine connectivity at their site, this approach doesn't leverage the expertise of engineers at other facilities who might have a better understanding of full connectivity. Thus, it is important to have broader insight when using the rubric to assess connectivity. To conduct a comprehensive assessment of connectivity at a facility, the author organized a workshop at the Katy Technology Center (KTC) and assembled automation team members from multiple sites that are more mature in the connectivity process (HCS and SCMF). KTC was selected to host the workshop because it is relatively developed in connectivity implementation compared to other sites focused on in this thesis. The site has no mechanisms for machine data collection and has limited resources dedicated towards connecting machines. The workshop helped identify the benefits the site can realize through machine connectivity and develop a plan of action for implementation.

5.2.1 KTC workshop agenda

The workshop was organized with the following objectives: 1) gain a better understanding of machines types and the status of machine connectivity at KTC, 2) showcase successful implementations of connectivity at other SLB facilities to managers at the site, and 3) leverage the expertise of automation teams from other SLB facilities to brainstorm and plan a connectivity roadmap at KTC. With these goals in mind, the workshop followed an agenda closely tied to achieving those goals.

The workshop began with presentations by the HCS and SCMF automation teams, showcasing their connectivity implementations at their respective facilities. The aim was to demonstrate the value of machine connectivity to KTC managers and share various connectivity approaches used across SLB centers within the automation community. These presentations sparked a collaborative discussion on KTC's connectivity needs and potential benefits from machine connectivity. The discussion also covered encountered obstacles, effective strategies, unsuccessful attempts, and cybersecurity considerations.

Following the presentations and discussions, Mr. Sean Filipow, quality manager at KTC, led a tour of the facility. The tour enabled the group to better understand the facility's product line, operations, and their current approach to connectivity. Specifically, the machines on the shop floor were noted, as they are important factors in determining the hardware and software necessary to implement connectivity. Additionally, the tour allowed the group to determine machines that were most in need for connectivity by identifying bottleneck machines and opportunities for capacity improvement. The workshop wrapped up with the development of a high-level strategic plan for KTC, including creating a business case for connectivity, employing a full-time automation team for implementation, designing network architecture to meet cybersecurity standards, and coordinating logistics.

5.2.2 KTC workshop summary

Overall, the workshop facilitated the sharing of valuable information between teams from various sites and helped orchestrate a strategic plan of action for KTC. The automation teams from HCS and SCMF showcased their connectivity implementations and the diverse applications they have utilized connectivity for, including process monitoring, data visualization, recipe management and quality reports. The connectivity implementations and network architectures at HCS and SCMF are detailed in sections 5.3.4 and 5.3.5, respectively.

The presentations led to an open conversation about KTC's potential applications for connectivity and current obstacles to implementation. The chief use cases for connectivity at KTC were identified to be 1) downtime management, 2) recipe management, and 3) DNC capability for CNC machines. Downtime management helps identify and reduce unscheduled downtime on machines. Minimizing downtime increases machine capacity, which can allow for increased throughput at bottleneck machines, and thus revenue. Additionally, higher capacity allows for in-house production of parts typically purchased from third-party vendors at premium prices, potentially leading to cost savings. Recipe management was determined to be helpful for multiple processes at the facility, particularly for painting stators and injecting and curing elastomers. These processes involve various parameters that frequently change based on customer specifications. Recording these parameters is essential for traceability and maintaining product quality. DNC capability is important because it allows for seamless transfer and management of data and NC files between computers and machines, and can enhance operational efficiency through better communication and coordination. It is worth noting that KTC has the infrastructure for an implementation of CIMCO DNC for their CNC machines. However, it is currently inoperative due to software incompatibilities, and they are looking to fix this issue.

The KTC team identified several obstacles that could delay the implementation of connectivity. The fundamental challenge is allocating resources and the amount of time, personnel, and funds needed to plan and execute machine connectivity. Although the need for, use cases, and benefits of connectivity are clear, a business case needs to be made in order to justify the high cost of planning and executing such a project. Firstly, KTC currently does not have personnel with the skills and expertise needed to initiate machine connectivity. Thus, the center would need to allocate funds and space to hire new employees with the appropriate skills and experience. Secondly, implementing connectivity at the site is capital intensive and requires large investments in both software licenses for ecosystems like Ignition and hardware for servers, network switches, and adapters. Some of KTC's bottleneck machines, such as their DESMA injection molding machines for elastomers, are quite old and fully depreciated. If these machines require substantial upgrades to their controllers to become connectivity-ready, the justification for connecting them will depend on the benefits that connectivity would provide.

To determine whether connecting some machines is justifiable, a detailed cost-benefit analysis needs to be conducted in order to determine the value that connecting each machine brings. Parameters to analyze include throughput, efficiency, downtime, scrap rate, upgrade costs, and lifespan. A temporary solution is being developed by manufacturing engineers at the site to quantify the value of recording downtime. The solution uses Andon lights controlled by electrical signals provided by the machines. The lights change color based on the machine's status: green indicates the machine is running, while red indicates it has stopped. IoT devices detect the color of the Andon lights and transmit data about the machine status to a central platform. This platform provides operators, engineers, and managers with a live overview of the shop floor, displaying the current status of each machine. Tracking machine status in real time can significantly help mitigate downtime, leading to increased capacity, higher throughput, and ultimately, greater revenue. While this solution may not fully align with current Industry 4.0 standards, it does offer valuable empirical data on the benefits of machine connectivity, particularly in reducing downtime.

The team was then able to determine which machines needed to be prioritized for connectivity with the tour of the shop floor. Several groups of machines were identified to be in need of connectivity: 1) the Weingärtner Vario CNC machines used for milling and turning rotors and stator cores, 2) CNC mill-turn machines that included two Mazak Integrex machines and a

DMG Mori Seiki machine used for other items including stators and bearings, 3) the DESMA injection molding machines for elastomer production, and 4) the new automated elastomer curing systems. The reasons for prioritizing these machines for connectivity vary, but they all offer significant opportunities for increased revenue and cost savings once connected.

Connecting the CNC machines is crucial for tracking and mitigating downtime, increasing capacity, and implementing DNC functionality. The Weingärtner machines, in particular, are the main bottleneck in rotor production. Enhancing their capacity would boost throughput and, consequently, revenue. One way to reduce downtime on the Weingärtner machines is by implementing automated quality checks. Currently, rotor diameters need to be manually checked at regular intervals, which involves opening and closing the machines and manually measuring the diameters. By automating these diameter measurements and adjusting parameters accordingly, significant time can be saved, enhancing overall efficiency. Conversely, while the Mazak and Mori Seiki machines are not bottlenecks, increasing their capacity could enable in-house production of parts typically purchased from third-party vendors at premium prices, resulting in potential cost savings.

