AN OPEN-SOURCE MANUFACTURING EXECUTION SYSTEM

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Lay Abstract

Industry 4.0 is a new wave of smart manufacturing. It's about connecting everything in a factory so machines can talk to each other and share information. This makes production faster and more efficient.

The Automation Pyramid is a structure that helps organize how information moves around in manufacturing. Think of it as a digital network that keeps things running smoothly.

There are special software tools called Manufacturing Execution Systems (MES) that help manage manufacturing processes. They are essentially digital assistants for factories, making sure everything works well.

The problem is, that MES systems can be expensive and complicated, especially for smaller companies. This study is about finding a way to make MES systems more affordable and easier to use for small and medium-sized businesses and giving them a platform to modernize their factories and become more efficient.

Abstract

Industry 4.0, also known as the 4th industrial revolution, represents the integration of the entire product lifecycle in manufacturing, involving both vertical and horizontal connectivity. A key aspect of Industry 4.0 is the interconnection of all devices within a manufacturing process, enabling data exchange both horizontally between devices and vertically across different departments in a company. This necessitates the development of automation models that govern data collection, sharing, and utilization throughout the product lifecycle.

The Automation Pyramid, comprising 4 to 6 layers, plays a crucial role in achieving this integration. The ANSI/ISA-95 international standard, established by the International Society of America (ISA), guides the integration of business enterprise systems (ERP) with shop floor operations. Manufacturing Execution Systems (MES) emerged in the 1990s as a solution to the limitations of ERP systems, aiming to bridge the gap between ERP and shop floor operations. While MES systems are vital for achieving Industry 4.0 goals, many companies hesitate to integrate them due to cost and integration complexity making them prohibitive for small to medium-sized enterprises (SMEs). This study seeks to address this challenge by developing an affordable MES solution tailored for SMEs, providing a cost-effective means to transition to Industry 4.0. The solution aims to act as a stepping stone into the realm of Smart Manufacturing with Industry 4.0 without necessitating a complete replacement of existing MES systems.

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Table of Contents

List of Figures and Tables

List of all Abbreviations and Symbols

AI	Artificial Intelligence
APM	Asset Performance Management
AR	Augmented Reality
BOM	Bill of Material
CNC	Computer Numeric Control
COM	Component Object Model
CMM	Coordinated Measuring Machine
DCOM	Distributed Component Object Model
DCS	Distributed Control System
EF	Entity Framework
ERP	Enterprise Resource Planning
HTTP	Hyper Text Transfer Protocol
IIS	Internet Information Services
IIOT	Industrial Internet of Things
ISA	International Society of Automation
KPI	Key Performance Indicators
MDM	Master Data Management
MES	Manufacturing Execution System
MESA	Manufacturing Enterprise Solutions Association
ML	Machine Learning
MOM	Manufacturing Operations Management
MVC	Model View Controller
OEE	Overall Equipment Effectiveness
OPC UA	Open Platform Communication Unified Architecture
ORM	Object Relational Mapping
PaaS	Platform as a Service
PLC	Programmable Logic Controller
ROI	Return on Investment
SCADA	Supervisory Control and Data Acquisition
SME	Small to Medium-sized Enterprises
SQL	Structured Query Language
SSE	Server Sent Event
SSMS	SQL Server Management Studio
TCP/IP	Transmission Control Protocol / Internet Protocol
UML	Unified Modeling Language
VR	Virtual Reality
WIP	Work In Progress

Chapter 1. Introduction

1.1 Background

Industry 4.0 also known as the 4^{th} revolution in the industry refers to the integration (Vertical and Horizontal) of the entire lifecycle of a product in manufacturing; it was preceded by steam-powered engines (1^{st}), mass production provided by electricity (2^{nd}), automation devices such as PLC's and HMI (3^{rd}) [1]. A big factor for Industry 4.0 is the connectivity of all devices in a manufacturing process enabling them to share information (Horizontal Integration) with the other departments in the company (Vertical Integration). This brought about the need for Automation models that define how information is collected, shared, and used within the product life cycle [2]. Figure 1 gives a visual representation of the various stages of lifecycle, and levels of operation.

The automation pyramid can range from 4 to 6 layers. The ANSI/ISA – 95 is an international standard set by the International Society of America (ISA) which defines how to integrate the business enterprise (ERP) with the shop floor. The standard defines 4 levels which include:

Level 1: The physical process. This defines all the devices on the shop floor that directly collect data from the environment (sensors), devices that affect the environment (actuators), and equipment used for production.

Level 2: Control layer. This defines all the devices used for monitoring and interacting with the field devices. The most common control devices are your Programmable Logic Controllers (PLC) Supervisory Control and Data Acquisition (SCADA), Distributed Control Systems (DCS), and Human Machine Interface (HMI).

Level 3: Manufacturing Operations Management/Manufacturing Execution System (MES) which covers control of production from scheduling production to resource allocation and quality management.

Level 4: Business Planning and Logistics. This level represents Enterprise Resource Planning (ERP), and it is responsible for translating business requirements to planned orders for the shop floor.

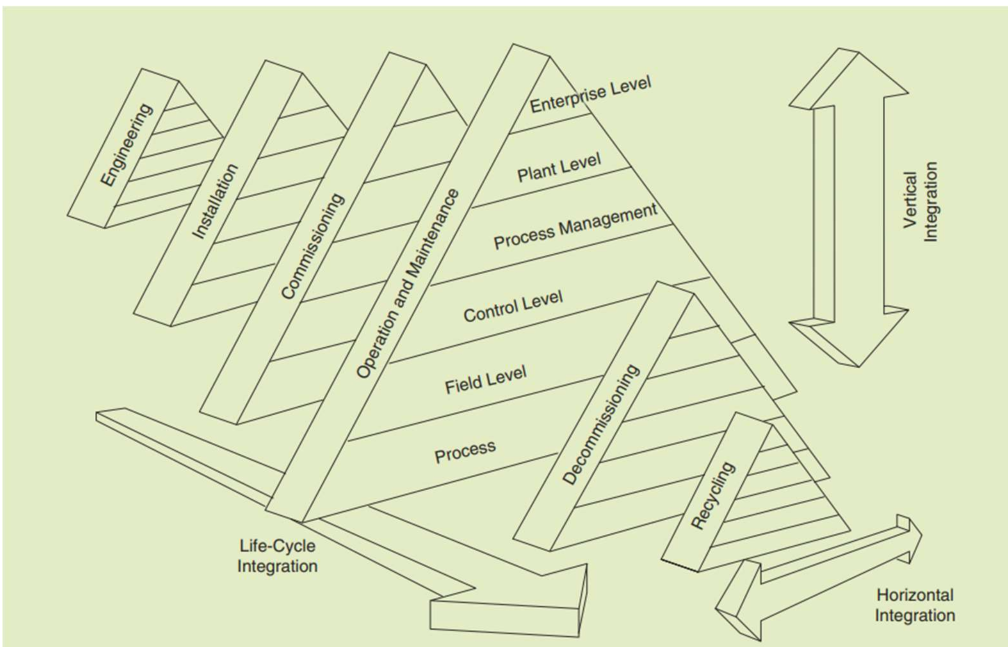


Figure 1: The different axes of automation integration [2].

ERP systems have gained significant popularity, leading to widespread adoption across global companies, with a market share reaching $50.84 billion in 2021 [3]. Despite this, investment in shop floor operations has lagged, with many companies relying on in-house solutions like spreadsheets to monitor activities [4]. However, the complexity of data acquisition and control on the shop floor has necessitated the development of more sophisticated systems, such as Manufacturing Execution Systems (MES), to address these challenges more effectively [5]. MES was first established in the 1990s as a solution to the limitations of ERP systems [6]. Based on the Automation pyramid, it seeks to connect the ERP system to the Shop floor. So why is MES not as popular as systems like ERP?

1.2 Barriers to the adoption of MES by SMEs.

An SME is any organization that has fewer than 500 employees and according to Statistics Canada, SMEs make up 98.1% of all businesses in Canada in 2021 [7]. Figure 2 gives an insight into the requirements of a factory being tagged as Industry 4.0. The first two stages are essential for Industry 4.0 and in turn MES.

- Computerization: This is the process of transitioning from manual data entry to the use of computers in the production cycle. SMEs must focus resources on building an effective Information Technology Infrastructure.
- Connectivity: Once computerization is achieved, there needs to be constant communication between each component of the production cycle ensuring each component receives and sends the required communication. Industry 4.0 is about the integration of all components in the industry.

Statistics Canada conducted research in 2022 analyzing the innovation activities of SMEs and it was found that 71.6% have no level of innovation in their businesses [8]. Another research was conducted on factors contributing to the non-adoption of advanced technologies.

The study revealed that a significant number of SMEs perceive that advanced technologies are not applicable to their business activities. This may point to an ineffective closed loop within most MES systems. A key contributing factor is the absence of clear performance measures and Key

Performance Indicators (KPIs) to evaluate the efficiency of Manufacturing Execution Systems (MES) within these companies [9]. Effective measurement of organizational performance should be grounded in factors such as productivity, machine downtime, inventory costs, and knowledge management, all of which necessitate data collection from the shop floor and its processing through the MES, hence the need for digitization and connectivity in the industry.

Additionally, the high costs associated with these technologies and the lack of technical skills required to support them were identified as major barriers to adoption [10].

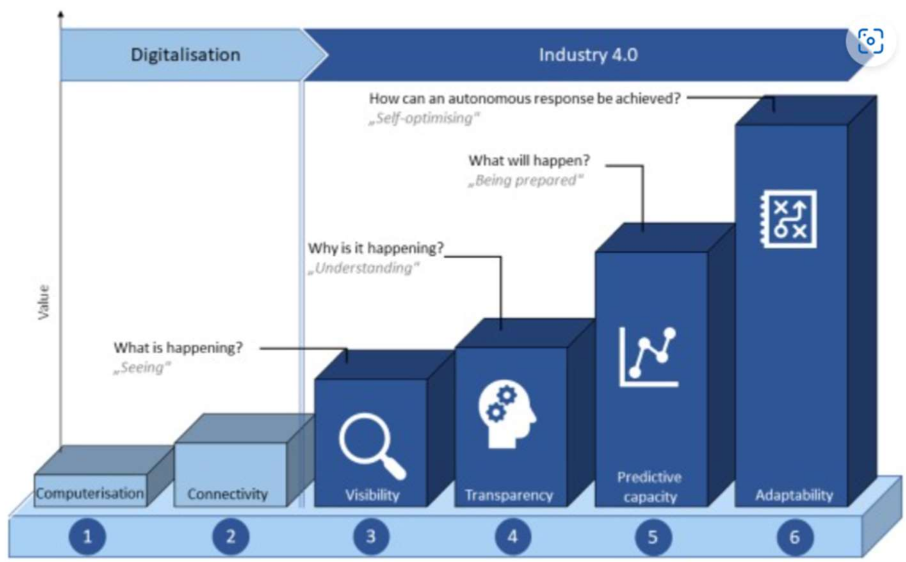


Figure 2: Industry 4.0 Maturity model [11].

The definition of MES and its core functions lack standardization across the industry. MESA (Manufacturing Enterprise Solutions Association) introduced its MESA Model outlining what it considers to be the essential functions of MES. Nevertheless, not all of these functionalities are found in present MES solutions, a topic that will be examined further in the literature review.

A case study on the benefit of MES in the semiconductor industry discovered that MES cannot monitor and track shop floor activities in real-time relying on manual inputs which requires a lot of time and in some cases could be inaccurate [12].

1.3 Motivation

Delving into the significance of Manufacturing Execution Systems (MES) and their pivotal role in modern manufacturing, it becomes evident that certain barriers hinder the widespread integration of MES systems into production processes. Two primary factors stand out: cost and ease of integration. The annual price range for MES systems is vast, spanning from $24,000 to $1 million USD.

For Small to Medium Sized Enterprises (SMEs), this cost may outweigh the perceived benefits of adopting MES into their operations. Consequently, there is a growing demand for a cost-effective MES solution that doesn't compromise on quality, especially for businesses looking to transition to Industry 4.0. The current landscape underscores the need for an affordable MES system that serves as a stepping stone into the realm of Smart Manufacturing without necessitating the complete replacement of existing MES solutions.

This study is dedicated to developing a solution tailored to the needs of small to medium-sized enterprises, aiming to bridge the gap between budget constraints and the advantages offered by MES systems. The envisioned solution seeks to be a viable and accessible option, ensuring that companies can embrace Industry 4.0 without sacrificing financial prudence or the benefits associated with MES implementation.

1.4 Thesis Layout

This thesis contains six chapters.

Chapter 1 provides a background into Industry 4.0 and MES, outlining their significance for SMEs and the advantages they offer.

Chapter 2 investigates the barriers SMEs encounter when adopting Industry 4.0 with an emphasis on MES. This section delves into the current state of MES, including its functionalities, costs, and areas needing further research.

Chapter 3 proposes an affordable MES system, exploring the key functionality essential for Industry 4.0.

Chapter 4 provides the framework behind the MES system exploring the architecture and the software libraries required for effective development.

Chapter 5 examines strategies for the implementation of the MES system exploring the potential ways it can be deployed to a client.

Chapter 6 summarizes the research findings and identifies future work.

Chapter 2. Literature Review of MES

To create a solution that still meets industry standards, a literature review was conducted to see the current state of MES, exploring its functions, costs, and research gaps.

Over the years, there has not been a set standard of MES functionalities, consequently, various organizations have come up with what they believe are the core features of a MES system.

Research Questions:

1.) What is MES and the benefits it provides?
2.) What are the current features of MES set by standards and vendors?
3.) How do they compare to each other?

2.1 Manufacturing Execution System

ERP systems are designed to streamline and enhance business operations within an organization. However, they face limitations in acquiring data at a sufficiently rapid pace, typically daily, which can impede their ability to respond promptly to changes originating from the shop floor. The concept of MES emerged due to the manufacturing industry's need to meet market demands in terms of responsiveness, quality, compliance with standards, cost reduction, and meeting deadlines [5].

In Figure 3, we can observe the flow of information across Levels 1 through 4 in the Automation Pyramid. Data from the shop floor provides real-time updates on equipment status and current production activities, serving as upstream input. This data is crucial for evaluating plant performance using a standardized metric known as Overall Equipment Effectiveness (OEE). OEE assesses equipment effectiveness based on three key factors: Availability, Performance, and Quality.

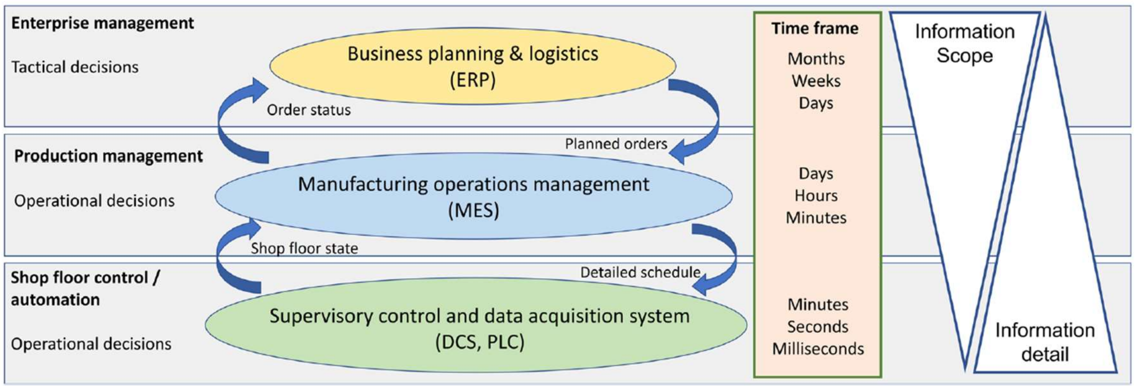


Figure 3: Information flow between the Automation Layers [6].

Availability measures the actual duration an equipment operates during a specific period, often a shift cycle, in comparison to its scheduled/planned runtime. This metric is essential for evaluating how efficiently equipment is utilized and how well it adheres to production schedules. Formula: Availability = $\frac{\text{Actual Time}}{\text{Scheduled Time}}$.

Quality compares the number of good parts produced to the number produced in each shift cycle.

Quality = $\frac{\text{\# of Good parts}}{\text{\# of Parts produced}}$.

Performance compares the parts produced (good/bad) to the theoretical number of parts (target) that should be produced when the machine is available. Formula: Target= $Scheduled\ time * standard\ rate$.

Performance = $\frac{\text{\# of Parts produced}}{\text{Target}}$.

These three are then multiplied to achieve the OEE score. OEE scores determine how effective a manufacturing process is while the different subcomponents show what areas a process may be poorly done in.

Downstream data flow takes planned orders from the ERP system and translates them into work orders for production [6]. The Key functionality of MES is its ability to connect the business side of a company to the shop floor. KPIs about the shop floor can be sent to the ERP for better decision-making as to when to release orders to the MES. This enables smart production bringing about the use of Cyber-Physical Production Systems and Cyber-Physical Systems [6]. Cyber-physical systems are physical objects or products equipped with embedded software and computing capabilities, allowing them to embody the "Smart" concept by possessing self-management capabilities. Cyber-physical production systems are the machinery used for production imbued with computing power which enables them to provide information about their state for autonomous decision-making [13].

MES systems have historically been modular typically having systems for each or a group of functions [5]. SEMATECH created an open framework which is used to integrate MES applications in the semiconductor industries [14]. Opcenter is a great example of this offering different MES systems for different industries including Opcenter Execution Discrete, Opcenter Execution Process, Opcenter Execution Electronics, etc [15].

MES through surveys and customer reviews has been known to provide benefits such as reducing lead times, improving product quality, and responding to unforeseen events [16].

MES and MOM (Manufacturing Operations Management) are word that are typically used interchangeably but what is the difference between both? According to Automation.com, a subsidiary of the International Society of Automation (ISA), MES focuses primarily on managing and executing manufacturing operations processes, including production, quality, logistics, and labor tracking. MOM, on the other hand, extends MES capabilities to include broader aspects such as warehouse management, maintenance, machine integration, and supply chain management, operating as a comprehensive and configurable manufacturing platform that supports decision-making with more extensive data and intelligence [17]. Although MES and MOM are frequently used interchangeably in the literature, this thesis will consistently use the term MES for clarity.