On the other hand, the DESMA and elastomer curing machines would benefit from connectivity through recipe management. Given the center’s production of various types and shapes of elastomers, it’s crucial to monitor the parameters used for each to maintain product quality and minimize scrap rates. Automated recipe management provides numerous benefits, such as: 1) ensuring machines consistently operate with precise settings, 2) reducing setup time, 3) minimizing the likelihood of human error, 4) offering centralized control for storing and managing machine settings, and 5) providing traceability through documentation and tracking changes. These benefits can help the center realize increased throughput and efficiency from these machines.

In summary, the workshop was instrumental in gathering insights from the SLB manufacturing community, identifying opportunities and obstacles in connectivity implementation, and developing actionable steps towards achieving KTC’s connectivity goals. The event paved the way for future collaboration between KTC and the automation teams at HCS and SCMF, facilitating the advancement of connectivity plans. Additionally, it helped create a strategic roadmap for implementing connectivity not only at KTC but also at other sites.

5.2.3 KTC connectivity assessment and roadmap

Following the conclusion of the workshop, the author used the rubric developed in section 5.1 to score connectivity at KTC and compare its maturity to other SLB sites. The site received a score of 19%, indicating relative immaturity in connectivity implementation. Currently, the site does not have adequate resources in terms of personnel to plan or execute a connectivity solution. A business case must be presented to management to justify hiring an automation team and investing in connectivity equipment. Due to the shortage of resources, progress on the remaining criteria is minimal, as personnel with connectivity expertise are required to complete these tasks. However, the workshop successfully completed preliminary steps for some of these criteria. A full scoring summary for KTC is provided in Table 5.3.

Due to the site's underdeveloped connectivity, the current actionable items include a combination of high-level strategic tasks and low-level technical tasks. At a higher level, stakeholders—specifically manufacturing engineers and managers present at the workshop, including Mr. Filipow and Mr. Nathan Fuller—should develop a proposal for machine connectivity implementation at KTC to present to site management. This proposal should explain the current manufacturing problems caused by inadequate connectivity, such as inefficiencies and delays, and how these challenges impact operations and productivity. This leads into a discussion of the justification for the investment needed, and explaining how connectivity can enhance productivity, and thus profitability. A detailed cost-benefit analysis should be done on implementing connectivity on high-priority machines, which were identified during the workshop. Additionally, the proposal can highlight the results of the ongoing experiment using Andon lights to track machine status. Positive results from this experiment can further support the business case for investing time and resources into connectivity for the entire center.

The goal of the proposal is to make a business case for 1) hiring engineer(s) with the required skills and expertise, specifically tasked with planning and executing a connectivity infrastructure at KTC, and 2) securing funding to upgrade existing hardware, procure additional hardware as needed, and acquire necessary software licenses. Once these goals are achieved, the hired engineer(s) will take charge of the connectivity implementation project and perform the technical tasks needed to implement connectivity. Initial tasks involve researching and identifying the necessary hardware to connect high-priority machines, such as USB to RS-232 adapters, Ethernet cables, and specialized connectors, and assessing whether any machines require significant upgrades, like installing new network cards or retrofitting older equipment with modern connectivity modules. Additionally, engineers need to evaluate and determine the most suitable connectivity ecosystem for the site. This evaluation should consider factors such as cost, including both initial investment and ongoing maintenance; use cases, such as real-time monitoring, data collection, and remote control; and compatibility with existing infrastructure and systems. The chosen connectivity solution can be pilot tested before full-scale deployment by using trial licenses and acquiring hardware for a limited number of machines. Lastly, the current network architecture at the site needs to be outlined in order to identify cybersecurity threats. Once identified, the infrastructure can be revised in conjunction with IT in order to mitigate risks and ensure compliance with cybersecurity standards.

Table 5.3: KTC connectivity assessment scoring breakdown

(a) Criteria	**(b) Score**	**(c) Score Explanation**	**(d) Weighted Score**
Resources available	1	Some managers are informed of the potential and benefits of connectivity, but no resources are currently allocated towards implementation, both in terms of personnel and money. A business case needs to be made to upper management to justify investing resources.	6.25%
Hardware	1.5	Machines to be prioritized in connectivity have been defined. Most of these machines require some additional hardware or controller upgrades; these will need to be investigated and procured by an on-site automation team.	7.5%
Software	1	Preliminary software investigation done from the workshop; possibilities of Ignition, CIMCO, and MT-Link*i* explored. No progress made on investigating licenses.	3.75%
Cyber-security	0	No cybersecurity measures have been considered, and there is no network architecture currently defined for the facility. IT will need to be informed of any plans for connectivity implementation.	0%
Connectivity level	0.5	Some CNC machines are connected to inoperable DNC system. No other machines are not connected.	1.56%
Usage level	0	Majority of machines are not connected, thus connectivity cannot be utilized. DNC system is currently inoperable due to software issues.	0%
		Total Connectivity Score:	**19%**

5.3 Assessment of Houston technology center connectivity

Upon development of the rubric, leaders of the manufacturing facilities that are focused on in this thesis were asked to examine the status of machine connectivity at their site based on the five evaluation criteria. They were then asked to self-evaluate their sites based on the rubric. The author took part in the evaluation process to help guide leaders score their sites accurately. This section details the results of the evaluation process at each of the facilities.

5.3.1 RBTC assessment

The RBTC shop floor has a mix of CNC machines and older machines controlled by PLCs. However, the center is currently prioritizing the connection of bottleneck CNC machines, as the machining done at these machines accounts for the majority of the time required to produce steel bits. For data collection, the center is in the process of implementing a FANUC MT-Link*i* ecosystem in order to connect its machines. Their current network architecture involves connecting machines to an SLB-managed switch on a local, isolated VLAN. This VLAN connects to an on-premises server, which then through SINet connects to an MT-Link*i* Integration Server in Dallas, TX. Local devices at RBTC such as PCs and tablets can then access data from MT-Link*i* from the Integration Server. For DNC functionality, RBTC uses Predator, with a similar network architecture as the one for MT-Link*i*, using a Predator server also located in Dallas, TX. The Predator system enables tracking of CNC programs and can be integrated with the site’s production data management to ensure traceability.

RBTC has successfully connected their FANUC-controlled CNC machines to MT-Link*i*, and staff at the site is able to monitor machines in real time, tracking machine status, errors, and alarms. The system also tracks and records various machine data parameters such as spindle feeds and speeds, along with program timing. Tracking program timing enabled a case study focused on monitoring machine time to enhance cycle time by adjusting various machining parameters. Further details can be found in Sun’s thesis [4]. With regards to the usage of Predator DNC, operators fully use the system for line-by-line feeding of NC files. This is done by saving the programs on the Predator server, which then pushes programs line-by-line to a local machine. If edits to the NC program are required, operators can download the file to a local computer at the machine workstation, make any edits required, and either save to a USB drive and transfer it to the machine, or upload the program back to the server and push it down via Predator.

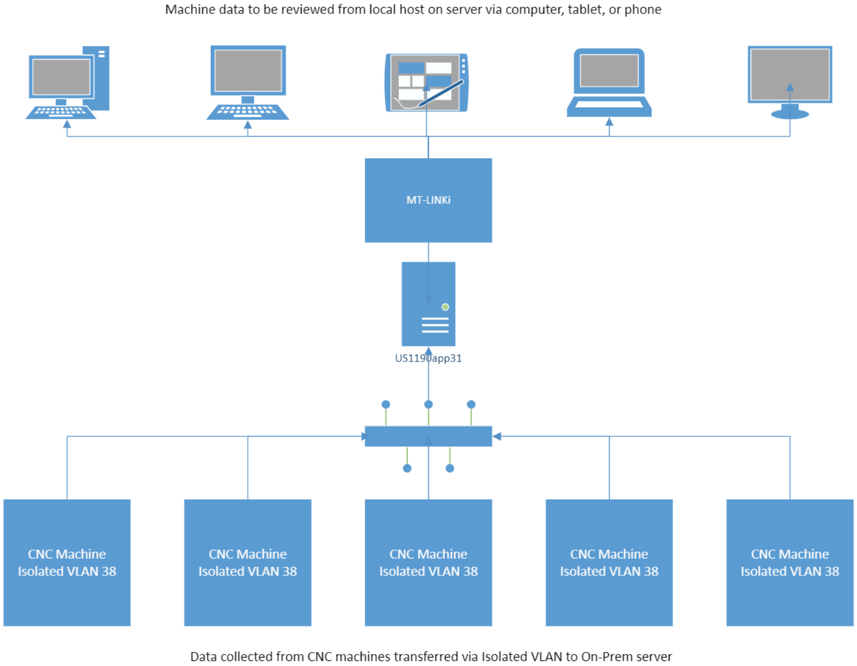

Figure 5.1: RBTC MT-Link*i* network architecture

This diagram outlines the network architecture RBTC uses to implement MT-Linki. The MT-Linki box represents the Integration Server in Dallas, TX.

The author consulted with Mr. Jared Tucker, who is responsible for connectivity implementation at the site, and Mr. Connor Golden, manufacturing engineer, to assess connectivity at RBTC. The site received a score of 68%, indicating that the site is not quite mature in its connectivity implementation but has made significant gains in the process. The site's main deficiencies are in resource availability and cybersecurity. In terms of staffing, only Mr. Tucker is employed to develop, operate, and maintain the system. More resources need to be dedicated towards the system in order to keep it online and develop its cybersecurity measures, which are non-compliant in several areas per an IACS security audit in July 2023. The network architecture at RBTC lacks segmentation, and network access control is not implemented to ensure that only authorized devices are allowed to access the network. With regards to hardware, the site has identified all the machines that need to be connected to help streamline the operations. The necessary hardware for connecting the remaining machines has been identified. This includes IoT connectors for Heidenhain and Siemens CNC controllers, as well as MOXA boxes for legacy machines. These devices are readily available, and once the center is ready to connect the remaining machines, they will be procured. The bottleneck machines have been successfully connected, and the remaining machines are scheduled to be connected once logistical arrangements are finalized. Software and usage level both received full scores because the MT-Link*i* ecosystem has been fully implemented and being utilized to its full extent. The only exception is NC file transfer, which is handled by the Predator DNC system. The system is also robust in that it is easily able to handle additional machines being connected.

Table 5.4: RBTC connectivity assessment scoring breakdown

(a) Criteria	(b) Score	(c) Score Explanation	(d) Weighted Score
Resources available	2	Management is fully on-board with connectivity. Only one person is responsible for maintaining the connectivity system. Logistical arrangements are being made to connect additional machines.	12.5%
Hardware	3	Machine list is fully defined, hardware for unconnected machines has been identified and can easily be procured. This includes IoT connectors and MOXA boxes.	15%
Software	4	MT-Link*i* has been fully implemented and is connected to FANUC-controlled machines.	15%
Cyber-security	1	The current working solution needs to be modified to comply with new standards. Only basic network security measures (e.g. firewalls) are in place, more resources need to be dedicated for cybersecurity efforts. No network segmentation or access control in place.	3.75%
Connectivity level	3	All FANUC-controlled CNC bottleneck machines are connected, and data is easily accessible through MT-Link*i*. CNC machines with other controllers are ready/have plans to be connected, pending logistical arrangements. Ecosystem is robust in that it can easily handle additional machines.	9.38%
Usage level	4	MT-Link*i* being fully utilized for machine monitoring of status, errors, and alarms. Shop floor overview created to monitor all connected machines. Machine data collection done for spindle feeds and speeds and program timings. Predator DNC system in use for DNC functionality.	12.5%
		Total Connectivity Score:	**68%**

5.3.2 Brookshire assessment

The Brookshire site features more than 30 production machines that are controlled by various types of old and new PLCs, including Allen Bradley, Siemens, and Omron. These PLCs have edge devices that connect to a local Kepware server using OPC-UA protocol. The Kepware instance then connects to Ignition, which hosts multiple production applications. The site is in the process of using Ignition to develop applications for multiple use cases. These use cases include traceability, downtime capture, recipe management, data analysis for tracking OEE, and real-time scheduling. The Ignition instance is located in a production iDMZ, and connects to various corporate applications such as SAP and email. The site uses an MSSQL database to record production data.