2.2 Current Features of MES set by standards

The Manufacturing Enterprise Solutions Association (MESA) was created in the 1990s and was introduced to address the increasing complexity of MES systems. It believes that MES is defined based on the functions it should provide in manufacturing.

2.2.1 History of the MESA Model

In 1997, MESA introduced the MESA-11 model which defines the 11 functions an MES system should provide. Labour Management. Quality Management, Data Collection, Maintenance Management, Production Tracking & Genealogy, Dispatching Production Units, Operations/Detailed Scheduling, Resource Allocation & Status, Performance Analysis, Process Management and Document Control.

In 2004, they introduced the Collaborative MES or C-MES model which focused on the core functions of MES and how they interact with the business side. C-MES reduced the 11 functions defined in MESA-11 to 8 core functions which include: Product Tracking & Genealogy, Resource Allocation & Status, Performance Analysis, Process Management, Data Collection Acquisition, Quality Management, Labour Management, and Dispatching Production Units.

In 2008, they introduced another model called the Strategic Initiatives Model, Figure 4, which defines the interrelationships between strategic initiatives, business operations, manufacturing operations, and production.

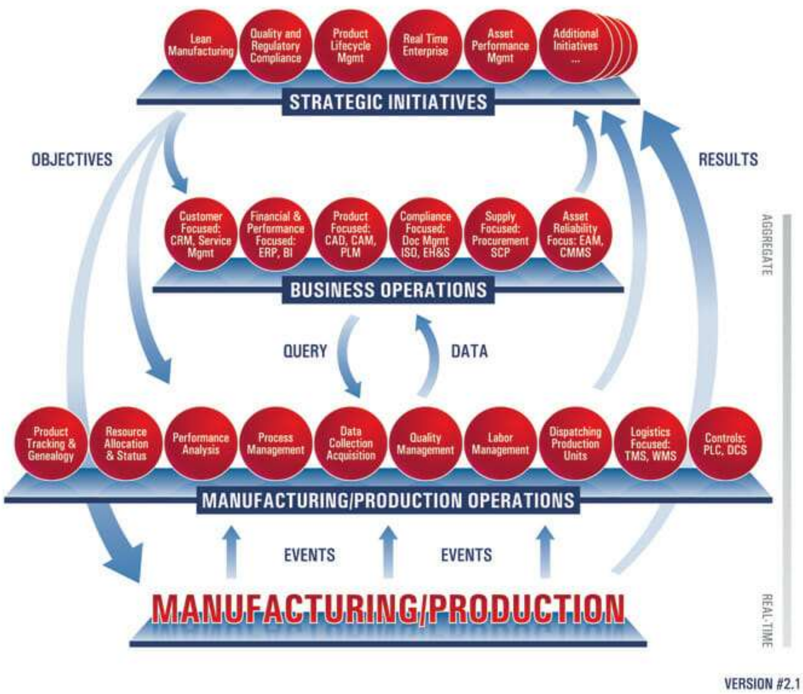


Figure 4: Strategic Initiatives Model [18].

These strategic Initiatives include lean manufacturing, quality and regulatory compliance, product lifecycle management, real-time enterprise, asset performance management (APM), real-time enterprise, manufacturing performance metrics, and return on investment (ROI). There has been a need for increased efficiency and improved quality in manufacturing hence the need to define how the objectives from the initiatives are translated to functional requirements for the MES and ERP.

In 2022, MESA introduced their new model which is centered around Smart Manufacturing. While MESA is still perfecting the model, there are 3 main concepts that the model introduces, Lifecycles, Cross-Life cycle threads, and Enabling Technologies. It is intended to provide a skeleton that can be used to define a lot of use cases by combining the different lifecycles using the cross-lifecycle threads using enabling technologies.

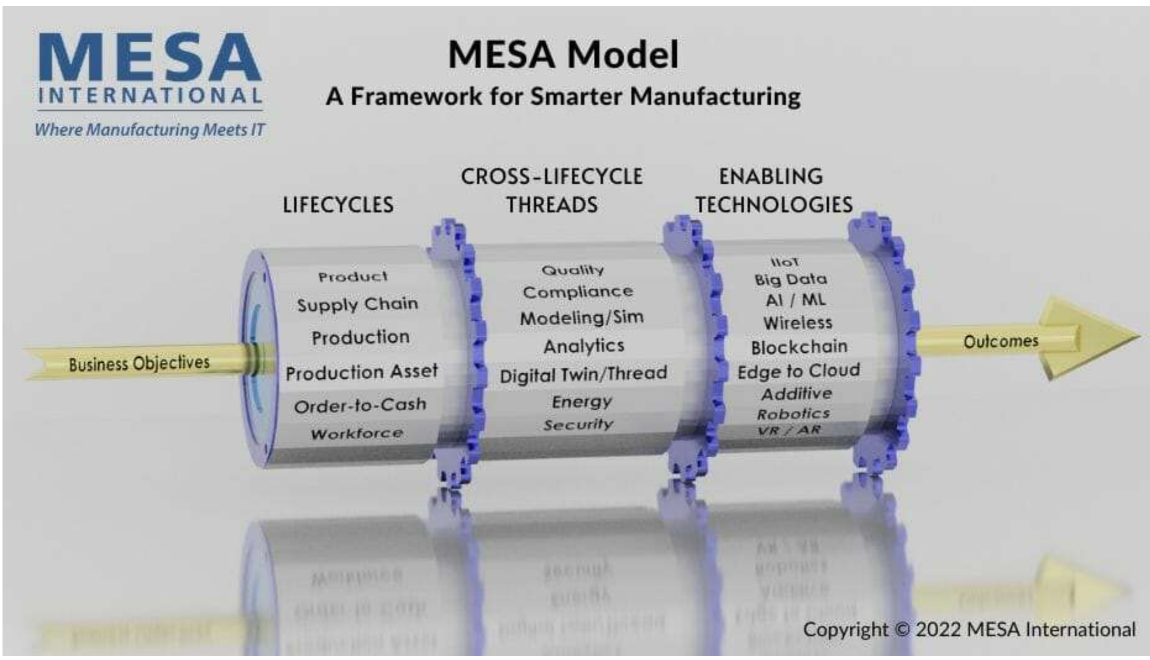


Figure 5: 2022 MESA Model, Smart Manufacturing [18].

Lifecycles represent the operations within a business that need to be optimized and streamlined. They include Production, Supply Chain, Product, Production Asset, Order-to-Cash and Workforce. These lifecycles apply to all manufacturing enterprises and the goal is to make all these lifecycles smart by working together.

Cross-Lifecycles threads are used as a bridge between the different lifecycles. They include Quality, Compliance, Energy, Analytics, Security, Digital Twin, and Modeling/Simulation. A use case can be, to ensure the quality of a product, the product lifecycle, supply chain, production, and workforce needs to be integrated.

Enabling technologies gives the ability to achieve the cross-lifecycle threads. They include the industrial internet of things (IIOT), big data, artificial intelligence (AI)/ machine learning (ML), virtual reality (VR)/augmented reality (AR), edge to cloud, blockchain, additive, robotics, and wireless. For example, a company is seeking to reduce the amount of energy (Cross-Lifecycle) needed for production (Lifecycle). To accomplish this, data needs to be collected to determine how much energy is used and what parts of the production use the most energy. IIOT can be used to connect the different equipment sharing the amount of energy consumed at a given time and decisions can be made about reducing/eliminating waste.

How does MES fit into this new MESA Model? Figure 6 shows 3 different lifecycles, Product, Production, and Business. These 3 lifecycles intersect at the Automation Pyramid. As previously stated in the introduction, an important function of MES is quality (cross-lifecycle thread), and one of the ways quality is measured is through OEE and to get data to calculate OEE, enabling technologies must be used.

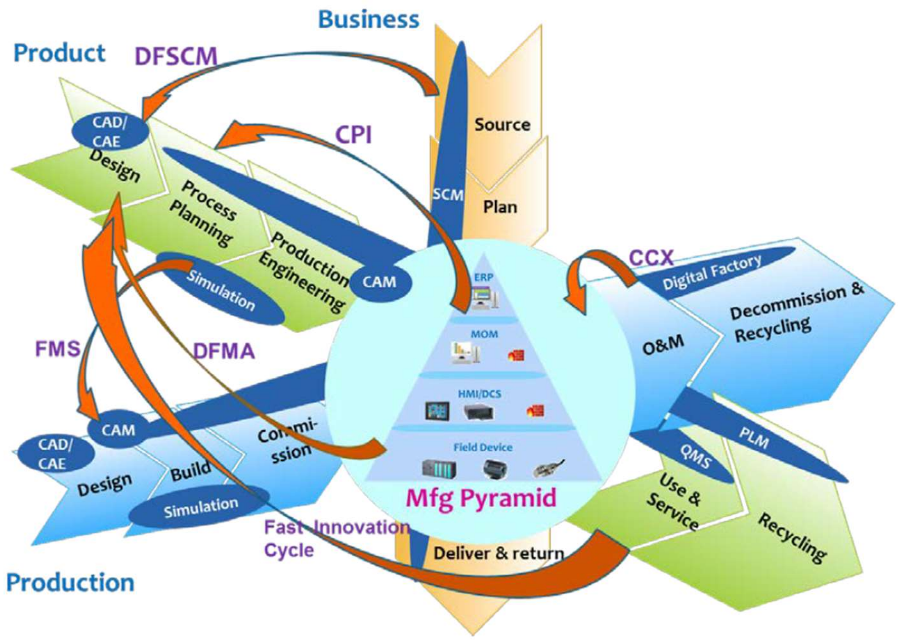


Figure 6: Smart Manufacturing Ecosystem [19].

2.2.2 NAMUR

NAMUR was formed in Germany by a group of experts specifically in the chemical, pharmaceutical, and petrochemical industries and builds on the ISA S95 definition [20]. Figure 7 highlights the important functionalities an MES system has right from production planning to Inventory management, Production control & Material flow, production documentation, and quality management.

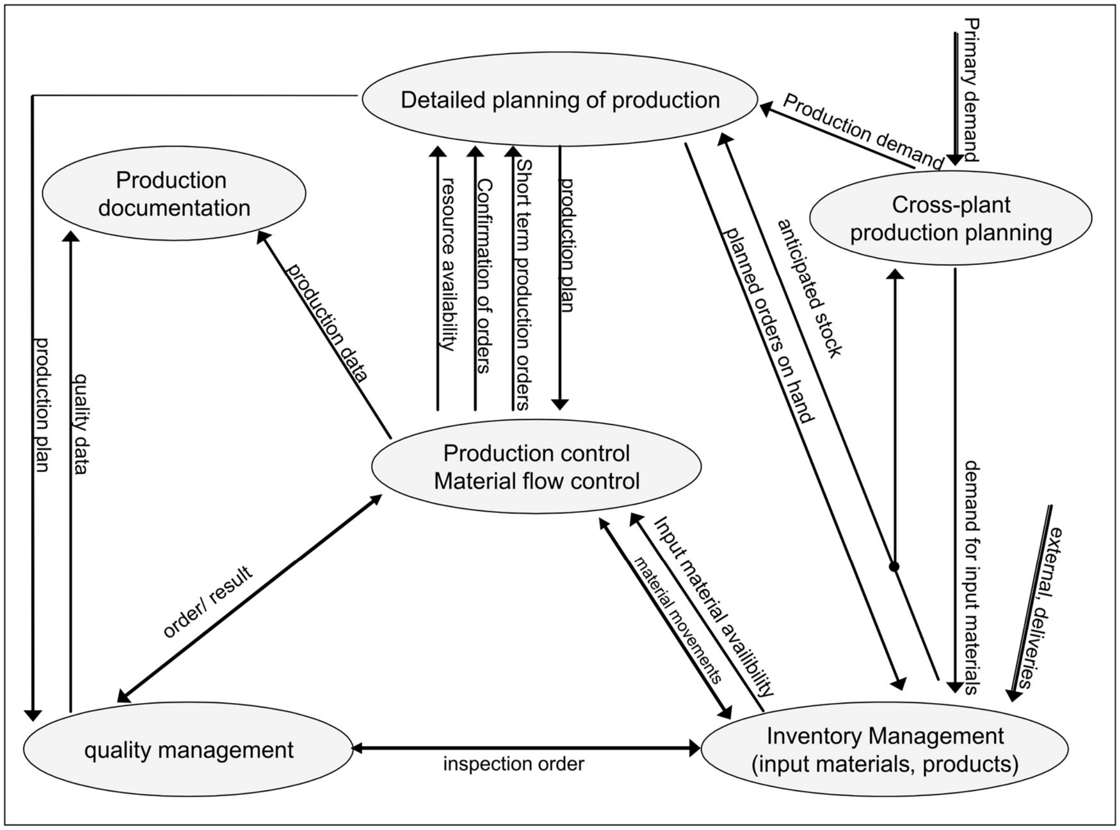


Figure 7: NAMUR MES Functionality [20].

2.2.3 VDI

The verein deutscher ingenieure (VDI), which translates to the Association of German Engineers, is an organization in Germany that provides standards and fosters innovation within German society. They released VDI 5600 which offers guidelines for implementing MES building on the MESA standard and updating it to reflect challenges faced by European manufacturers [21].

2.2.4 NIST

The National Institute of Standards and Technology (NIST) is a federal agency that falls under the United States department of commerce. One of its functions includes providing measurements and standards in Manufacturing processes. In the year 2000, they released an article in response to OMG's (Object Management Group) request for information concerning the MES area [22]. Just like VDI, NIST's standard builds on the MESA standards defining its standard for multiple software which are integrated to become a Distributed MES system.

2.3 Current MES Solutions

Gartner has released a graphic known as the "Magic Quadrant," categorizing popular MES solutions into four distinct quadrants. In this discussion, our focus will be on the Leaders quadrant, shown in Figure 8, which represents companies that demonstrate outstanding performance in MES core functionalities and are strategically positioned for future success [23].

Figure 8: Gartner Magic Quadrant [24].

For an MES system to qualify for inclusion in the Magic Quadrant, it must meet Gartner's Core MES functionality criteria. These criteria encompass various aspects such as manufacturing data management, operational data storage, dispatching, production management and execution, in-process quality monitoring, manufacturing-related quality management processes, procedural enforcement, tracking and genealogy, integral analytics and reporting, as well as extensive integration capabilities leveraging modern technology approaches.

Gartner Core MES Functionalities

Manufacturing data management: This capability refers to handling data gathered manually by users, periodically from data storage systems like data historians, or directly from equipment. The data encompasses areas such as quality, process status, job/order status, regulatory compliance, labor tracking, and product genealogy, among others. It may also involve managing master data to support manufacturing operations.

Operational data store: Involves having a database where all data that will be used by the MES is stored. This widely ranges from a basic relational database to an IIOT (Industrial Internet of Things) platform. This database provides a platform for managing manufacturing data effectively.

Dispatching: This involves assigning work orders based on information from the ERP system. It also works in hand with resource availability, and scheduling demands to effectively manage operations in the facility.

Production management, execution, and in-process quality monitoring: This encompasses overseeing the production process from the order release to shipment or use, monitoring and recording all aspects of production.

Manufacturing-related quality management processes: This function includes managing in-process quality through the collection of quality data, both from human input and automated machine-driven processes, along with tracking and monitoring quality throughout production.

Procedural enforcement: This guarantees that all manufacturing steps are executed in the proper sequence, at the appropriate times, by trained and certified personnel, and in compliance with quality standards.

Tracking and genealogy: This involves tracking items using various unique identifiers as well as equipment, and operators involved in the production of the WIP or finished goods.

Integrated analytics and reporting: These are methods used to produce key performance indicators (KPIs), conduct advanced analytics, and create dashboards and datasets for monitoring and reporting performance.

Sophisticated integration capability: This involves the use of modern integration techniques to communicate with other levels in the automation pyramid.

2.3.1 Plex Systems (Rockwell Automation)

Plex Manufacturing MES stands at the forefront of MES solutions, celebrated for its pivotal role in advancing smart manufacturing across the globe. Its suite of features is designed to enhance manufacturing operations through increased visibility and connectivity among all processes involved. Key features offered by Plex include Production Finite Scheduling, Closed-Loop Quality Management, Inventory Management, and comprehensive Production Management.

In our quest to understand the financial aspect of adopting Plex's MES system, a dialogue was initiated with Plex Manufacturing. The outcome introduced us to two pivotal options: the Plex MES – Private Cloud, and their Production Monitoring solution. The Plex platform distinguishes itself through the seamless integration of its ERP (Enterprise Resource Planning) and MES (Manufacturing Execution System) systems, promising a unified approach to manufacturing management.

Delving deeper into the Production Monitoring aspects of Plex's offerings, we uncover its foundational requirements. For a successful deployment, certain static data elements must be configured accurately. These include:

Shifts: The operational timelines during which production activities are conducted. Proper scheduling and management of shifts are crucial for optimizing production efficiency and worker productivity.

Work center: These are specific locations or machines within a manufacturing facility where production tasks are performed. Each WorkCentre is a critical node in the manufacturing process, requiring precise configuration to ensure smooth operations.

Work center Status: These statuses provide real-time insights into the operational state of each WorkCentre, such as active, idle, or under maintenance. This data is vital for monitoring production flow and identifying bottlenecks.

Process Routing: This involves defining the sequence of operations or steps that materials undergo through the WorkCentre. Proper process routing ensures that the manufacturing process is efficient and products meet quality standards.

Approved work centers: Identifying which Work Centers are approved for specific tasks or production lines is essential for maintaining quality control and optimizing resource allocation.

Plex Settings: A series of configurations within the Plex system that need to be tailored to the specific operational needs and preferences of the manufacturing setup.