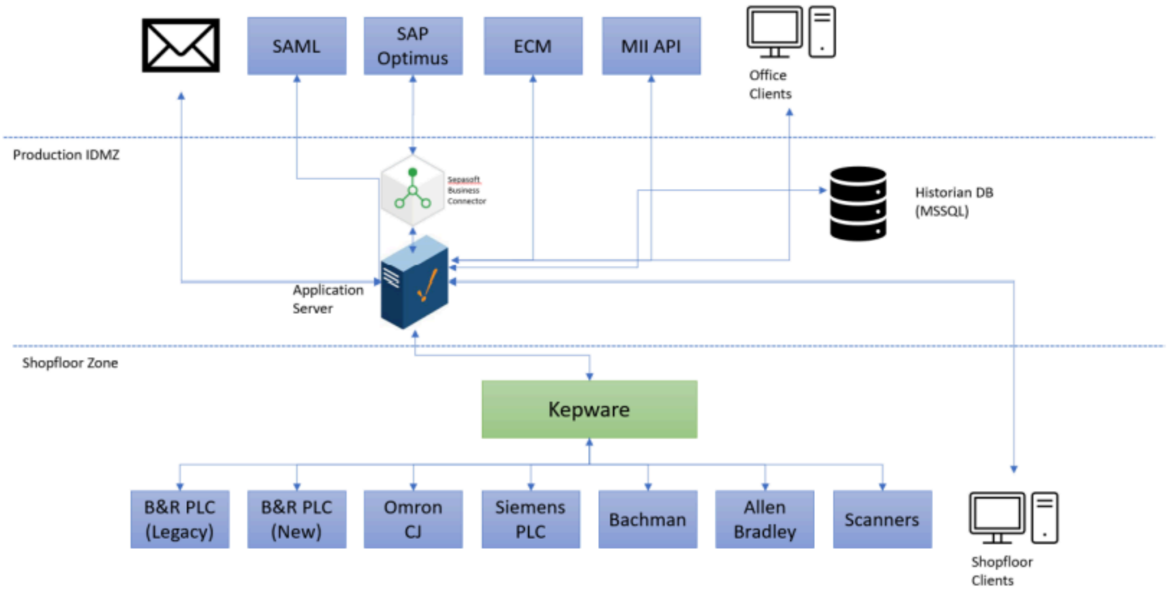

Figure 5.2: Brookshire site network architecture

This diagram displays a high-level network architecture of the connectivity implementation at Brookshire.

The author evaluated the Brookshire site's connectivity infrastructure in conjunction with Mr. Luke Dupree, automation engineer at the site. The site received a connectivity score of 80%, indicating relative maturity in connectivity. The site has a fully staffed automation team with full resources dedicated towards connectivity, however there are some proficiency gaps on the team with regards to the skills required for maintaining the system. The hardware and software needed have been procured and deployed, and the team is in the process of developing applications on Ignition for their desired use cases and training the operators on using them. The site has completed NAQP and DPQP, but is also currently working to improve its cybersecurity infrastructure to better comply with SLB IT standards, including increased network segmentation. All production machines have been connected with exception to 3-4 older machines that require some additional work. Data is being collected, but has not been analyzed to provide any significant impact on operations. A detailed scoring and justification is provided in Table 5.5. Going forward, the team intends to complete their connectivity in the short future by connecting remaining machines, fixing cybersecurity issues, and increasing team competency. The team expects to be able to use machine and process data to evaluate and improve process and part quality.

Table 5.5: Brookshire connectivity assessment scoring breakdown

(a) Criteria	(b) Score	(c) Score Explanation	(d) Weighted Score
Resources available	3	Full-time automation team on-site but there are some proficiency gaps relating to programming, maintaining, and troubleshooting issues relating to connectivity and system bugs. Regular budget allocated towards licenses and maintenance.	18.75%
Hardware	4	All hardware needed to connect machines has been procured.	20%
Software	3.5	The connectivity ecosystem has been created and the Ignition software has been acquired and deployed. The team is in the process of training operators and developing applications to use machine data for the center's use cases.	13.13%
Cyber-security	2.5	NAQP and DPQP completed for Ignition applications. SAQP is nearly completed. An IACS cybersecurity audit was conducted in 2023, with specified action items that need to be completed to build a more secure infrastructure. The automation team is working through these items to ensure compliance with IT standards.	9.37%
Connectivity level	3.5	All production machinery has been connected to Ignition with the exception of 3-4 older machines. The team is in the process of establishing connectivity for the legacy machines.	10.94%
Usage level	2.5	All machine data can be collected and historized. Automation team is working with a machine learning team to analyze data and obtain useful insights. The data has not yet delivered any concrete impact on operations, but the use cases are well established.	7.81%
		Total Connectivity Score:	**80%**

5.3.3 CHPC assessment

The shop floor at CHPC features various processes that require many different types of machines, including machines controlled by both CNC controllers and PLCs. Most machines are not connected, however, and the machines that are connected are using a highly outdated setup that is inoperable. The center is currently using CIMCO PDM, a previous generation of CIMCO's production data management solution. Unfortunately, PDM lacks the capability to deliver real-time data insights and other essential features required by CHPC's modern manufacturing operations. The local server hosting PDM is also unusable because it runs on Windows 7, an operating system no longer supported by Microsoft, rendering it susceptible to various security threats. Additionally, NC file transfers are currently done through the outdated CIMCO server and the files are accessed from local edge devices and transferred manually to CNC controllers via USB flash drives. The current network architecture is shown in figure 5.3.

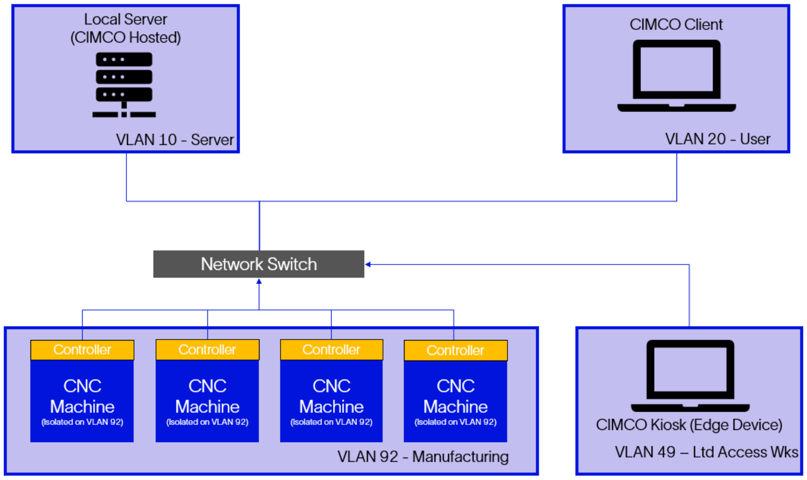

Figure 5.3: CHPC current network architecture

This diagram illustrates an integrated network architecture designed for the CHPC manufacturing environment, showcasing the distribution of devices across various VLANs.

Currently, the center is in the preliminary stages of implementing a new connectivity solution. The center is looking to implement a CIMCO suite ecosystem that includes DNC-Max and MDC-Max for DNC and machine data collection capabilities, respectively. The implementation process would include acquiring a new local server to host the DNC-Max server. This server would be capable of operating on two separate networks—the local manufacturing VLAN and SINet—simultaneously, while isolating them to prevent any traffic from passing between them. The combination of a new server and network segmentation through the use of separate VLANs can mitigate security threats. The network architecture is in development with IT, and CIMCO has developed their own network infrastructure recommendations that emphasize security through network segmentation, which will be a resource as the center looks to construct their connectivity architecture [3].