Exploring the cost implications and the functionality of Plex Production Monitoring is a journey toward optimizing manufacturing efficiency. By understanding and configuring these fundamental aspects, businesses can leverage Plex's robust platform to enhance their production visibility, control, and overall efficiency, marking a significant step toward achieving smart manufacturing excellence [25].

These services encompass a range of offerings, including Plex MES – Private Cloud, Quality Management System, Tooling, and Plex MES Automation and Orchestration. What sets these solutions apart is their amalgamation of both ERP (Enterprise Resource Planning) and MES (Manufacturing Execution System) capabilities, although distinguishing which aspects cater specifically to ERP or Plex can be challenging.

On average, the adoption of Plex Systems, which encapsulates a blend of ERP and MES functionalities, amounts to approximately $60,000 USD annually. This investment encompasses not only the initial setup but also ongoing maintenance and support, ensuring a seamless and efficient integration of manufacturing processes.

2.3.2 Opcenter Execution

Opcenter Execution Discrete is an MES system designed for intricate jobs within factories providing the following functionalities: Production process and flow control, Integration with MOM and PLM, product route enforcement, execution management, tracking and tracing, defect tracking and nonconformance management, paperless manufacturing and reporting, electronic data collection, and additive manufacturing support [26].

Opcenter joins a lot of companies moving from perpetual licenses to subscription-based licenses having different modules to better tailor MES to customers' specifications.

User management is crucial for any system as it enables the control of access to sensitive information, ensuring that only individuals with the necessary expertise and position within the organizational hierarchy are authorized to perform specific tasks [26].

In Opcenter Execution Discrete, the fundamental elements of user management include:

- Users and groups
- Roles
- Certifications

The foundation of all production engineering in Opcenter revolves around processes. A process refers to the sequential operations and steps needed to produce a particular product. It is similar to what Plex Systems defines as a process route. A group of all processes is defined in the bill of process (BOP) and it encompasses all processes as well as their sub-elements, equipment and materials used in production.

Opcenter Execution Discrete tracks information related to material consumption, assembly, and disassembly. The genealogy report screen presents data related to a batch, serial number, or work order in a hierarchical tree view. According to AWS marketplace, the cost of purchasing a one year license for 20 users is about $121,000 CAD using the current exchange rate of a dollar USD to 1.37 CAD [27].

2.3.3 Proficy Smart Factory (GE Digital)

GE Digital takes a different approach from Opcenter offering a single MES solution it calls, Proficy Smart Factory, for all process, discrete, and mixed manufacturing. It functions include: Efficiency Management, Quality Management, Production Management, Batch and Process Analysis, Manufacturing Product Data Management, Scheduling, Digital Operations, Hybrid Cloud Industrial Data Management for Analysis and Reporting, Industrial Advanced Analysis, and Work Process Management [28].

Efficiency Management: Proficy Smart Factory tracks and monitors key performance indicators (KPIs) including Overall Equipment Effectiveness (OEE) to assess the productivity of a facility. This provides manufacturers with visibility into the performance of each station, allowing them to identify and address any issues efficiently.

Quality Management: The solution offers real-time trends, statistics, Statistical Process Control (SPC), and notifications to maintain control over quality levels. It integrates data from manual and automated sources, ensuring comprehensive information storage with support for 21 CFR Part 11 compliance. Moreover, Proficy Smart Factory aids in reducing production costs by minimizing waste and rejects. It captures reasons for out-of-spec conditions, facilitating faster resolution of quality issues. This leads to fewer rejects and downgrades, and reduced customer complaints and returns.

The pricing for Proficy Smart Factory is $115, 080 CAD for MES [29].

2.3.4 iTAC Software

The iTAC.MOM.Suite ensures seamless access to interconnected data across departments, enabling comprehensive control over production processes. This tailored system is designed to provide real-time monitoring of all processes for increased efficiency and flexibility, leading to time and cost savings in production[30]. Like the other MES Vendors, its functions include Work Order Execution, Traceability, Scheduling, Reporting, Maintenance, and Material Management. While integration is key, iTAC primarily offers ERP integration to SAP, and integration with other

ERPs requires less standardized methods [24]. The price of iTAC MES Suite is a one-time fee of about $37,000 per user [31].

2.3.5 Werum PAS-X (Korber)

PAS-X is an MES system developed specifically for the pharmaceutical industry. In the pharmaceutical industry, MES systems must adhere to stringent regulations set by authorities in Europe and the U.S., such as the FDA's GMP and electronic records requirements, to ensure high-quality software development and maintain compliance. The GAMP V-model is widely accepted for guiding the development and validation of software through specific phases, each requiring formal verification to confirm compliance with set criteria. Comprehensive change management and quality management systems are essential to maintain consistent documentation and prove compliance throughout the software lifecycle [32]. No information was found on the pricing of PAS-X.

2.4 How do the functionalities of different standards compare with each other?

While comparing the functions listed by the different standards in Table 1, there is no set standard for what a MES system should be.

Table 1: MES Function comparison across automation standards [33].

	MESA	NAMUR	VDI	NIST	GARTNER
Labour Management	x		x		
Requirements Planning		x			x
Gross Planning		x			
Detailed Planning	x	x	x	x	x
Quality Management	x	x	x	x	x
Prod. Inventory Management	x	x		x	x
Resource Management	x		x	x	x
Equipment Management	x		x	x	
Manufacturing Control	x	x			x
Traceability/Genealogy	x			x	x
Production Reporting	x		x	x	x
Machine Control	x				
Production Data Acquisition	x		x	x	x
Master Data Management	x	x	x	x	x

Otto et al. presented a functional reference model for MES systems applied in the automotive industry, categorized into three groups. The model outlines core MES functionalities, functionalities partially covered by MES, and functions beyond MES scope.

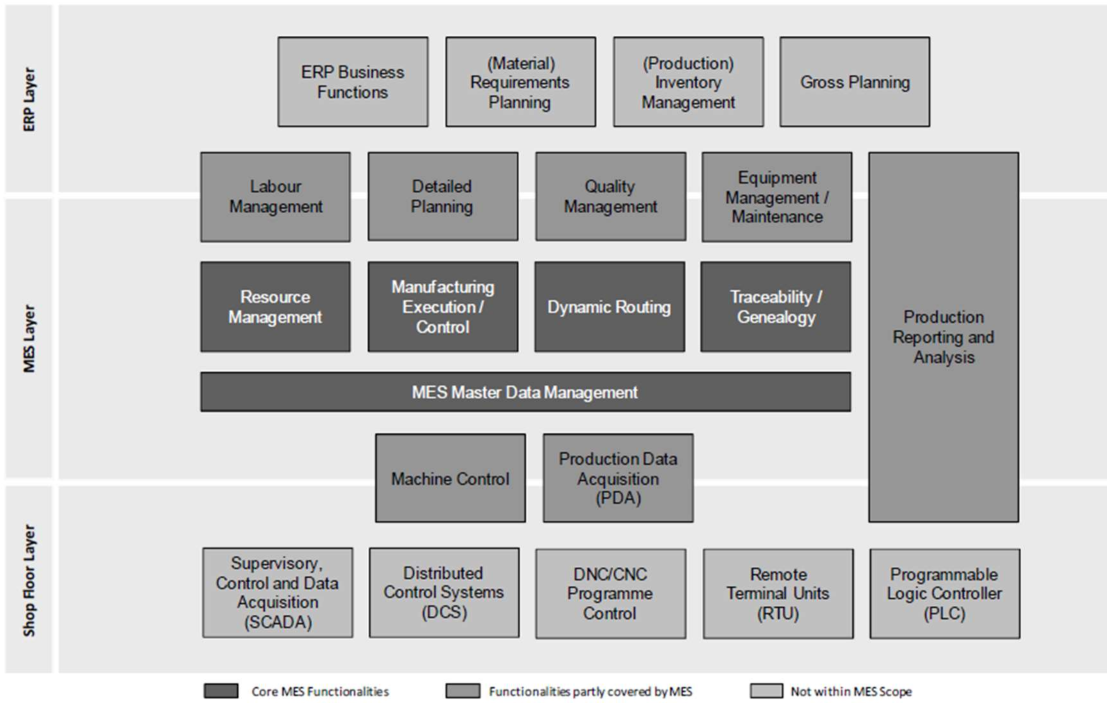


Figure 9: A reference model for MES functionalities [33].

The core functions, pivotal to MES operations, encompass:

- Manufacturing Control/ Execution manages work orders from the ERP system and converts them into recipes and control modules for the operators and Control systems.
- Traceability/ Genealogy is the ability to track the movement of products and their components during production keeping track of the “family tree” of all products, components, and processes.
- Resource Management is the management of machinery, and labor by scheduling, monitoring performance, and providing visibility of all resources used.
- Production Reporting involves monitoring and communicating the status of production activities in the facility. This involves having real-time data acquisition and performance metrics as well as traceability.

- Master Data Management involves having a centralized location where all data that pertains to the production is stored and determines which information needs to go upstream to the ERP system and which information needs to go downstream to the Shop floor.

The literature review underlines the significance of MES for SMEs and the potential benefits it offers. However, despite the extensive research highlighting these advantages, the adoption rate among SMEs remains low. Several key barriers contribute to this trend, including the lack of standardization among automation standards and vendors, the high acquisition costs associated with Industry 4.0 technologies, the absence of robust digitization processes, and an over-reliance on manual inputs.

Furthermore, while Manufacturing Execution Systems (MES) offer a wide range of functionalities that can significantly enhance operational efficiency and competitiveness, not all of these functionalities are essential for SMEs at the initial stages of transitioning to Industry 4.0. Therefore, a tailored approach that focuses on identifying and prioritizing the most critical functionalities based on the specific needs and capabilities of SMEs is crucial for facilitating a smoother and more cost-effective transition.

Addressing these challenges requires collaboration between industry stakeholders to develop a standardized framework for designing a user-friendly and affordable MES system tailored to SMEs.

Chapter 3. MES Core – Open-source MES

3.1 Introduction to MES Core

MES Core is an open-source MES system developed to solve the rising need for an affordable Manufacturing Execution System. It will play a crucial role in the manufacturing industry by serving as a vital link between planning and execution. MES Core coordinates various aspects of production, including resource allocation, process monitoring, and real-time analytics. This technology enhances visibility, control, and efficiency throughout the production lifecycle, bridging the gap between enterprise resource planning (ERP) systems and the shop floor. MES Core enables manufacturers to streamline workflows and achieve higher levels of productivity and product quality, making it a cornerstone in the pursuit of agile, data-driven manufacturing ecosystems.

3.2 What are the requirements of MES Core?

A case study was conducted on the existing manufacturing processes at the McMaster Learning Factory, an SME, which primarily produces custom-made walking canes. This facility operates on a make to order system, allowing each cane to be specifically tailored to the individual requirements of the customers, as illustrated in Figure 10.

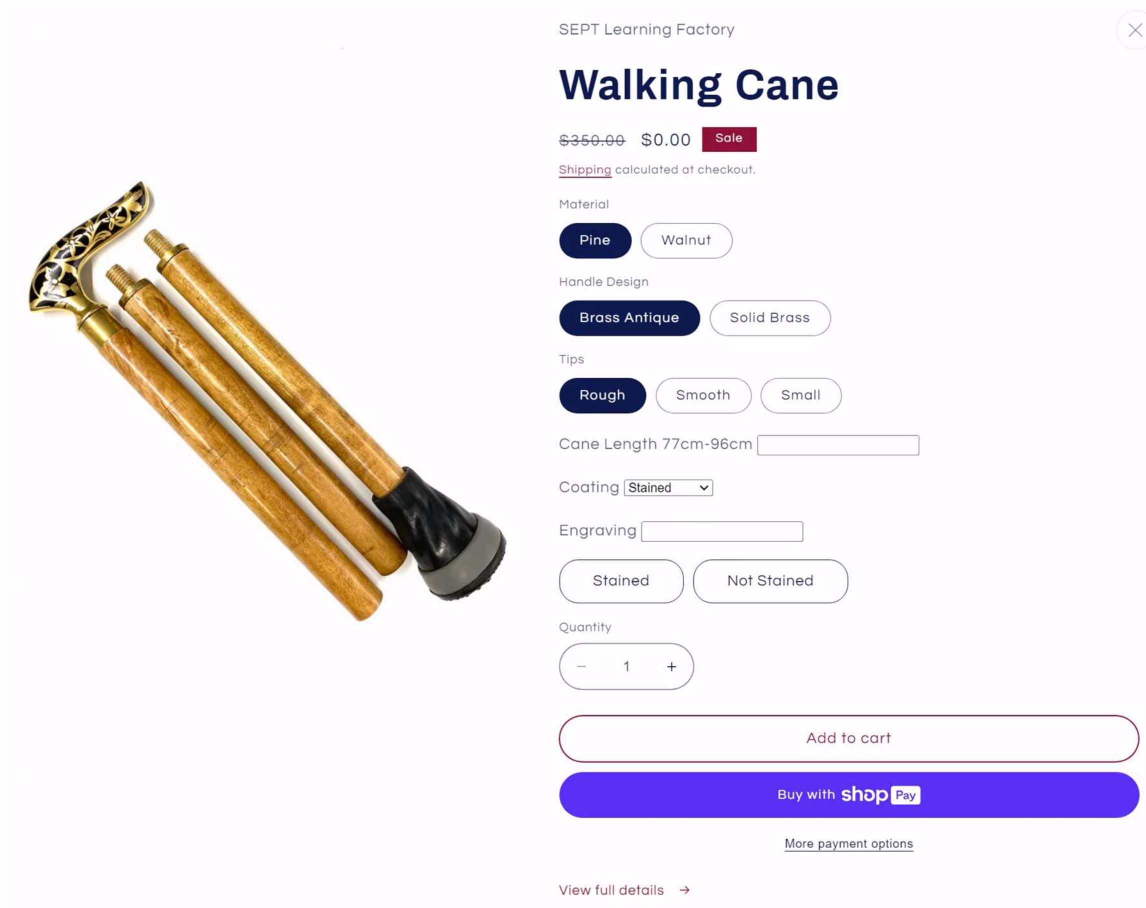


Figure 10: Learning Factory Shopify website.

The manufacturing process for walking canes at the McMaster Learning Factory begins when a customer places an order through Shopify, selecting from various customization options. Upon receiving the order, the Manufacturing Execution System (MES) generates a Work Order tailored to the customer's specifications. If the required parts are insufficient, the MES initiates an order to suppliers for the necessary components before approval for production.

The parts are then routed to the Quality Inspection station, where they undergo thorough checks to ensure they meet the factory's quality standards. Any defective parts are flagged as scrap, prompting the MES to reorder replacements. Subsequently, the parts progress through different workstations, where their production and any scrapped items are recorded.

Once the manufacturing process is complete, the finished walking canes undergo final inspection to verify their quality. If everything meets the standards, the product is dispatched to the customer, and the MES updates the order status in Shopify to "fulfilled." This streamlined process ensures that customer orders are met efficiently while maintaining high-quality standards throughout production. Refer to Appendix-B for the flow chart.

The manufacturing process of walking canes, as outlined, indeed requires key functionalities of a Manufacturing Execution System (MES) as delineated by industry standards. These functionalities—manufacturing execution, master data management, product inventory management, Traceability, and production data acquisition—are foundational to the efficiency and effectiveness of MES systems in managing complex manufacturing operations.

3.3 Modeling MES Core with UML Diagrams

A Unified Modeling Language (UML) diagram provides a visual representation of a system. It is particularly useful in breaking down complex software development, leveraging real-world entities enabling even non-technical users to understand [34].

There are several types of UML diagrams classified under structural diagrams and behavioral diagrams as shown in Figure 11. Structural diagrams establish the system's framework through the definition of objects, attributes, operations, and relationships while behavioral diagrams portray how the system behaves. It illustrates the system's actions and interactions, both internally and with external entities such as users or other systems [35].

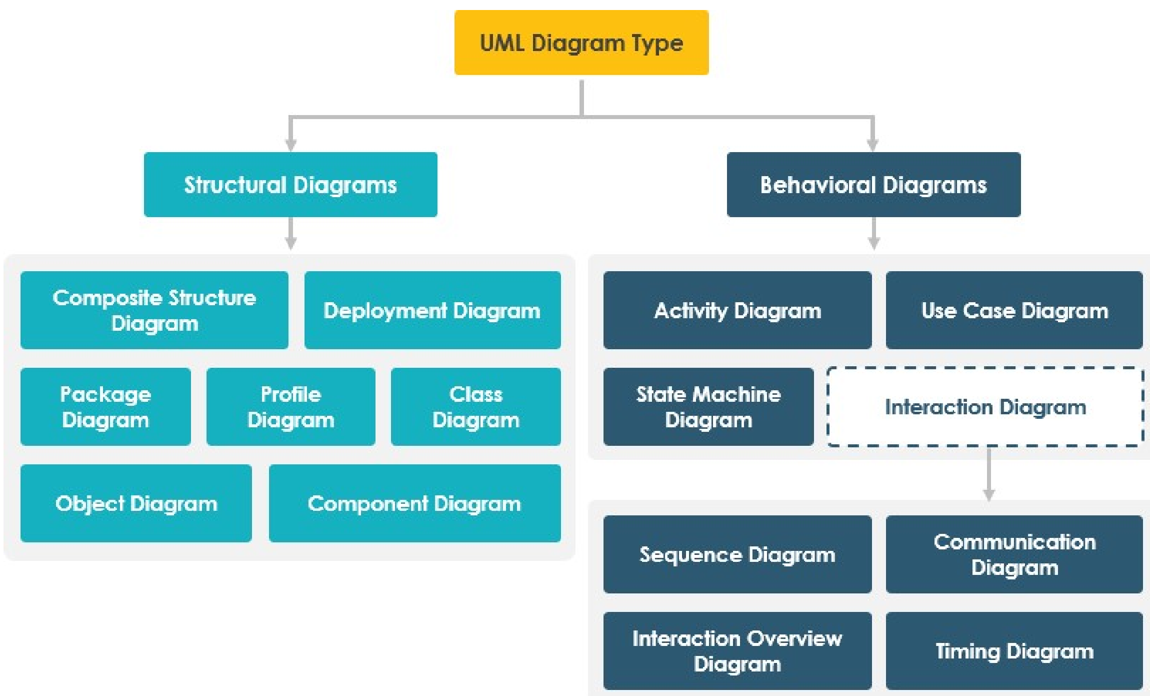


Figure 11: Types of UML diagrams [35].