Table 5.6: CHPC connectivity assessment scoring breakdown

(a) Criteria	(b) Score	(c) Score Explanation	(d) Weighted Score
Resources available	2.5	Management is well-versed on connectivity, and is looking to update current infrastructure and has allocated the budget for it. However, there is limited headcount with expertise on site to execute updates. Most of the progress made so far has been made by Mr. Pal's temporary project.	15.63%
Hardware	2.5	Machines to be connected are fully defined, with controllers, connection methods, and IP addresses all recorded. Hardware options for connecting older legacy machines identified and are awaiting procurement.	12.5%
Software	3	The CIMCO ecosystem has been selected for the site. Currently inquiring about licensing from the vendor.	11.25%
Cyber-security	2	Current network infrastructure is non-compliant and needs adjustment. New plans pending IT qualification.	7.5%
Connectivity level	1	Some machines are connected in that they are routed to the network, but no data is being collected. A connectivity plan is in development for the facility.	4.69%
Usage level	1	No data is being collected to be used.	3.13%
		Total Connectivity Score:	**55%**

The author consulted with Mr. Chris Hernandez, manufacturing engineer at CHPC, and Mr. Kanishk Pal to evaluate machine connectivity through the rubric. With a connectivity score of 55%, the assessment revealed that CHPC is less developed in connectivity compared to other SLB facilities, especially ones that rely on process and precision machining operations. Although preliminary steps have been made towards planning connectivity implementation, such as defining the hardware and software needed, there is limited headcount dedicated towards planning and executing connectivity at the center. The old network architecture used to be compliant before IACS initiatives made them non-compliant. Plans for adherence are completed, are highlighted in Mr. Pal's thesis, and are awaiting qualification from IT [3]. With regards to connectivity, some machines are connected through the old ecosystem, but no useful data is being generated. Table 5.6 provides a detailed score breakdown and justifications for CHPC. Mr. Pal's current project relating to establishing connectivity guidelines for a CIMCO product suite at CHPC will be handed off to Mr. Hernandez following the completion of the thesis.

5.3.4 HCS assessment

Upon initial assessment, HCS has a robust implementation of machine connectivity. On the shop floor, there are several machines that are each controlled by 3 to 4 PLCs. Most of the PLCs on the floor are supplied by Allen Bradley and Siemens. These PLCs have wired connections to an edge router that utilizes NAT to effectively conceal the machine LAN IP addresses when translating them to the manufacturing VLAN. These machine connections feed into Kepware, which translates the various protocols it receives into an OPC-UA protocol. The IP address of the Kepware instance again undergoes NAT and connects to SLB managed switches in the server VLAN. On the server VLAN, there are two Azure cloud-based instances of Ignition: one for development and testing, and another for production. Kepware enables connectivity for all devices to both instances. This setup allows for the development of various applications, reports, or dashboards in the test gateway before deploying them to the production gateway. Data storage is managed using a MySQL database.

To better understand and assess the connectivity implementation at HCS, the author consulted with Mr. Wayne Ling, automation engineer at the site. Machines are well-connected at the facility and there is full resource dedication towards implementation and maintenance. However, the site has some security deficiencies due to newer SLB cybersecurity initiatives through IACS. Specifically, it was mentioned that the site needs to segregate their network by machine instead of grouping all machines into one LAN, and each device needs to have its IP address reassigned. Grading the site using the rubric, HCS earned a score of 84%. Overall, HCS is mature in connectivity implementation relative to other SLB sites. It received full scores in resource availability, software, and connectivity and usage levels. There is a full automation team in place to maintain connectivity, the Ignition/Kepware system is fully in place, and all machines are connected with data being readily used and analyzed. The site's only deficiencies were in hardware and cybersecurity. While all hardware is fully deployed, some components are not industrial grade. Additionally, the current network architecture needs to be revamped to meet new standards. To address these issues, a new solution is being developed in collaboration with IACS and a third-party consultant. A detailed score breakdown and explanation for HCS is provided in table 5.7.

Table 5.7: HCS connectivity assessment scoring breakdown

(a) Criteria	(b) Score	(c) Score Explanation	(d) Weighted Score
Resources available	4	Management is fully convinced of the benefits, and the budget is allocated for license renewal and server costs. The automation team has the know-how to implement and maintain the complete connectivity solution, working closely with the maintenance team.	25%
Hardware	3	Hardware is fully deployed, but some routers and cables are not labeled properly and not industrial grade.	15%
Software	4	Kepware is in place as a local OPC-UA server. Ignition is in place as a SCADA/MES platform on Azure cloud, with MySQL as its database.	15%
Cyber-security	1	The current working solution needs to be modified to comply with new standards. The target state development in collaboration with SLB IACS and a third-party consultant is in progress. SAQP is submitted and being reviewed.	3.75%
Connectivity level	4	All connectable machines are connected and fully integrated into Ignition. Machine data can be easily accessed with Ignition dashboards.	12.5%
Usage level	4	Ignition is used throughout the shopfloor to visualize machine data. It allows operators to be away from the line but still keep an eye on key process parameters. The connectivity allows manufacturing engineers to create and apply production recipes. There is also an ongoing machine learning project to use the collected data to predict hardware failure.	12.5%
		Total Connectivity Score:	**83%**

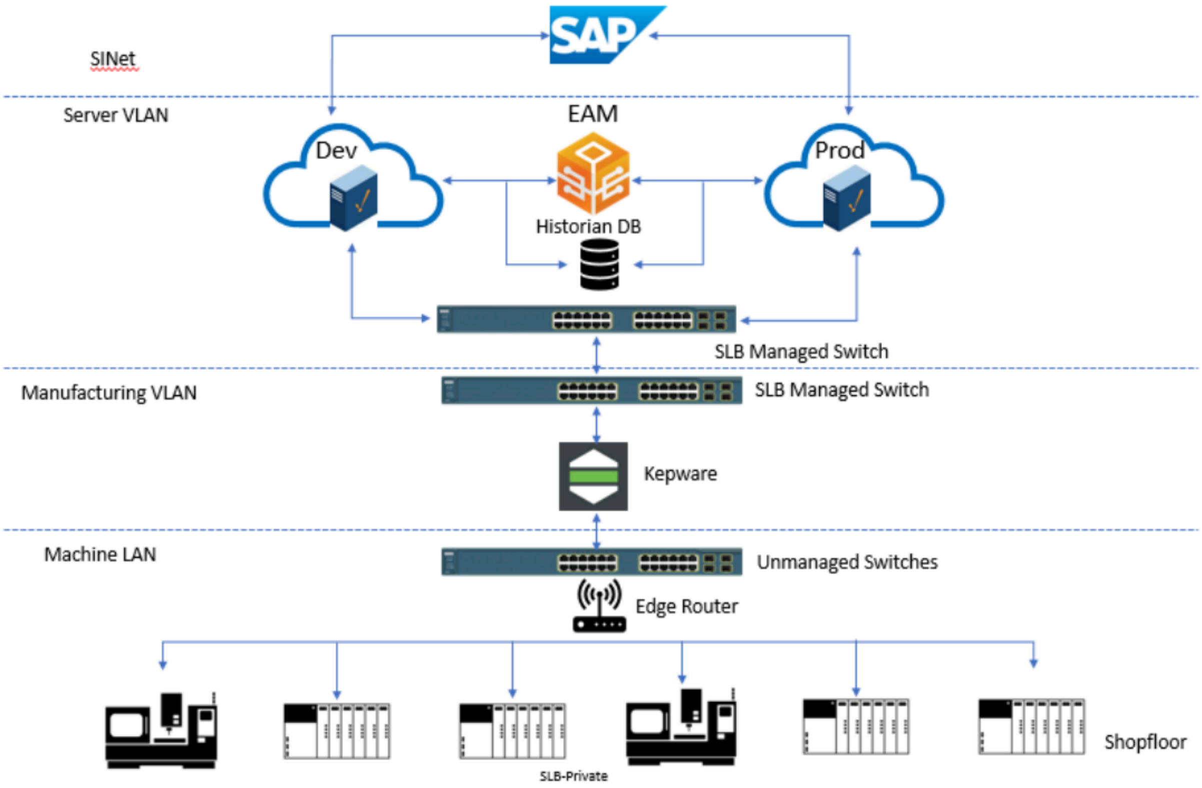

Figure 5.4: HCS Ignition/Kepware network architecture
This diagram displays a high-level network architecture of the connectivity implementation at HCS.

5.3.5 SCMF assessment

SCMF is one of SLB's newer manufacturing facilities. Consequently, the automation team had a hand in the design and establishment of the production lines, which allowed for the integration of connectivity and standardization right from the inception. The network architecture at SCMF is centralized around a local Ignition server, connecting to all machines and various other entities. Because the facility uses the Ignition server to not only read data but also control machines, it is critical that server remains online during operations and that downtime be minimized to the fullest extent possible. Thus, the server runs on a Linux machine, which is known to be more reliable than Windows and requires less IT updates.

With regards to connections, on the machine side, the facility has multiple production bays that are each controlled by a central PLC. This PLC reads data from and controls all automated devices within its bay through Ethernet IP. Since the automation team had major involvement in the development of the facility, they were able to standardize these PLCs, and uniformly chose them to be Allen Bradley controllers. The controllers then connect to a local Ignition server through Ethernet IP. This connection is bi-directional. The other side of the Ignition instance is connected to several entities that allow for the reading and controlling of machines. MySQL databases are connected to the Ignition server to log historical and production data. At the same time, operators are able to manipulate and control machines from HMIs. Each production bay has its own HMI cell that its HMIs connect to, which then connects to the server. To connect to systems outside the local manufacturing environment, the Ignition server is connected to another server in a firewalled DMZ, which then connects to several entities that allow users on SINet to access the network. The intermediary server is in place to prevent a direct connection from machines, which are considered high risk for exposure, to SINet, and compromising company cybersecurity. The intermediary server can connect to various functionalities including LDAP, SAP, and emails, ensuring users are up-to-date on information and can access the network remotely.

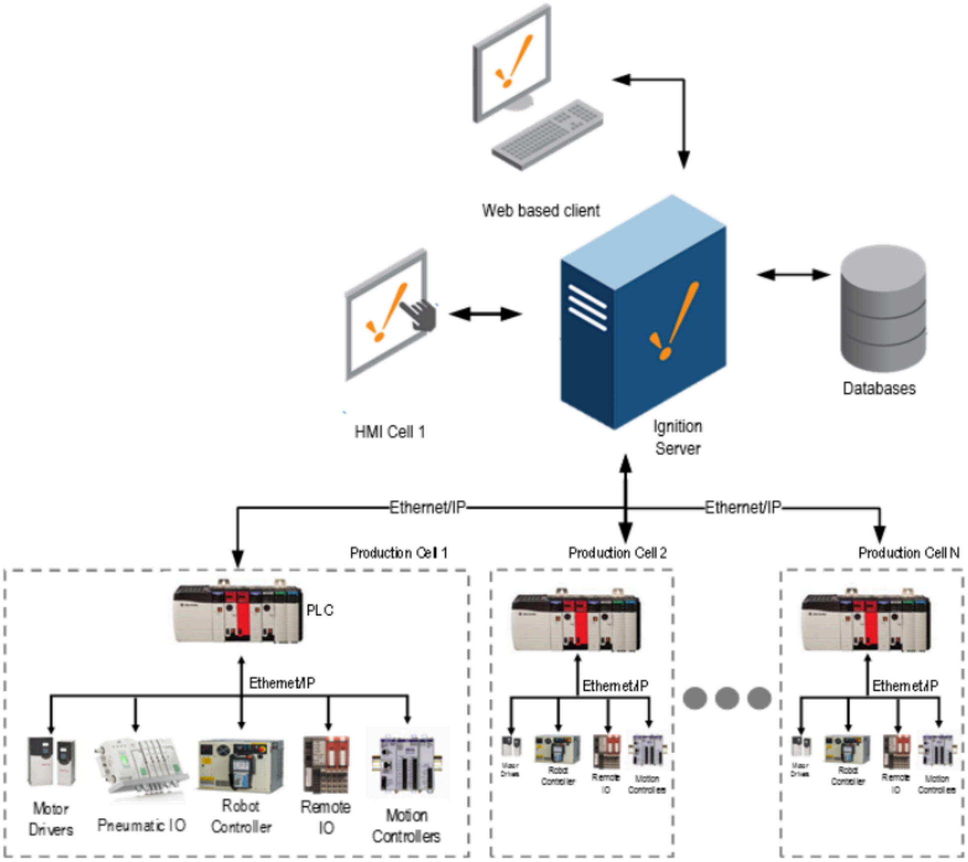

Figure 5.5: SCMF Ignition network architecture

This diagram is a high-level overview of connectivity implementation at SCMF. Connections to the intermediary server are not shown.