A use case provides a concise description of how a system interacts with its actors to achieve specific goals, serving as a tool for documenting system requirements [36]. Use case diagrams consist of:

- Actor(s) is a person or system that interacts with the use cases. There are two types of actors, primary and secondary. Primary actors initiate the use cases while secondary actors react to the use cases. An actor must be linked to at least one use case.
- Uses case defines system function are defined by a verb. A use case may or may not be linked to an actor.
- Communication link establishes an actor to a use case.

There are also 3 types of use case relationships:

- Include relationship is used when a base use case requires the operation of the extended use case. The extended use case is denoted by the arrow pointing to it. For example, in the MES Core use case, the MES automatically commits the required inventory once the ERP sends the customer orders.
- Extend relationship is used when an extended use case is called only in certain circumstances. For example, MES only orders required resources if they are not in stock.
- Association relationship is the most basic form of a relationship establishing that there is a connection between two or more use cases.

To effectively communicate the requirements of the Learning Factory, a use case diagram has been employed as illustrated in Figure 12. This diagram outlines the various operations required by MES Core, identifying all involved actors and the actions they perform. For instance, the ERP system sends customer orders, enabling MES to automatically commit the necessary inventory and generate work orders. In cases where inventory is insufficient, a purchase order is dispatched to the respective supplier.

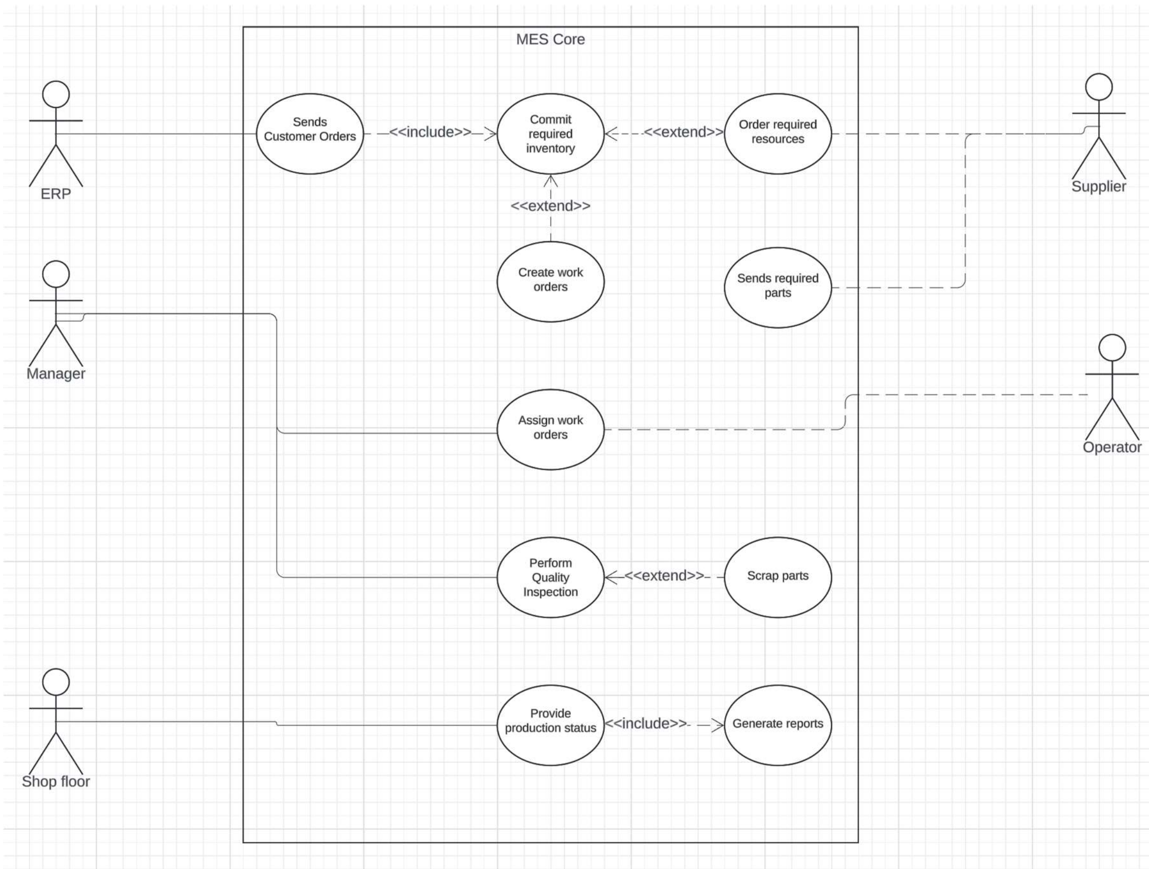


Figure 12: MES Core Use case diagram.

A UML class diagram will be utilized to outline the system's structure, simplifying its representation. Separate UML class diagrams will be created to address the various requirements of the MES Core. MES Core will be broken down into four different modules, manufacturing execution module, master data management module, product inventory module, and production monitoring module with supporting functions.

A UML class diagram comprises three sections: the top section displaying the class name, the middle section listing all attributes defining the class, and the bottom section detailing any methods or functions associated with the class.

Attributes can have different types of visibility. A private attribute, denoted by a '-' sign prefixing the attribute name, signifies that only members of the same class have access to that attribute. On the other hand, a public attribute, denoted by a '+' sign, indicates that members of any class can access that attribute. Lastly, a protected attribute, denoted by a '#' sign, denotes that only members of the same or derived class have access to that attribute.

Different types of relationships exist between classes:

1. Inheritance: This relationship is typically between a parent class and a child class where the child class has access to all the attributes of its parent class. For example, a circle, rectangle, and square have one thing in common, they are all shapes. In this case, the shape is the parent class, and all the child classes inherit attributes from the shape class. In a UML diagram, an inheritance relationship is defined using a closed arrowhead pointing towards the parent class.
2. Association: This relationship defines that there is a connection between the two classes. It is represented by a solid line between the two classes.
3. Aggregations: This relationship defines that a class is part of another class however can exist on its own. For example, a leaf is part of a tree. There are also cases of multiplicity where many leaves can be part of one tree. This relationship is denoted using a solid line with an unfilled diamond towards the tree class.

4. Composition: This relationship is similar to aggregation, however in this case, a class cannot exist without the other class. This relationship is defined using a solid line with a filled diamond.

Multiplicity explains the ratio of objects between classes that take part in the relationship. These include exactly one – 1, zero or one – 0..1, many – 0..* or *, one or more – 1..*, the exact number, 3..4 [37].

3.3.1 Manufacturing execution module

Product definition within the MES Core involves mapping out the process route and outlining the sequential steps to transform raw materials into finished products. These routes are critical and encapsulate key details, including the type of operation, the designated workstation (e.g., CNC machine), and the requisite parts for a specific operation. For instance, a process route might involve milling as the operation, a CNC machine as the workstation, and a specific part, like a block, as the material to be machined. The outcome of a process route can manifest as either an existing subpart, a new work-in-progress (WIP) part, or a new product. Figure 13 shows the classes involved in manufacturing execution and how they are all connected.

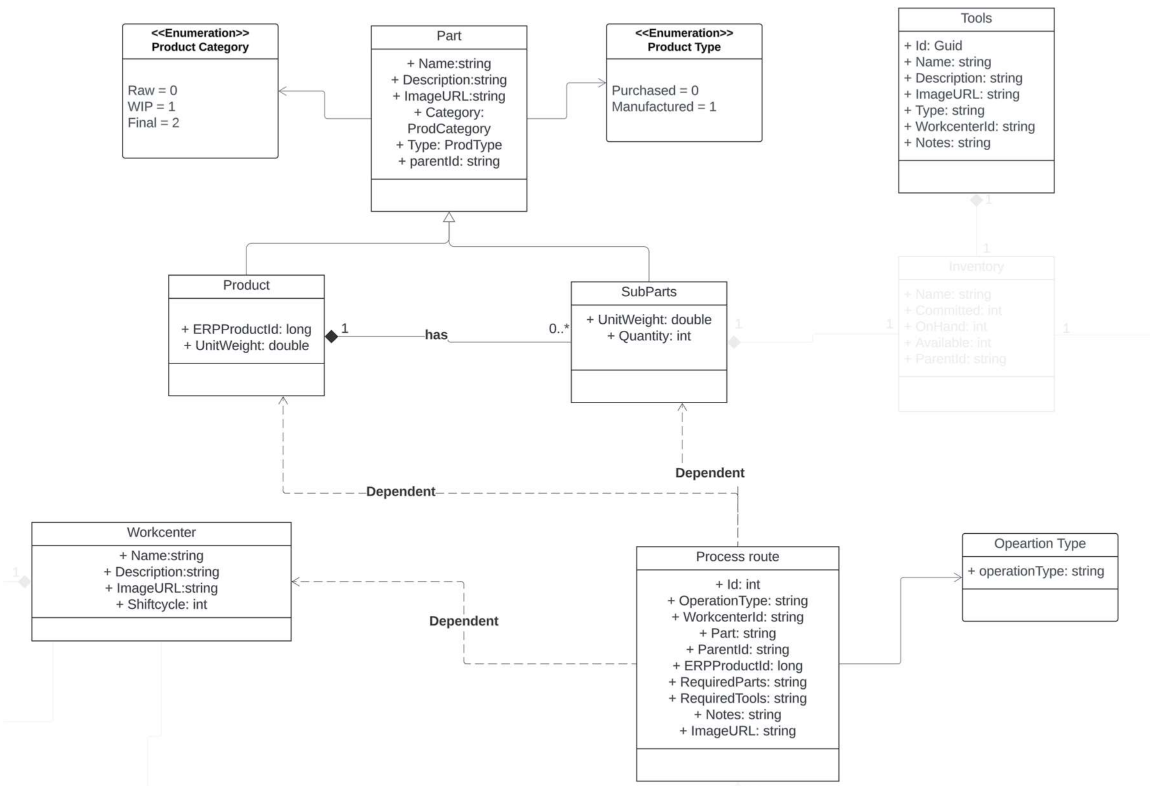


Figure 13: Manufacturing execution class diagram.

A WorkCentre serves as the physical station within this process, encompassing assembly stations, work areas, and specific manufacturing equipment such as but not limited to computer numeric control (CNC) machines, 3D printers, or coordinate measuring machine (CMM) devices. Each work center is characterized by essential fields—name, description, image, and shift cycle, where the shift cycle represents the estimated daily operational duration.

A product defines the physical product being manufactured. It can be a standalone product or have multiple subparts. Both product and subpart class inherit from the part class as they are both parts. Key attributes of the part class are its category and type which specify if it is a raw, work in progress (WIP), or final and if it is purchased or manufactured in-house.

3.3.2 Product inventory module

Effective inventory management is a critical component in the realm of manufacturing. A company's success hinges on its ability to effectively monitor the quantity of inventory at its disposal and to seamlessly trace its utilization in the production process. Furthermore, maintaining a vigilant eye on suppliers and implementing timely reordering strategies when inventory levels dip is paramount.

Within the Manufacturing Execution System (MES) core, a comprehensive recording system is established for all resources needed for production including tools, sub-parts, and extra materials as shown in Figure 14.

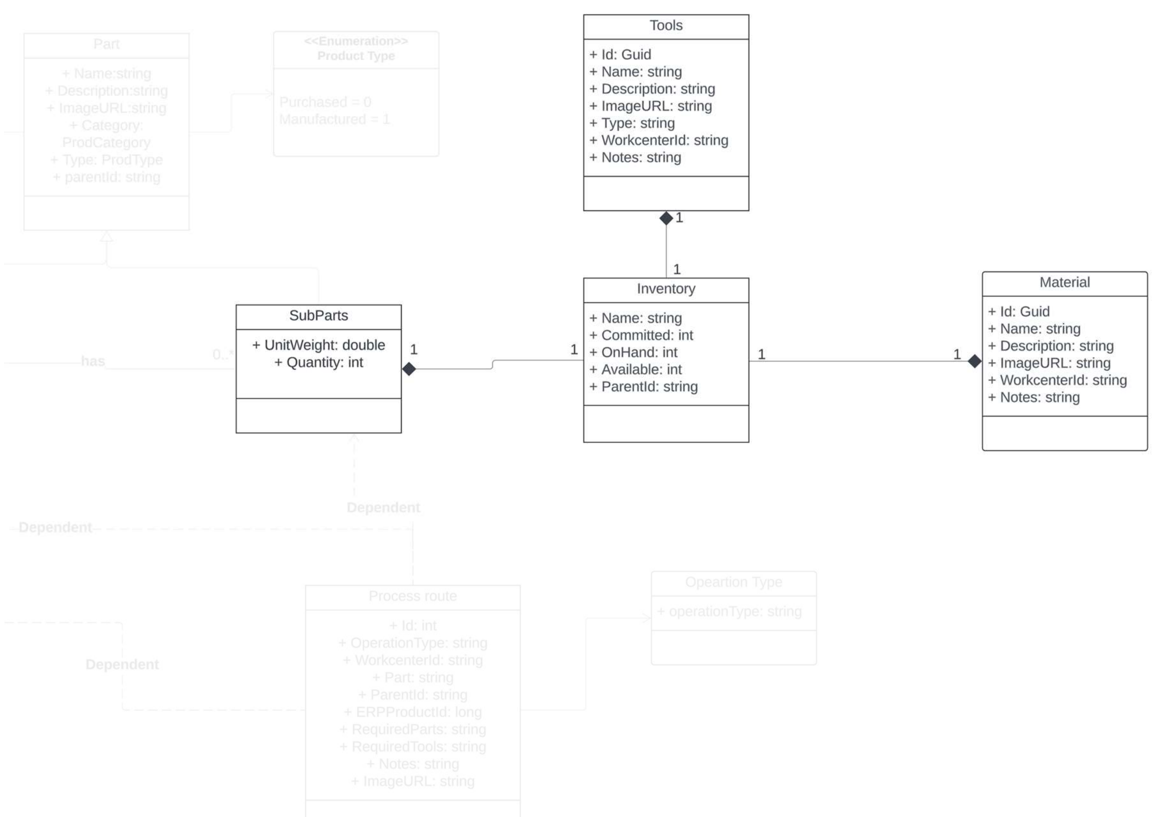


Figure 14: Product inventory class diagram.

The Inventory table was modeled after Shopify's inventory system and modified to be used for MES Core. This inventory tracking system comprises three pivotal records: Inventory On-Hand, Inventory Committed, and Inventory Available.

Firstly, Inventory on hand serves as the definitive metric for the total quantity of inventory available for a specific part or product. It encapsulates the tangible assets readily accessible within the company's facilities.

Secondly, Inventory Committed encapsulates the total count of parts that have been allocated and earmarked for fulfilling customer orders. This record signifies the inventory that is in the process of being utilized to meet existing commitments.

Finally, Inventory Available is the net result of subtracting Inventory Committed from Inventory On-Hand. This metric represents the actual quantity of inventory that is currently unallocated and available for deployment in various production processes. In essence, Inventory Available serves as a real-time indicator of the surplus inventory that can be strategically leveraged to meet unforeseen demands or production fluctuations.

In essence, this tracking and categorization of inventory not only ensures transparency in the manufacturing process but also empowers the company with data-driven insights for informed decision-making and optimal resource utilization.

3.3.3 Production scheduling

This integral process revolves around the strategic allocation of resources and determining the optimal sequence for production activities, considering factors such as resource availability and priority. Within this framework, MES Core assumes a pivotal role, capable of seamlessly scheduling production upon the receipt of an order. Leveraging the defined process route, the MES ensures an efficient and streamlined execution by confirming the availability of essential resources required for production. This dynamic capability not only enhances the overall coordination of manufacturing operations but also contributes significantly to meeting customer demands with timeliness. In essence, the synergy between production scheduling and MES functionality underscores the importance of strategic planning and resource optimization in the intricate landscape of manufacturing processes.

A sequence diagram will be used to show the production scheduling (work order creation) use case from Figure 12. A sequence diagram is a type of behavioral diagram that shows in detail how an operation is performed.

Figure 15 illustrates a production scheduling scenario. The manager initiates a synchronous request to retrieve customer orders from the ERP system, receiving a response containing the orders. Subsequently, the manager requests the creation of work orders, a task carried out by MES Core using process routing. An automatic message is then triggered, setting all work order statuses to "pending" and awaiting approval for production. One of the approval criteria is adequate inventory, leading to two possible scenarios. If sufficient inventory is available, it is allocated to the work order; however, if inventory is insufficient, MES Core sends an order request to the ERP system.

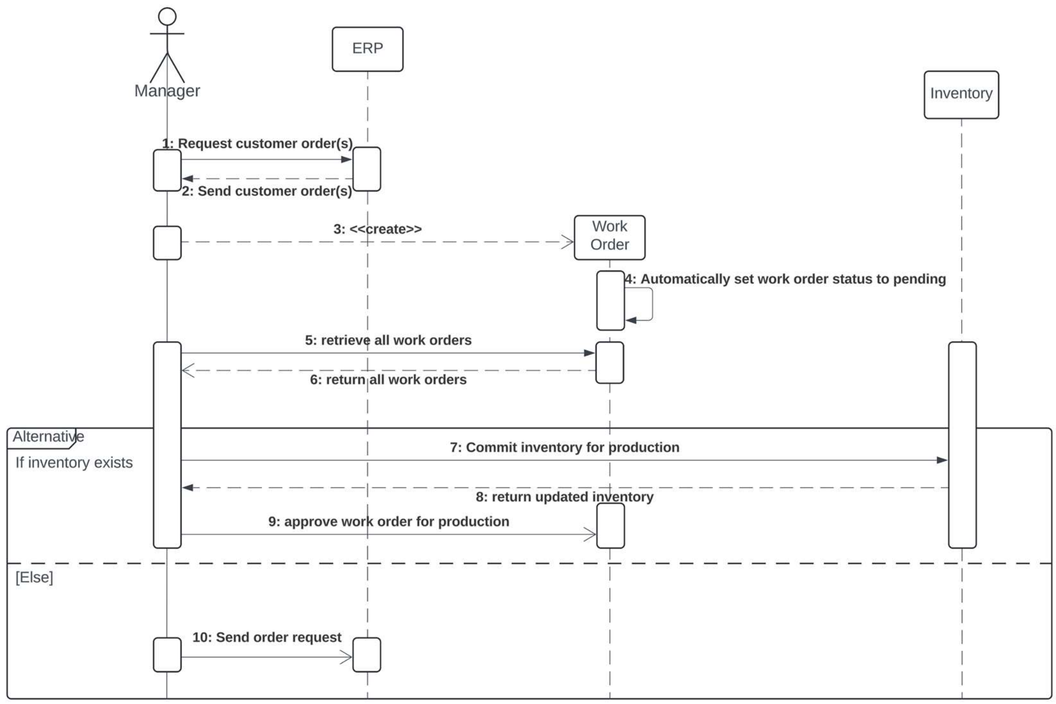


Figure 15: Example of production scheduling sequence diagram.

3.3.4 Production monitoring module

Establishing visibility within a production facility is paramount, and the ability to monitor operations at both the company and individual WorkCentre levels is a key facet of this endeavor. This granular visibility provides invaluable insights into the performance of each segment of the company, pinpointing areas for enhancement. Within the MES Core, each WorkCentre is equipped with a dedicated dashboard page, offering real-time information on the ongoing production. This includes details on the current production, runtime duration, any instances of scraps, and Overall Equipment Effectiveness (OEE) performance. Armed with this comprehensive data, businesses can conduct thorough analyses to identify operational strengths and areas in need of improvement. Moreover, this data serves as a valuable resource for AI algorithms, allowing businesses to uncover patterns and relationships within the dataset. The integration of AI facilitates predictive capabilities, enabling organizations to forecast the outcome of a process even before its execution, thus empowering proactive decision-making in the realm of production optimization.

3.3.5 Security and Roles

MES Core handles the substantial flow of data through a secure system, necessitating robust security measures to guarantee appropriate data access for authorized personnel. To achieve this, MES Core incorporates a login authentication system, requiring users to establish accounts for accessing its features. Additionally, the implementation of role-based access control ensures fine-tuned control over information accessibility on the platform.

Five default roles have been established within MES Core to cater to diverse organizational needs: Admin, Manager, Supervisor, Operator, and Suppliers. The admin role serves as the master role, exempt from security restrictions, and possesses the exclusive authority to assign roles to other MES Core accounts. This hierarchical structure ensures that sensitive information is only accessible to individuals with the requisite roles, enhancing the overall security posture of MES Core, Figure 16.

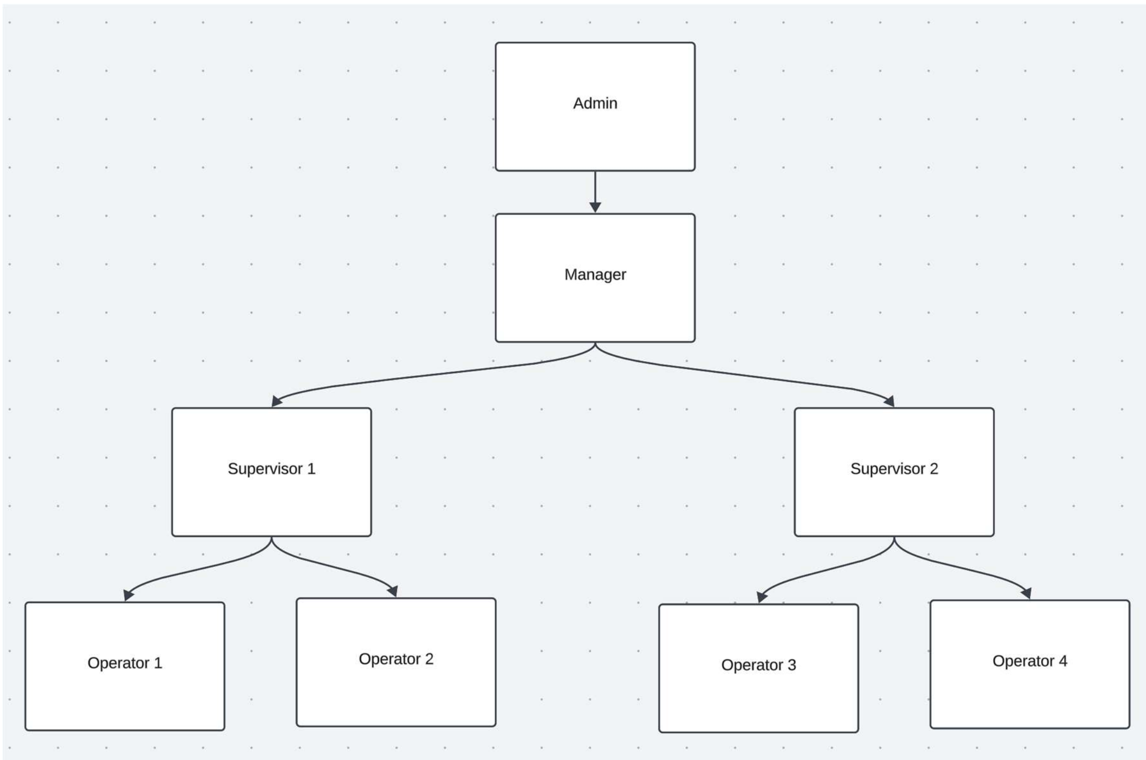


Figure 16: Role Hierarchy in MES Core.

The admin role is pivotal, accompanied by the default Admin account provided to customers. This account empowers users to assign roles and configure essential settings for optimal MES Core functionality. Alongside this, each facility is structured with a manager overseeing all shop floor operations. Like the Admin role, the Manager role has unrestricted access.

Under the Manager, a tiered hierarchy supports efficient operations. Managers are responsible for a team of supervisors, who in turn, oversee operators on the shop floor. This hierarchical structure streamlines workflow management and ensures efficient communication.

A unique role within this system is the Supplier role, specifically designed for the Company's suppliers. Suppliers are granted a dedicated page where they can access, and review orders generated by MES Core. This feature enables them to fulfill orders promptly, fostering seamless collaboration between the company and its suppliers.

In summary, the Admin role serves as the foundation, allowing users to set up MES Core, while Managers, Supervisors, and Operators work collaboratively in a structured hierarchy. The Supplier role, being specialized, enhances the interaction with external partners by providing them with a dedicated platform for order fulfillment.

3.3.6 Master data management module

Master data in a business context refers to independent entities that remain relatively stable throughout their lifecycle and are used consistently across different levels of automation. Examples include customers, products, suppliers, work centers, tools, and materials. These are standalone entities that maintain their integrity and relevance across the various levels of the automation pyramid [38].

Over many years, organizations have accumulated master data in isolated systems focusing on data attributes that are most important to them, leading to discrepancies in how data is defined, formatted, and valued. This creates a challenge for organizations to effectively utilize their master data due to a lack of consistency and structure. Master Data Management (MDM) is meant to provide a roadmap for organizations to create a unified perspective on key data. This enables organizations to make more informed decisions and improve data quality [39].

In MES Core, the master data have been defined as part, tools, work center, materials, user, customer, and supplier. Data can be generally classified into three domains. Party, thing, and Location [38] as shown in Figure 17.

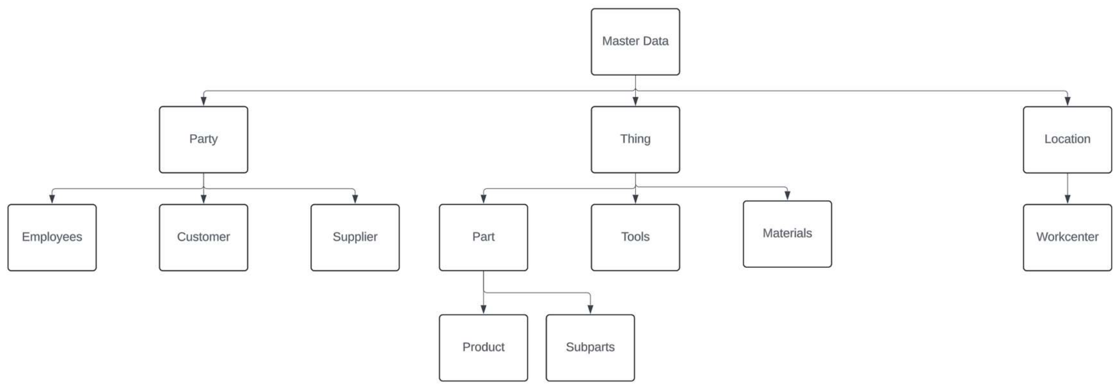


Figure 17: MES Core master data.

For parties, such as employees or customers, there are fundamental attributes like ID, first name, last name, email, phone number, and address that are crucial for identification and contact purposes. Additionally, all employees should have roles assigned within the company to delineate their responsibilities and permissions.

Regarding "Thing" entities, which could represent products or assets, essential attributes include name, description, image URL, category, type, and parent ID. These attributes help in describing and categorizing a thing effectively. The category of a thing can be classified as raw material, work-in-progress (WIP), or final product, which is crucial for inventory and production management. The type of thing can be defined as either a part that is manufactured internally or purchased externally, which influences supply chain and production strategies.

Furthermore, tools within an organization should have an assigned location attribute to track their physical whereabouts and usage. This information is important for maintenance, inventory management, and optimizing tool utilization across different departments or locations.

In conclusion, the development of MES Core, an open-source MES system has been guided by a comprehensive exploration of the requirements of an SME in manufacturing, illustrated through the McMaster Learning Factory. Through this exploration and a thorough literature review, four key functionalities crucial for SMEs have been identified and broken down into modular components, visualized through UML class diagrams.

The aim of MES Core is clear: to serve as an introductory platform for SMEs seeking an MES solution. By addressing fundamental challenges such as production scheduling, inventory management, quality assurance, and real-time monitoring, MES Core offers a structured and accessible approach to enhancing manufacturing operations for small and medium-sized enterprises.

Through its customizable modules and open-source nature, MES Core empowers SMEs with the tools they need to improve efficiency, optimize resources, and gain better visibility into their production processes. It represents a bridge between theoretical insights and practical implementation, making advanced manufacturing technologies more accessible and manageable for SMEs looking to thrive in today's competitive landscape.

Chapter 4. MES Core Web Development

This chapter builds on the planning phase of MES Core, exploring different approaches to developing and implementing an MES system. Most MES vendors offer their solutions through software as a service (SaaS) or cloud computing.

Software as a Service (SaaS) is a delivery model that grants customers access to software applications over the internet, functioning as a service rather than a product. A single monthly or per-use charge covers the expenses of infrastructure, software usage rights, hosting, maintenance, and support services in the Software as a Service (SaaS) model [40]. While this provides many advantages, it cannot be overlooked that it raises the cost of implementation and running on a platform.

A solution that retains some advantages of SaaS is to utilize the customer’s infrastructure to host the web application directly on the customer's server and use a local database. The choice of Microsoft's ASP.NET Core framework is ideal because it allows for hosting the web application on a local IIS server, while also offering the flexibility to host it on Microsoft AWS as a SaaS solution.

4.1 Introduction to Microsoft ASP.NET Core Web Development

ASP.NET Core is an open-source and cross-platform software developed by Microsoft. It was officially announced in November 2014 however its initial release was in September 2021 called ASP.NET 5. It was designed to address a few of the underlying issues with the .NET framework. Its cross-platform feature means it can work on most operating systems including, Windows, MacOS, and Linux. It is also modular which means that you can choose to include only components that are relevant for your application resulting in a more efficient and lightweight solution.

ASP.NET Core adopts the Model-View-Controller (MVC) method, Figure 18, which dates to 1978. It involves splitting a complex application into three separate sections, Model, View, Controller, which have distinct functions and interact with each other. As an overview, a user makes a HTTP (Hyper-Text Transfer Protocol) request to the controller for a specific View, the controller gets the page and demands from the Model the required data needed to populate the View. The data with the View is then passed on to the user as a response.

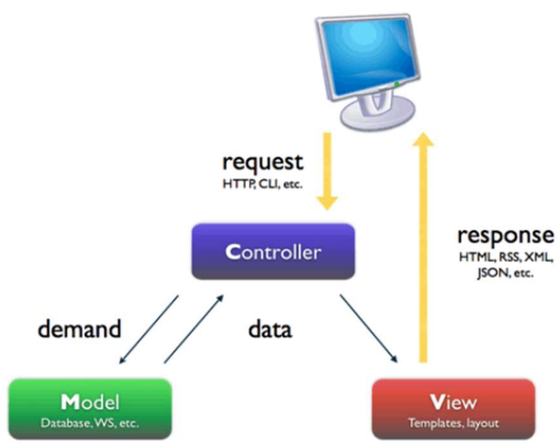


Figure 18: ASP.NET MVC System [41].

4.1.1 Model

The Model section represents a model of a physical concept that handles all data-related tasks. It communicates with the database to get related data-based user requests [42]. The model can be divided into 3 different sections, which include, data access, validation, and business Logic, Figure 19.

4.1.1.1 Data Access

Data access is responsible for integrating the model classes with the SQL databases. It does this using the Entity Framework (EF) which is a popular Object-Relational Mapping (ORM) framework in ASP.NET Core. ORM is a technique that provides the infrastructure for developers to define how the model is mapped to a relational database table. In the context of EF, Entities are the models that represent the database tables, The DbContext class in Entity Framework serves as the primary interface for interacting with the database in an application. It functions as a session manager, coordinating operations such as querying, saving, and tracking changes to objects. With DbSet properties, the DbContext exposes collections of entities, allowing developers to query and modify data within the application [43].

4.1.1.2 Validation

Validation is used to ensure the data entered by the user satisfies the requirements before the data is sent to the SQL database. One way this is implemented is using Data annotations which defines validation rules on specific properties of the model class. For example, an attribute [Required] can be used which states that the user must input data into this property before the model is accepted.

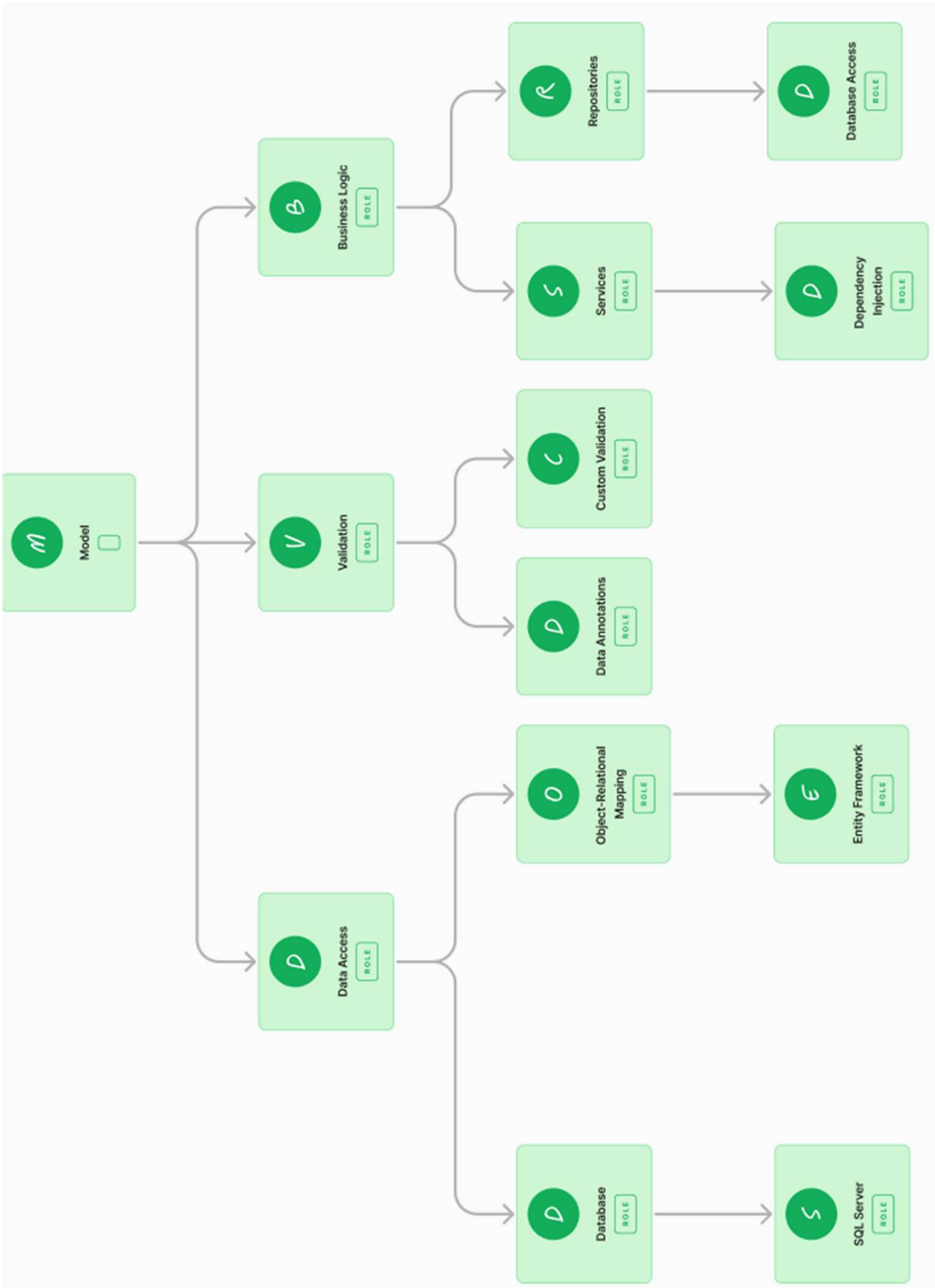


Figure 19: ASP.Net Core model Structure.