To better assess connectivity at SCMF, the author consulted with the automation team lead at the site, Mr. Kaveh Nikou. Overall, the facility is mature in connectivity relative to other SLB facilities in the Houston-area. In addition to a general overview of the network architecture at the facility, Mr. Nikou mentioned several points that are important to consider in future implementations of connectivity. At present, the configuration at SCMF includes a primary Ignition server instance dedicated to production, complemented by an additional backup server ready to take over should the main server fail or require replacement. A more ideal arrangement would be to deploy three distinct servers on three separate virtual machines, each designated for production, testing, and development environments respectively. The development environment is designed to facilitate the creation of new features without disrupting ongoing operations. Once these features are developed, they are transferred to the testing environment for validation. Upon successful verification, they are then implemented into the production server. This structure allows for a clear separation of concerns, ensuring that each environment is isolated and optimized for its specific purpose. Additionally, it was noted that the intermediary server at SCMF currently has a firewall implemented solely on one end, specifically between SINet and the server itself. Moving forward, to enhance compliance with cybersecurity standards, it will be necessary to install an additional firewall. This will be positioned between the intermediary server and the Ignition server to fortify security measures separating the local production setting from the broader corporate network.

After jointly grading machine connectivity with Mr. Nikou and Mr. Shaoqing Chen, SCMF received a weighted final score of 96%. Their automation team is fully staffed and has developed and operated the connectivity structure at the facility for years. All of their machines are fully connected, and machine data is being recorded, stored, and analyzed to be used as benchmarks and make decisions, meriting a full score for resource availability, hardware, software, and connectivity and usage levels. With regards to cybersecurity, SCMF has undergone the DPQP and NAPQ processes, and the automation team is working on an action plan for fully complying with SAQP, thus the site received a score of 3 out of 4 for cybersecurity. SCMF's high score on the rubric establishes it as one of the most well-connected facilities out of the centers focused on in this thesis, and SLB manufacturing management is able to focus efforts on implementing connectivity elsewhere. A detailed score breakdown and explanation for SCMF is provided in table 5.8.

Table 5.8: SCMF connectivity assessment scoring breakdown

(a) Criteria	(b) Score	(c) Score Explanation	(d) Weighted Score
Resources available	4	Three automation engineers and an automation team lead are employed full-time, along with a manufacturing support manager overseeing automation projects and an automation technician specialized in automation projects. A sufficient budget is allocated towards maintaining the SCADA and PLC development software, which have been operating for years.	25%
Hardware	4	Most equipment has Ethernet connectivity. Some serial protocol devices have Ethernet encapsulation converters, and are connected with the internal manufacturing LAN.	20%
Software	4	SCADA and MES functions are fully built on the Ignition platform.	15%
Cyber-security	3	DPQP, NAQP, and Legal Review are finished for digital portfolio management. Other reviews pending approval. Site is currently working on SAQP task list.	11.75%
Connectivity level	4	All machines are fully connected to Ignition. Machine data is stored into MySQL database. Various ways of collecting data are being developed.	12.5%
Usage level	4	Engineers are using machine data collected to analyze equipment problems. Most of the projects were proposed and executed based on the result of analysis. The results are also used as benchmarks for the performance. Managers frequently monitor the data to make decisions and changes.	12.5%
		Total Connectivity Score:	**96%**

Chapter 6 Discussion and future work

The objective of this thesis is to examine the benefits of machine connectivity for manufacturing, conduct a thorough evaluation of machine connectivity at multiple SLB manufacturing facilities and construct comprehensive guidelines on implementing connectivity at facilities in the future. This chapter discusses the results of the connectivity evaluation conducted on six SLB technology centers and establishes a connectivity roadmap for facilities yet to be connected.

6.1 General connectivity summary

Evaluating machine connectivity at each facility proved to be useful in identifying the facility's needs and developing implementation plans. Holistically assessing and comparing multiple facilities can offer valuable insights for SLB's transition to Industry 4.0. Therefore, compiling individual results and examining company-wide connectivity is crucial. Table 6.1 summarizes the scores of the six centers assessed in this thesis.

Table 6.1: Machine connectivity assessment scoring summary for Houston-area technology centers

This table summarizes the connectivity assessment results of each of the evaluated centers. Column a lists the center being scored, column b provides the manufacturing model (P for process, PM for precision machining, and AT for assembly and test) that center uses to make their products. Columns c thru h contain the scores for each center for the rubric criteria (in order): resource availability, hardware, software, cybersecurity, connectivity level, and usage level. Column i contains the total connectivity score for each center.

(a) Center	(b) Mfg. model	(c) Resource avail.	(d) Hard-ware	(e) Software	(f) Security	(g) Conn. level	(h) Usage level	(i) Total Conn. Score
KTC	P + PM	1	1.5	1	0	0.5	0	19%
RBTC	P + PM	2	3	4	1	3	4	68%
Brook-shire	P	3	4	3.5	2.5	3.5	2.5	80%
CHPC	PM + AT	2.5	2.5	3	2	1	1	55%
HCS	P	4	3	4	1	4	4	83%
SCMF	P	4	4	4	3	4	4	96%

6.1.1 Identified trends

Although these six centers are not representative of SLB manufacturing as a whole, when compiling their scoring information into one table, multiple patterns can be drawn. An important observation is that centers with high scores for resource availability tend to score highly on all other criteria. This indicates that once a center allocates the necessary time and resources to connect their machines, the implementation process can be quickly completed due to the availability of personnel and funding to plan and execute the connectivity project. This vindicates the high weight placed upon resource availability when calculating total connectivity score, because that criteria takes the longest amount of time and effort to be fulfilled, and once completed, the path to full connectivity becomes much clearer.

Another observed pattern was that no center received a full score on cybersecurity. A potential explanation for this is that the category is graded based on updated security standards defined from the IACS initiative, which the company has only recently adopted. As such, centers might not have had the time and resources available to comply with the new standards.

Lastly, it can be observed that facilities relying solely on process manufacturing (Brookshire, HCS, and SCMF) generally scored higher in total connectivity. This may be because these facilities predominantly use machines controlled by PLCs, allowing for a more uniform approach to connectivity. Additionally, all these facilities use Kepware and/or Ignition, which are highly flexible and can accept data from a wide range of machines. Collaboration between these facilities on implementing the ecosystem solution may have also expedited the connectivity process. On the other hand, facilities that also rely on precision machining (KTC, RBTC, and CHPC) generally scored lower in connectivity. This may be due to the diversity of machines, which include both CNC controllers for precision machining and PLC controllers for process manufacturing. The variety in machine types complicates the standardization of hardware and the determination of a suitable connectivity ecosystem. Additionally, since machining is often the bottleneck operation at these centers, there is a tendency to prioritize connecting CNC machines while deprioritizing other machines that offer less immediate value when connected. It is also worth noting that these centers have fewer resources dedicated to implementing connectivity. It is unclear whether this is merely coincidental or if certain factors prevent these centers from prioritizing connectivity at this time.

6.1.2 Connectivity by manufacturing model

The discussion relating manufacturing models to connectivity scores can lead into another topic: minimum connectivity thresholds for facilities with different manufacturing models. The three manufacturing models found at SLB and described in section 2.3.2 are: 1) process, 2) precision machining, and 3) assembly and test. Machine connectivity can benefit each of these models in different ways.

Process manufacturing can greatly benefit from machine connectivity by enabling real-time monitoring and control of production processes through recipe management. Sensors and IoT devices can continuously monitor and adjust production parameters, ensuring consistent product quality and reducing waste. Recipe management allows for the tracking and recording of machine parameters used in the production process, which is particularly useful for product lines with numerous options and varying customer requirements. Additionally, integrated systems can track raw materials and finished products throughout the process, enhancing overall efficiency. These benefits are best seen at the process-oriented facilities assessed in this project: Brookshire, HCS, and SCFM. Each of those facilities relies on machine monitoring and recipe management to maintain productivity and efficiency while delivering quality products.

Precision machining (i.e. CNC machines) also benefits from connectivity for monitoring, control, and maintenance purposes. The ability to monitor and record machine status allows operators and engineers to quickly respond to alarms and other errors. Machine uptime can also be maximized by tracking reasons for downtime, such as emergency stops and lunch breaks. Collecting data from machining processes can help identify inefficiencies and areas for improvement, leading to optimized production and reduced waste [4]. Connectivity also allows CNC machines to be controlled through DNC systems, allowing for centralized control and improved efficiency by reduced setup times and errors. It also allows for enhanced data management, ensuring that the latest versions of programs are always in use, thereby reducing the risk of outdated programs. In terms of maintenance, continuously monitoring uptime and spindle loads allows for effective tool wear tracking. This proactive approach helps reduce unscheduled downtimes by ensuring timely tool replacements.

Connectivity can also be advantageous for assembly and test manufacturing in several ways. It enables real-time quality checks at various stages of assembly, ensuring defects are caught early and reducing the need for rework. Automated testing systems can also be integrated into an assembly line, performing functional tests on components and finished products to ensure they meet specifications. Connecting different parts of the assembly line can also allow them to communicate seamlessly, coordinating tasks and reducing bottlenecks, leading to higher efficiency and productivity.

Because of the timeline of the project, the author was unable to evaluate any facilities with focus on assembly and test. Although CHPC does utilize this model for completion valves, the author chose to concentrate primarily on the facility's precision machining aspects to better streamline the project. Thus, it is currently unclear how SLB facilities employing the assembly and test model can leverage connectivity and what specific benefits they might gain. This is because many of these facilities, such as the Houston Formation Evaluation (HFE) center in Sugar Land, TX, hand-build large products (i.e. downhole tool assemblies) at low volumes. Further evaluation of assembly and test facilities needs to be conducted to better understand their connectivity needs.

6.2 Machine connectivity roadmap

The results of the facility evaluations were able to provide guided recommendations for SLB on connectivity implementation in the future. This section identifies three key guidelines for central manufacturing leaders at the company to follow when pursuing and standardizing connectivity across all technology centers: 1) further assessment of all SLB manufacturing facilities, 2) identifying facilities most in need of resources for connectivity execution, and 3) encouraging collaboration between facilities.

6.2.1 Further connectivity assessments

The rubric was effective in assessing the overall connectivity status of a facility, identifying specific areas that need improvement, and comparing its connectivity maturity with other facilities. To better understand the general state of connectivity at the company, leaders at the company should use the rubric to conduct an evaluation of all 68 SLB manufacturing facilities across the world. This helps both central manufacturing headquarters and individual facilities advance connectivity at the company. Central manufacturing leaders can use the evaluations to compare connectivity maturity at various facilities and identify those most in need of resources. Individual facilities can use the individual criteria scores of their evaluation to identify areas that need improvement, such as cybersecurity or usage level. The company-wide evaluation process can also facilitate the improvement and refining of the rubric to provide a more comprehensive assessment of connectivity. Specifically, the inability to evaluate facilities using the assembly and test manufacturing model during this project means that the rubric does not address the unique aspects of that model that need assessment. It is crucial that these types of facilities are evaluated so that their connectivity needs and the benefits they gain from connectivity are better understood.

It is also important that these evaluations are done collaboratively with multiple people, including both facility employees and external individuals in order to incorporate multiple perspectives. During the author's evaluation process, it was observed that when multiple individuals participated, the scores for various criteria varied based on each person's knowledge of the current state of the criteria and their experience with connectivity at other facilities. Although the rubric outlines the parameters for assigning scores to each criterion, differences in knowledge and experience, particularly when comparing to other facilities, can lead to variability in the scores given by different individuals. Collaborative assessment can help both provide the best estimate for connectivity and facilitate exchange of knowledge and expertise between various members of the organization.

6.2.2 Resource allocation

The rubric serves as a tool for manufacturing leaders to compare the state of machine connectivity of multiple facilities. Because resource availability is weighted heavily in the rubric due to the time and effort it requires, along with the observation that most facilities that had low total connectivity scores also had scored low in resource availability, it is assumed that most facilities that receive low total scores require more resources in the form of funding and personnel. Allocating resources will streamline and accelerate connectivity implementation at a facility. Once a dedicated automation team is in place with the necessary budget, the remaining criteria can be met relatively quickly. Automation engineers are best suited to identify priority machines, determine the required hardware for connectivity, and develop and implement a secure connectivity ecosystem. The most time-consuming and effort-intensive part is presenting a business case for connectivity and making facility management aware of its needs. Thus, central manufacturing can use the total connectivity scores and the individual resource availability scores to present such a business case and allocate efforts and funding accordingly.

Upon further discussion with manufacturing leaders and automation teams, it was deemed that facilities with total connectivity scores of 75% and above are considered “mature” in connectivity. In the context of this thesis, these facilities are Brookshire, HCS, and SCFM, which have fully implemented connectivity systems and only require minor adjustments for hardware and cybersecurity. Thus, they require less resources from central manufacturing to advance their connectivity ecosystem. A goal is therefore set to support other, less mature facilities to a connectivity score of 75% through the allocation of funding in order to push them to connectivity maturity.

6.2.3 Facility collaboration

The process of implementing and advancing machine connectivity at multiple facilities can be expedited through collaboration between the different automation teams. Multiple teams working together facilitates sharing of knowledge and expertise on challenges and strategies during the implementation process. For example, it was observed that the three highest scorers in the evaluation in this thesis—Brookshire, HCS, and SCFM—all use Ignition as their connectivity ecosystem. It was also noted that the automation teams from all three of these facilities collaborated to implement the system, develop Ignition applications, and debug software issues. The joint efforts were thus important in advancing connectivity at these sites.

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