4.1.1.3 Business Logic

The business logic is responsible for defining all the services and repositories that will be used to query the database. While DBContext is responsible for creating a session with the database, the services and repositories are registered through a dependency injection container which allows controllers and other services to request an instance of the DBContext as needed. The DBContext is usually registered with a scoped lifetime which means a new instance is created with each HTTP request.

4.1.2 View

The View section handles all graphical interfaces the user sees and interacts with. The primary languages used to build the view pages are hypertext markup language (HTML), cascading style sheet (CSS), and JavaScript, Figure 20.

HTML is a markup language used to define the structure and layout of the view page which includes but is not limited to headings, paragraphs, tables, and forms. To pass data from the controller to the view page, a model or view model can be used which are the model classes that have been created. CSS handles how the HTML elements are presented to the user. In the context of MES Core, a third-party UI (Syncfusion) was used in conjunction with HTML and CSS to present information to the user. Syncfusion includes a framework for ASP.NET Core MVC and provides state-of-the-art components that can be included in your view pages. Some components used are its DataGrid, Buttons, Charts, Input Controls, Dashboard Layout, and dropdowns. To use Syncfusion, a license can be bought however there is also a free community license for individual developers and small businesses.

With the separation of the View and the Model, there is less room for error when changes are made to either section. The View section is designed by the front-end developer and his objective is to present data into information that the user can understand and interact with.

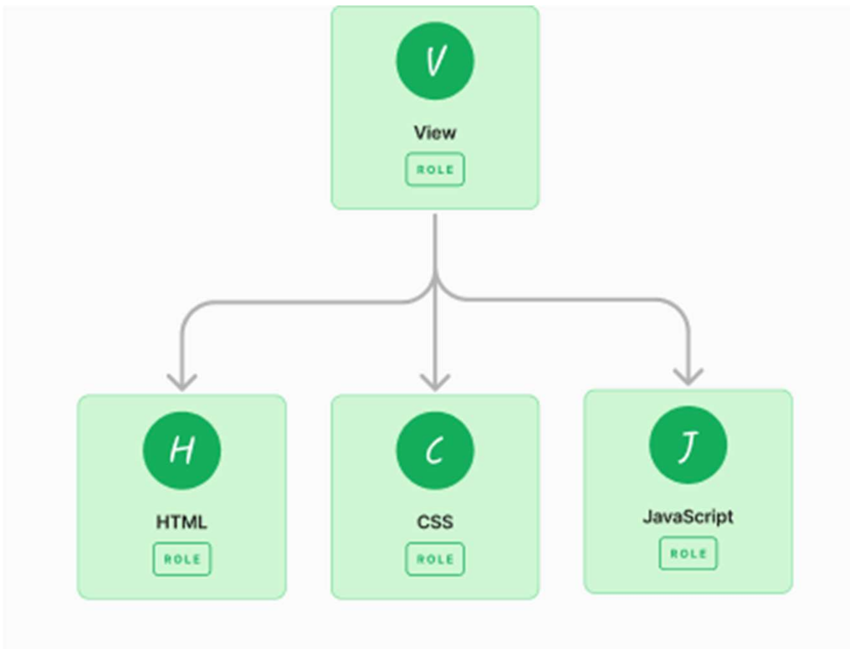


Figure 20: ASP.NET Core View Structure.

4.1.3 Controller

In the MVC (Model-View-Controller) architecture, the Controller serves as a crucial intermediary, bridging the View—what users interact with—and the Model, which represents the application's data or business logic. When a user selects a URL, the MVC routing engine determines the appropriate Controller to handle the request. This Controller then interacts with the Model to retrieve the necessary data, which it subsequently passes to the View for presentation[44] as shown in Figure 21. Take, for example, the URL http://MESCore.com/Product/Create: this URL structure typically follows a standard format where 'http://MESCore.com/' is the base address, 'Product' is the Controller managing the request, 'Create' is the action method within that

Controller, and in this case, no additional parameters are provided. This format not only specifies which Controller and action method to invoke but also influences the selection of the View page to be returned, facilitating a streamlined process for rendering the user interface based on user actions.

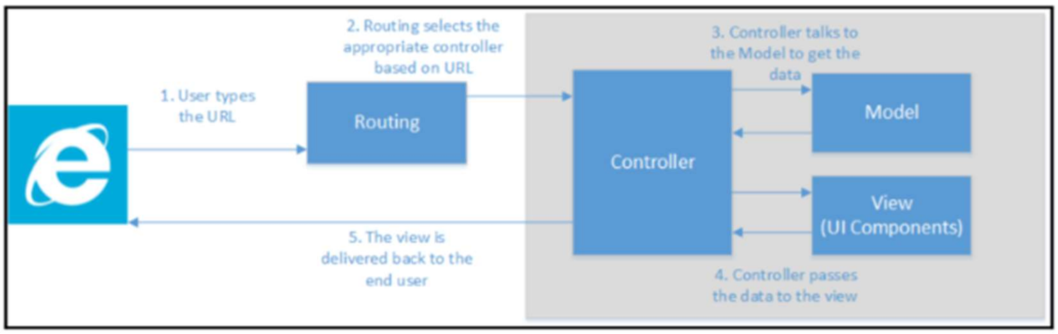


Figure 21: MVC information flow [44].

Due to its modularity and being an open-source platform. ASP.NET Core is a suitable platform that can be used for MES web development.

4.1.3 JavaScript

JavaScript, a client-side scripting language, empowers developers to manipulate elements within a webpage dynamically without the need for HTTP requests or page reloads. Today, we delve into AJAX (Asynchronous JavaScript and XML), a crucial technique for seamless data exchange with the server, enhancing web applications' responsiveness and interactivity. At its core, AJAX employs XMLHttpRequest, an API facilitating HTTP requests without disrupting the webpage's state [45]. Figure 22 illustrates the flow of an AJAX request to the server, followed by the reception and processing of the server's response, all accomplished without reloading the entire page.

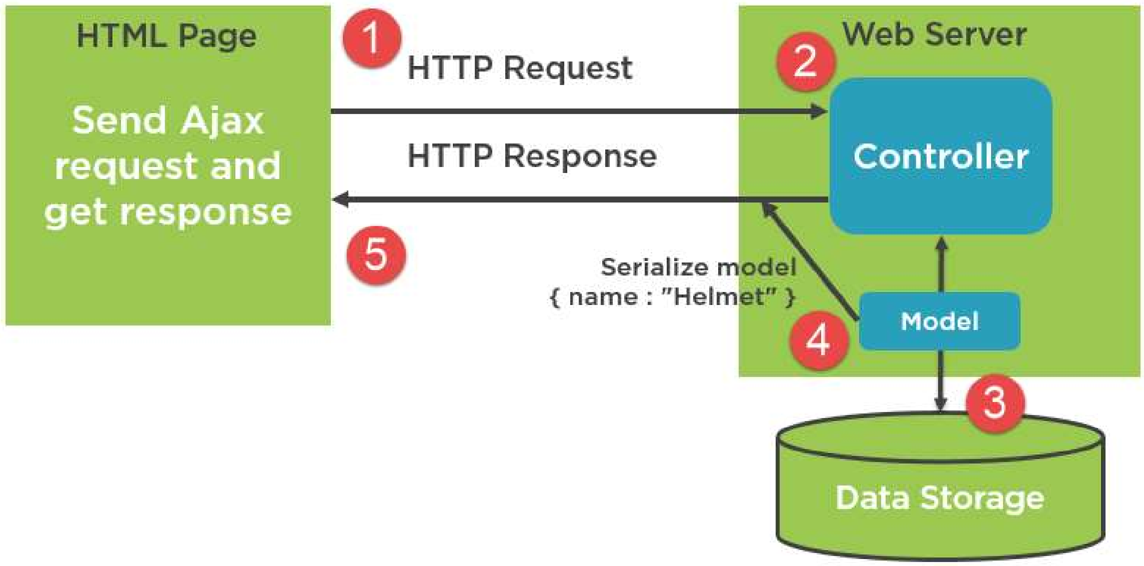


Figure 22: AJAX Request & Response [45].

4.1.4 Microsoft SQL Server Management Studio (SSMS)

Data storage plays a crucial role in web application design. Using Microsoft SQL Server Management Studio, we create an SQL database. The database tables are structured using .NET Core Migrations. For efficient database creation and synchronization with the web application, we leverage Entity Framework Core's Migration feature. Entity Framework Core, much like ASP.NET

Core, is an open-source, cross-platform framework that facilitates seamless data management in databases [46].

Figure 23 outlines two approaches to employing Entity Framework:

Database-first Approach: This approach, while offering limited support, utilizes existing database tables to generate the necessary Entity classes (Models).

Code-first Approach: The focus of our discussion today, this method allows for database and table generation through domain classes (Models).

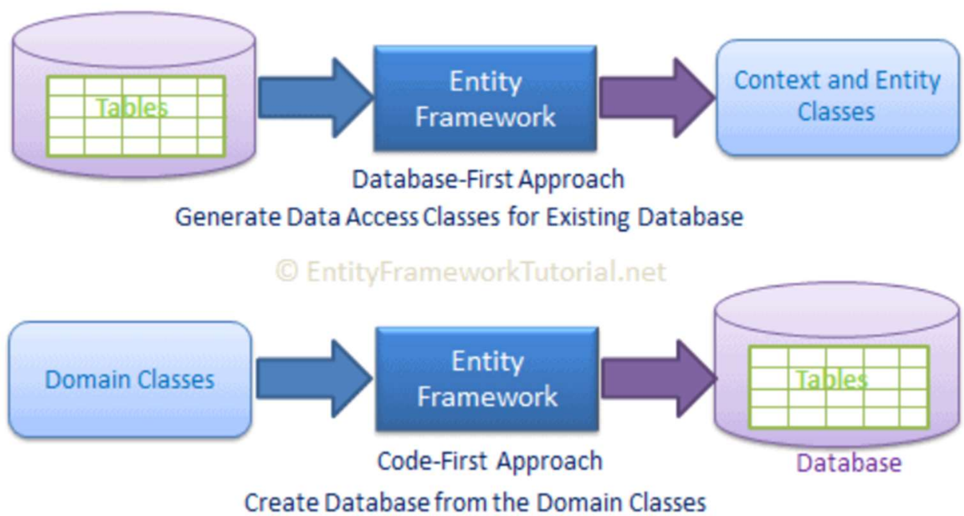


Figure 23: Entity Framework [46].

Migrations play a crucial role in converting domain classes into database tables. They achieve this by generating SQL scripts based on the Models. To utilize this functionality, a NuGet package, Microsoft.EntityFrameworkCore.Tools needs to be installed, providing the ability to perform essential operations such as creating, updating, or removing tables in the database seamlessly.

4.1.5 OPC UA Communication

The open platform communication classic (OPC Classic) is a protocol standard established in 1996. It operates on a server/client model, where an OPC Client initiates a request to the server, which then responds with the necessary data. This setup is crucial for data exchange in industrial environments.

Most PLCs require specialized proprietary drivers. This limitation makes connecting different PLCs challenging. OPC solves this problem by providing a standardized interface. It includes a predefined set of drivers from major PLC manufacturers, allowing the OPC server to access PLC memory locations through these drivers. An OPC Client, such as a Manufacturing Execution System (MES) Core, can communicate with an OPC server using OPC Communication protocols. This setup enables seamless data access and exchange between devices and systems in industrial automation scenarios.

OPC Unified Architecture (UA) builds on its predecessor, OPC Classic, with a platform-independent moving away from the traditional COM/DCOM to TCP/IP, Figure 24. DCOM/COM are developed by Microsoft hence OPC Classic is limited to Windows operating systems however the increase in other platforms like Linux, Web Architecture, and IOT made the OPC Foundation develop OPC UA which communicates over TCP/IP [47].

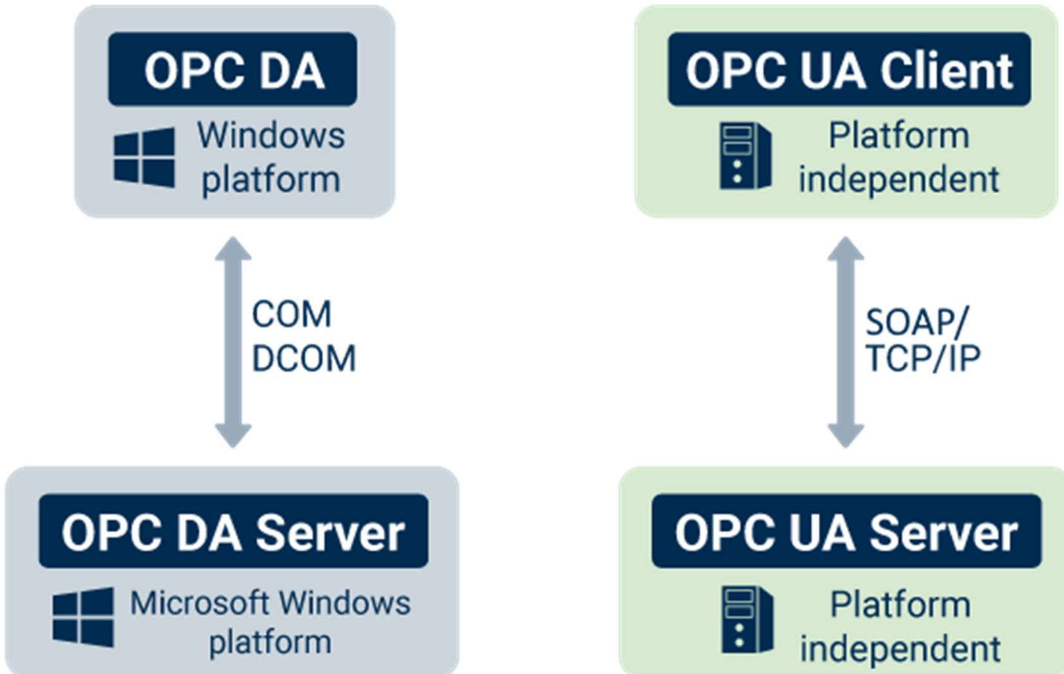


Figure 24: OPC DA vs OPC UA [47].

Key Components of OPC UA Communication:

OPC UA Server: This is the heart of the OPC UA communication model. It connects directly to physical devices, such as PLCs, through a set of predefined drivers. These drivers are designed to communicate with equipment from a wide range of manufacturers, overcoming the limitation of proprietary communication protocols as shown in Figure 25. The OPC UA Server is responsible for collecting data from these devices, organizing it, and making it accessible upon request. There are two popular OPC Servers. Servers from a hardware vendor for example some PLCs are now equipped with their own OPC Servers or standalone OPC servers like Kepware, and softing.

OPC UA Client: The OPC UA Client is the requester in this communication model. It sends queries to the OPC UA Server to retrieve data or send commands. In the context described, the Manufacturing Execution System (MES) Core acts as the OPC UA Client, seeking to access device data for monitoring, control, and analysis purposes.

The Communication Flow: Request and Response Mechanism: The OPC UA Client (e.g., MES Core) sends a request to the OPC UA Server for specific data. The server, having direct access to the PLCs' memory locations via its broad set of drivers, retrieves the requested data.

Accessing PLC Data: The OPC UA Server's unique ability to communicate across various PLCs' proprietary protocols enables it to serve as a universal translator. It accesses the memory locations of these PLCs through its comprehensive driver list, fetching the necessary data without needing custom drivers for each device.

Data Transmission: Once the OPC UA Server has collected the requested data, it responds to the OPC UA Client's request by transmitting the data back. This process ensures that the MES Core receives accurate and timely information directly from the shop floor equipment, regardless of the manufacturer.

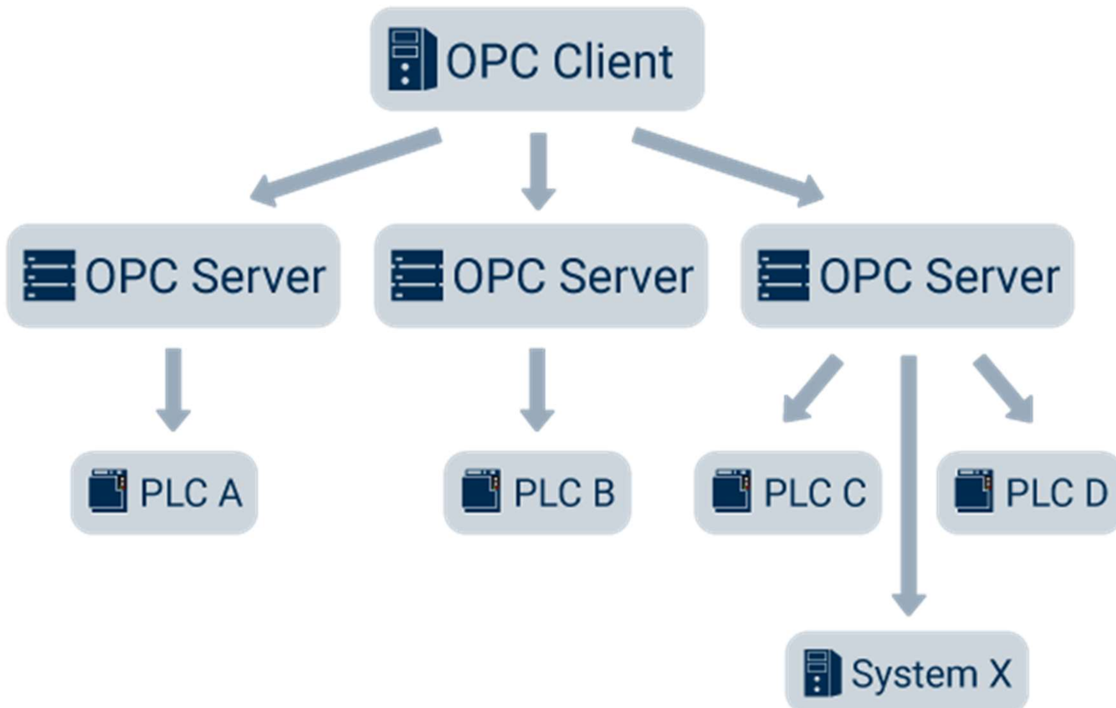


Figure 25: OPC Server/Client Architecture [47].

OPC UA helps to combat the increasing need for vertical integration in the Automation Pyramid and bring Industry 4.0. Now MES can effectively and in real time communicate with the shop floor using OPC.

4.1.6 SignalR

In traditional web applications, communication between the client and server follows a request-response pattern over HTTP. The client sends a request, the server processes it, sends back a response, and the connection is closed. This approach makes establishing real-time communication challenging, as it requires the client to continuously send requests to the server to get updated data, leading to inefficiency and increased load on the server.

To address the limitations of the HTTP request-response model for real-time scenarios, techniques like Comet have been developed. Comet employs long polling—a method where the client initiates a request to the server, and the server keeps this connection open until it has new information to send. Once the update is sent, the client immediately initiates another request, and this cycle continues indefinitely [48]. While this improves over the basic request-response model by reducing the latency in communication, it's still a workaround rather than a solution to real-time communication.

Enter SignalR, a library designed for .NET developers to enable real-time web functionality. SignalR transcends the limitations of both the traditional HTTP model and methods like Comet by establishing a persistent, two-way connection between the client and server. This allows the server to send updates to clients instantly, without waiting for a request, facilitating real-time data flow in applications such as live chat, notifications, and interactive gaming.

SignalR smartly abstracts away the complexity of managing these real-time connections. It automatically selects the best available transport mechanism to maintain a persistent connection with the client. The options include WebSocket, which is ideal for real-time communication due to its full-duplex communication channel; Server-Sent Events (SSE), a unidirectional protocol where the server sends updates to the client; and Long Polling, a fallback method where the client periodically polls the server for updates.

By leveraging SignalR, developers can easily implement real-time communication in their web applications, enhancing the user experience and interaction without the heavy lifting of handling connection management, transport selection, and scalability concerns. SignalR not only makes real-time updates feasible and efficient but also significantly simplifies the development process by providing a high-level API for both the server and client sides.

4.2 MES Core Implementation

4.2.1 Manufacturing execution

The planning process involves several interconnected models that play crucial roles in managing detailed operations. These models are product, subparts, process route, part inventory, required parts, work center, work order, and bill of material (BOM). Each of these models serves a specific purpose and contributes to the overall planning and execution of manufacturing processes.

Product and subparts: A product can either stand alone or consist of various Subparts. The relationship between Products and Subparts is established through the Product's Name and the Subpart’s 'ParentId' attribute, which links it to the Product table, Figure 26. This structure allows for the management of both standalone items and complex assemblies with multiple components.

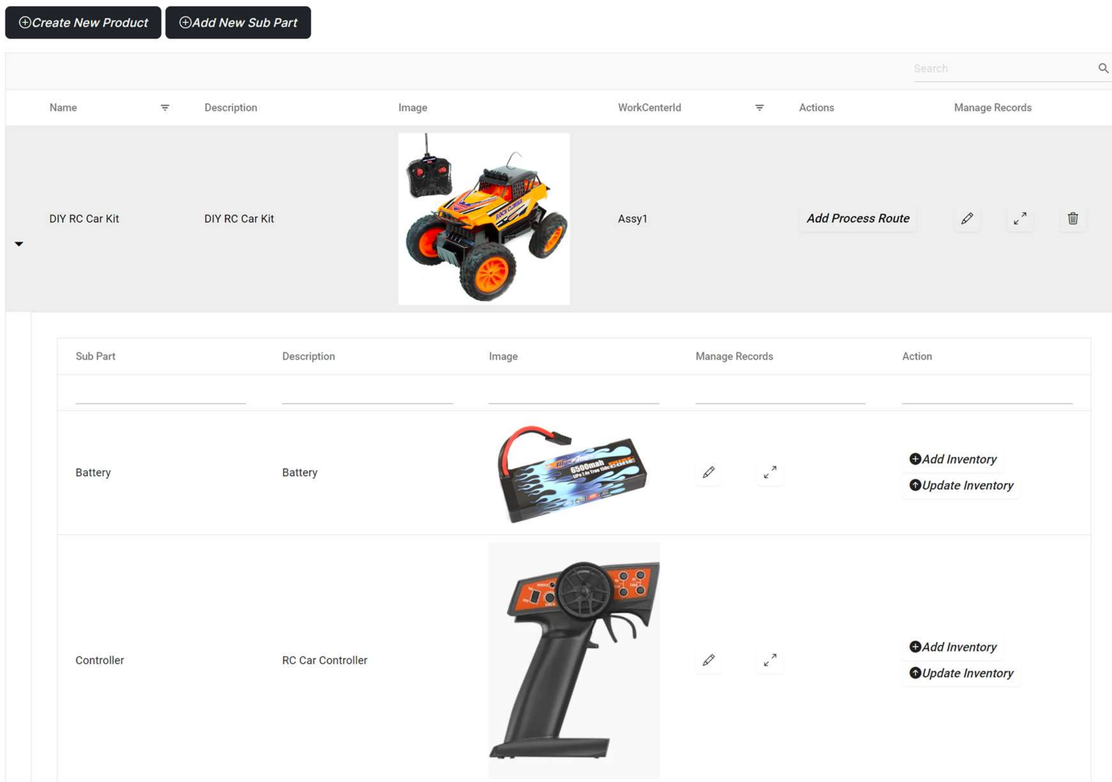


Figure 26: MES Core Product Page.

The product controller serves as the central hub for managing Product and Subparts-related operations within the system. It handles all CRUD functions, including Create, Update, and Delete actions, allowing users to efficiently manage the inventory and configurations of products and their associated subparts.

Upon accessing the product controller, the default Index page is displayed, showcasing a comprehensive list of all products along with their respective subparts. This presentation is achieved using the Syncfusion DataGrid table, a powerful tool that facilitates seamless data visualization and interaction.

The Index page provides users with a convenient overview of the entire product catalog, including details such as product names, descriptions, quantities, and associated subparts. This intuitive display layout enhances user experience and simplifies navigation within the system.

Through the Product Controller and its associated Index page with the Syncfusion DataGrid table, users can perform a range of actions, including:

Viewing product and subpart details: Users can easily access detailed information about each product, including its attributes, specifications, and the components (subparts) that make up the product assembly.

Adding new products and subparts: The Create functionality enables users to add new products to the catalog and define their corresponding subparts, facilitating the expansion and customization of the product lineup.

Updating existing products and subparts: Users can modify product attributes, quantities, and subpart configurations as needed, ensuring accurate and up-to-date information within the system.

Deleting products and subparts: The Delete function allows users to remove outdated or no longer relevant products and their associated subparts, maintaining a streamlined and organized inventory.

By leveraging the capabilities of the Product Controller and the user-friendly interface provided by the Syncfusion DataGrid table, organizations can efficiently manage their product portfolios, optimize inventory management, and enhance overall operational efficiency. To preserve data security access to CRUD functionality is limited to role types of manager and administrator.

Process route: This model outlines the sequence of steps or processes required to manufacture a Product. It defines the routing information such as the operations, work centers involved, and the order in which tasks are performed. The process route is essential for scheduling and optimizing production workflows.

Part inventory and required parts: Part inventory tracks the available inventory of parts, while required parts identify the components needed for production. These models ensure that the necessary materials are on hand for manufacturing and help prevent shortages or delays.

Work center: Work centers represent the physical locations where manufacturing operations take place. Each Work center can be associated with products and subparts, indicating where specific tasks or processes are carried out. Work centers play a vital role in resource allocation and capacity planning.

Work order: A work order is a specific instruction or directive to produce a certain quantity of a product or subpart. It includes details such as production quantities, scheduling information, and the associated process route. Work orders facilitate the execution and tracking of manufacturing tasks.

Bill of material (BOM): The BOM lists all the components, parts, and materials required to assemble a Product. It provides a hierarchical structure that outlines the relationships between items and their quantities, guiding the procurement and assembly processes.

Additionally, each work center is associated with a 'Current Production' table, which records real-time information about ongoing operations. This includes details like the part being produced, operational duration, scrap rates, and other key performance indicators. Monitoring Current

Production helps in evaluating WorkCentre efficiency and addressing any issues that may arise during production.

The interconnectedness of these models forms a comprehensive framework for effective planning, execution, and control of manufacturing processes. By leveraging these relationships and data insights, organizations can streamline operations, optimize resource utilization, and enhance overall productivity.

4.2.2 Production Monitoring

The Production Monitoring section integrates two primary Models: Work center and Current Production. This integration is pivotal for displaying real-time production statuses across different work centers, achieved through the Index page's dashboard. Each work center's dashboard is uniquely tailored to show live updates from the Current Production table, offering a detailed snapshot of ongoing operations, Figure 27.

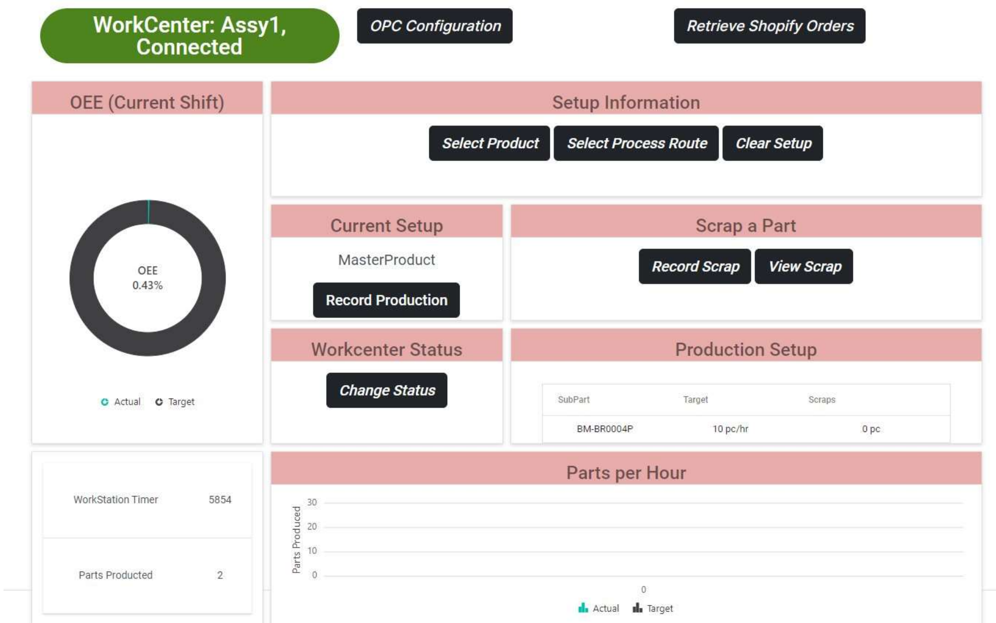


Figure 27: MES Core Dashboard.

To facilitate the real-time data capture necessary for these updates, MES Core leverages Traeger's OPC Client Library to interface with Programmable Logic Controllers (PLCs). This setup is crucial for industrial environments where PLCs play a central role in controlling machinery and processes. The data flow begins with the incorporation of specific Tags from the PLC into an OPC server, which acts as a mediator for data exchange between the PLCs and MES Core. The current OPC server in use is Kepware Enterprise 6, renowned for its robustness and compatibility with diverse industrial equipment.

Critical information required for this connection includes the OPC Server address and the names of the Tags. These pieces of information are essential for establishing a seamless link between the

MES Core system and the machinery on the factory floor. Once the connection is set up, real-time data from the PLCs is continuously fed into MES Core.

To ensure that this data is reflected immediately on the dashboard, MES Core utilizes Microsoft's SignalR technology. SignalR facilitates the push of real-time updates to the web-based dashboard, ensuring that the current production statuses displayed are always up to date. This dynamic update mechanism is key to enabling operational transparency and efficiency, allowing for immediate responses to production changes or issues as they arise.

The integration of Work center and Current Production Models, coupled with advanced OPC communication and real-time web updates via SignalR, forms the backbone of the Production Monitoring section in MES Core. This system architecture not only ensures operational visibility across work centers but also enhances the decision-making process with up-to-the-minute production data.

To configure the OPC Connection, there is a button "OPC Configuration" on the dashboard shown in Figure 28, and it requests key information that needs to be defined. Configuration for all Work centers need to be defined to enable MES Core to connect to all physical stations.

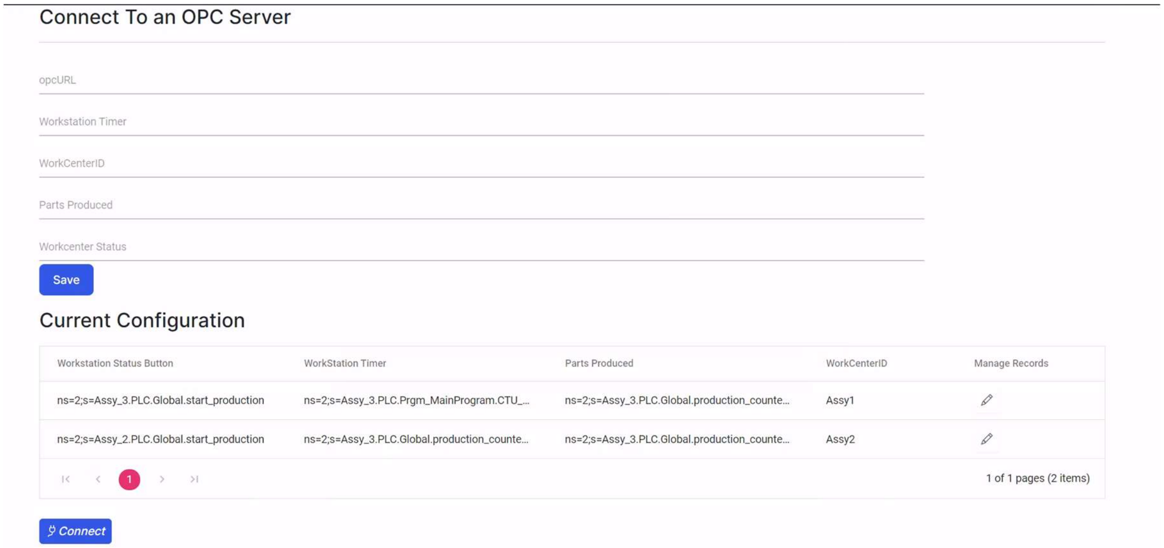


Figure 28: MES Core, Connecting to an OPC Server.

Reports

The Historical Production Report is a cornerstone feature within the MES Core system, designed to provide a comprehensive overview of production activities. This report captures and details the operations carried out at each work center, focusing on key metrics that are crucial for assessing production efficiency and operator performance. The parameters covered in this report include:

Production Output: It details the quantity of parts produced during a specific period, providing insights into the productivity levels of each work center.

Operational Duration: The report specifies how long each work center was operational, offering a measure of time efficiency and equipment utilization.

Operator Information: Identifying which operators were involved in the production processes at each work center adds a layer of accountability and helps in evaluating operator performance.

Moreover, the MES Core system recognizes the need for flexibility in how this data is reviewed and analyzed. To accommodate various user preferences and requirements for data analysis, the system includes an option to export the Historical Production Report in two commonly used formats: PDF and Excel, Figure 29.

Historical Production

Excel Export PDF Export CSV Export

Product	Sub Part	Production Time	Parts Produced	Start Time	End Time	Assigned Operator
MasterProduct	BM-BR0004P	0	0	09/01/2024 01:15 PM	09/01/2024 01:19 PM	Manager1
MasterProduct	ST-WW0002P	1	0	04/12/2023 03:43 PM	04/12/2023 03:44 PM	Manager1
MasterProduct	BM-BR0004P	0	0	09/01/2024 02:19 PM	09/01/2024 02:22 PM	Manager1
MasterProduct	BM-BR0004P	3	2	19/12/2023 11:02 AM	19/12/2023 11:06 AM	Manager1
MasterProduct	BM-BR0004P	5	0	18/12/2023 02:14 PM	18/12/2023 02:19 PM	Manager1
MasterProduct	BM-BR0004P	0	0	15/01/2024 11:13 AM	16/01/2024 09:46 AM	Manager1
MasterProduct	BM-BR0004P	0	0	16/01/2024 02:56 PM	16/01/2024 02:56 PM	Manager1
MasterProduct	BM-BR0004P	12	0	18/12/2023 04:02 PM	18/12/2023 04:16 PM	Manager1
MasterProduct	BM-BR0004P	3	5	04/12/2023 03:45 PM	04/12/2023 03:48 PM	Manager1
MasterProduct	BM-BR0004P	0	0	16/01/2024 09:51 AM	16/01/2024 02:51 PM	Manager1
MasterProduct	BM-BR0004P	0	5	06/12/2023 08:58 AM	01/01/1901 12:00 AM	Manager1
MasterProduct	BM-BR0004P	3	3	18/12/2023 01:32 PM	18/12/2023 01:35 PM	Manager1

1 2 3 4 5 — 1 of 5 pages (59 items)

Figure 29: Historical production report.

4.2.3 Inventory Management

In the MES Core system, inventory tracking is managed for every product and component. As outlined in Figure 30, the interface provides a straightforward option for users to either add new inventory items or update the records of existing ones. To ensure data integrity and prevent duplication, a JavaScript-based validation mechanism is employed. This guards against the creation of duplicate inventory entries once an item is already recorded.

To facilitate these operations, an Inventory Controller is deployed. This component is central to managing inventory interactions, including the display of all inventory items, the addition of new inventory, and the updates to existing records. Figure 30: MES Core part inventory page, offers a glimpse into the layout of the inventory page designated for parts, detailing how inventory data is organized and presented.

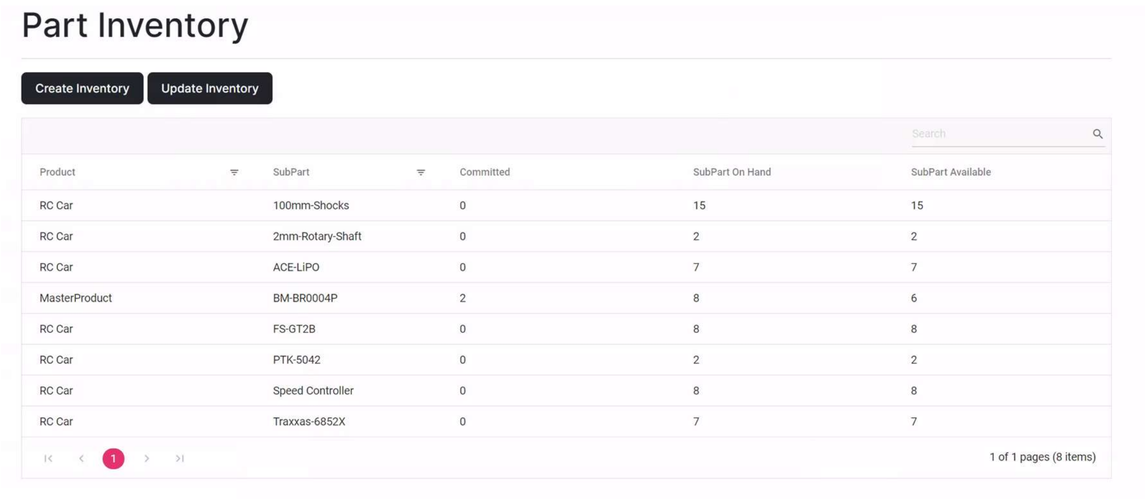
The inventory data includes several critical columns, each serving a distinct purpose:

The "Committed" column indicates the quantity of parts that have been reserved or allocated for specific work orders. This reflects the inventory that is currently in use and not available for new projects.

The "subparts on hand" column aggregates the total inventory count, encompassing both committed items and those freely available. It represents the comprehensive stock level of components.

Lastly, the "subpart available" column calculates the difference between the "subpart on hand" and "Committed" parts. This figure represents the actual available inventory, highlighting those subparts that are not earmarked for existing work orders and are freely available for future use.

This structure was modeled after Shopify's inventory tables and it ensures a clear and detailed view of inventory levels, allowing for precise management and allocation of parts and subparts within the MES Core system. It facilitates an efficient workflow, from tracking inventory to allocating resources for work orders, ensuring a smooth operational process.



Product	SubPart	Committed	SubPart On Hand	SubPart Available
RC Car	100mm-Shocks	0	15	15
RC Car	2mm-Rotary-Shaft	0	2	2
RC Car	ACE-LiPO	0	7	7
MasterProduct	BM-BR0004P	2	8	6
RC Car	FS-GT2B	0	8	8
RC Car	PTK-5042	0	2	2
RC Car	Speed Controller	0	8	8
RC Car	Traxxas-6852X	0	7	7

Figure 30: MES Core part inventory page.

4.2.4 Security and Roles

The Login Section of the system is intricately designed to encompass all the functionalities associated with account creation, user management, logins, and roles. This setup leverages Microsoft Identity, a robust framework designed for managing authentication and authorization within ASP.NET Core Web applications. This framework is pivotal in securing the application and ensuring that user credentials and access rights are managed efficiently.

As outlined in Chapter 3.4 of the document, the system is pre-configured with five default roles. These roles are foundational to the application's security and access control mechanisms, dictating what users can and cannot do within the system. Access to the user roles page is exclusively granted to Administrators, who bear the responsibility of managing these roles. This management includes viewing all available roles, creating new roles as needed, assigning roles to users, and modifying existing user roles to suit evolving access requirements, Figure 31.

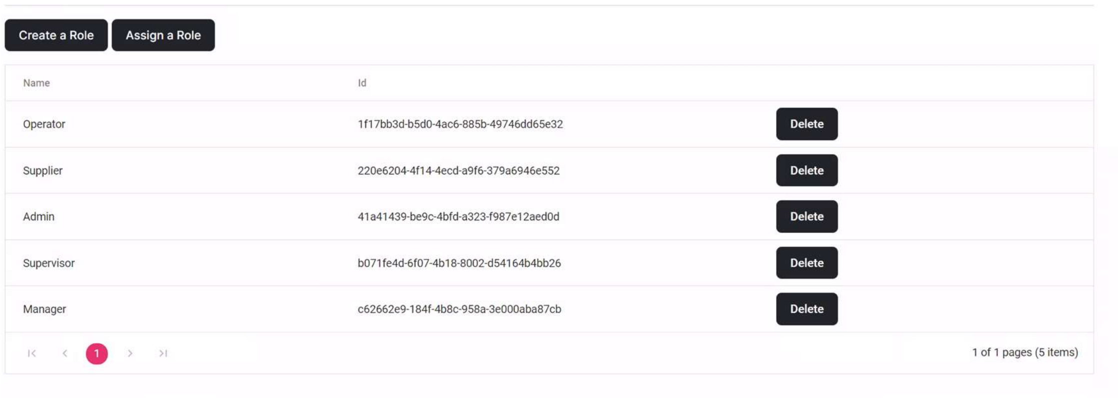


Figure 31: User role.

Figure 32 offers a peek into the process of assigning roles to users. It presents a list of all users, showcasing their current roles, and provides an interface for changing these roles as needed. This functionality is critical for maintaining the security and operational integrity of the application, ensuring that users have appropriate access levels based on their responsibilities and requirements.

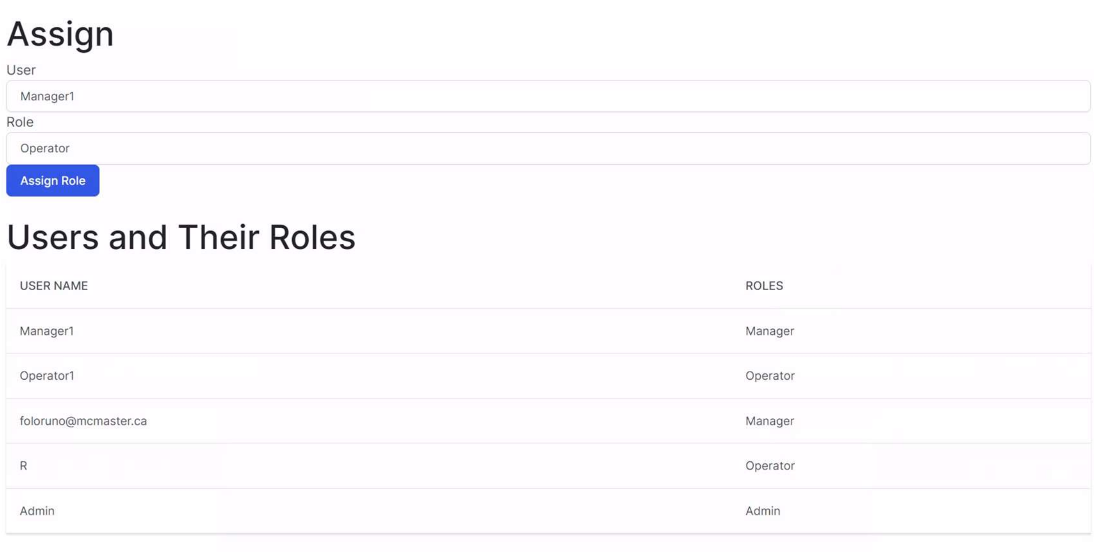


Figure 32: MES Core role assignment.

4.2.5 MES Core Architecture

Figure 33, illustrates the integration and interaction of MES Core within the broader context of the automation pyramid, particularly detailing its connectivity with systems at different levels. Here's a clearer breakdown of how MES Core functions within this framework, especially in its role akin to an ERP system, with Shopify being used as a stand-in for demonstration purposes:

Shopify to MES Core Integration

Process Flow: The integration between Shopify and MES Core primarily revolves around the exchange of customer orders and their statuses. Shopify, acting as the ERP layer in this context, sends customer order details to MES Core which is enabled through its API.

Conversion to Work Orders: Once MES Core receives these orders, it transforms them into work orders for production.

Status Updates: MES Core updates Shopify on the status of these orders through the same API, ensuring that the ERP system (or, in this case, Shopify) and the customer remain informed about the order progress.

MES Core to PLC Integration

Requirement for OPC Communication: To establish communication between MES Core and the Programmable Logic Controllers (PLCs) that manage physical machinery, an OPC (OLE for Process Control) server is essential.

Implementation: In this research, KepServer serves as the OPC server. This choice allows for a robust interface through which MES Core and the PLCs can exchange data.

Role of KepServer: KepServer acts as the mediator that facilitates communication. While MES Core and the PLCs function as clients, KepServer enables them to interact seamlessly, ensuring that MES Core can send commands to the machinery and receive status updates or data in return.

This configuration highlights the critical role of MES Core in bridging the gap between high-level order management systems (like Shopify) and the shop floor control (via PLCs), ensuring that customer demands are efficiently translated into manufacturing actions and feedback loops are maintained for order status updates.

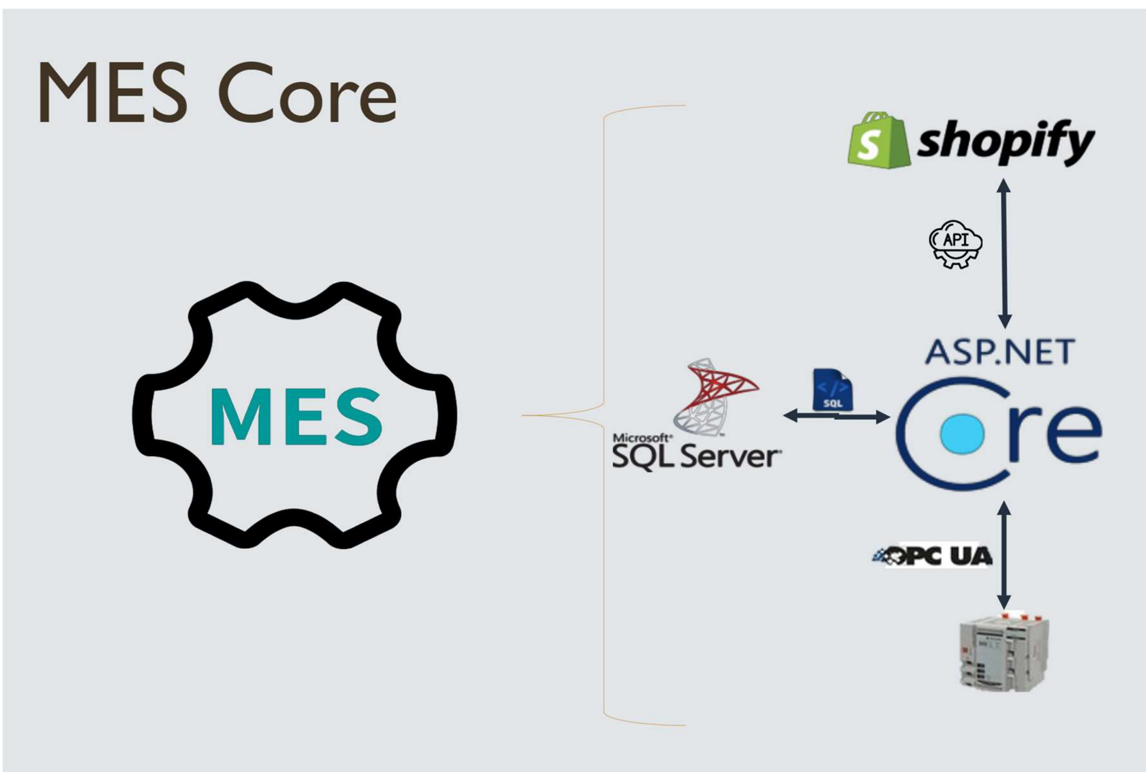


Figure 33: MES Core Architecture.

Chapter 5. Publishing of MES Core

5.1 Internet Information Services (IIS)

IIS, or Internet Information Services, is a versatile web server developed by Microsoft. It provides a robust platform for deploying and hosting web applications, including those developed with ASP.NET Core. This capability makes IIS an ideal choice for deploying MES Core for clients. Utilizing IIS, MES Core can be hosted on a local server, offering a reliable and efficient environment for the application.

Additionally, IIS integrates seamlessly with local SQL databases managed via SSMS (SQL Server Management Studio). This integration allows for the creation of a dedicated database for MES Core. Through the process of migration, necessary tables and structures are established within the database, ensuring MES Core operates smoothly and efficiently.

One of the appealing aspects of IIS is its accessibility; it is free and pre-installed on many computers. For those systems where it is not pre-installed, IIS can be easily downloaded from the Microsoft website, ensuring wide availability for users wishing to deploy web applications like MES Core. This combination of IIS and a local SQL database creates a powerful, yet cost-effective solution for hosting and managing MES Core, providing clients with a stable and performant environment for their manufacturing execution system needs.

5.2 Microsoft Azure App Service

Azure App Service is an HTTP-based hosting service designed for .NET Core web applications.

Unlike traditional local server hosting like IIS, Azure App Service is a Platform as a Service(PaaS)solution, handling development and deployment entirely in the cloud. However, unlike IIS, which is mostly free, Azure App Service requires a subscription fee.

To calculate the cost of running an App Service and a SQL database, Microsoft's pricing calculator and documentation was utilized. Several factors influence pricing:

Region: The cost varies by region. For instance, regions within the US are priced around $54.75 USD, while locations like Canada cost $60.59 USD.

Operating System: Azure supports both Windows and Linux. Windows is the default option, but Linux is also available.

Tiers: Azure offers six different tiers for app service. The Free and Shared Plans are suitable for testing and development, with limitations on CPU usage. The Basic Plan, which was selected here, is ideal for moderate traffic and is well-suited for MES Core [49].

In this scenario, the approximate monthly cost for the App Service is $60.59 USD, Figure 34.

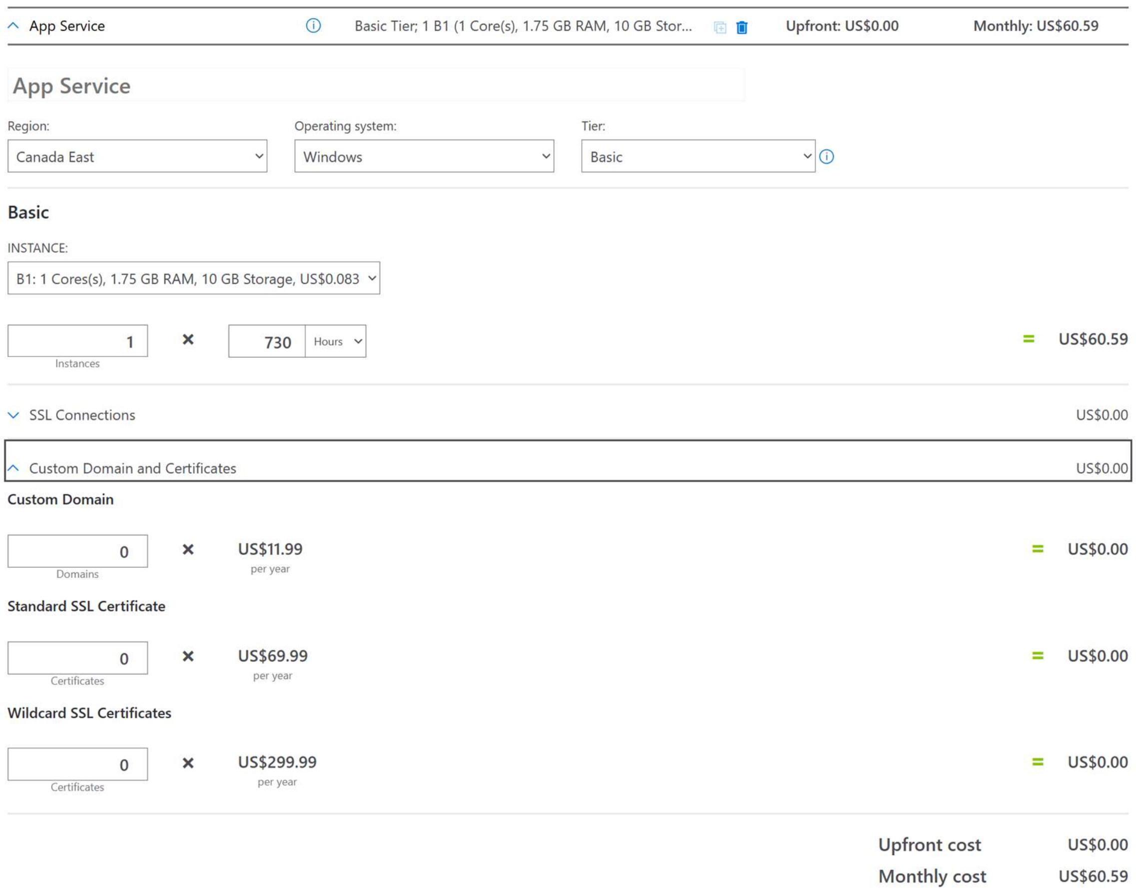


Figure 34: Microsoft app service price estimate.

Azure SQL Database

Just like Azure App Service, the pricing of SQL databases is influenced by several key features:

Type: There are two database types: Single database and Elastic Pool. A single database is a dedicated resource with its own server, while Elastic Pool allows for managing multiple databases on a single server with shared resources, making it suitable for multi-customer web applications [50].

Purchase Model: Two purchasing models are available: vCore and DTU. vCore (virtual core) allows customization of CPU cores, memory, and storage, while DTU offers preset configurations of these resources.

Service Tier: Azure offers three service tiers: General Purpose, Business Critical, and Hyperscale, each providing different performance levels to suit various needs.

Compute Tier: Azure provides two compute tiers: Provisioned and Serverless. Provisioned computes are for predictable usage patterns, while Serverless billing is based on usage in seconds, pausing billing during inactivity.

These factors collectively determine the pricing structure for SQL databases, offering flexibility and scalability to meet different application requirements and usage patterns, Figure 35.

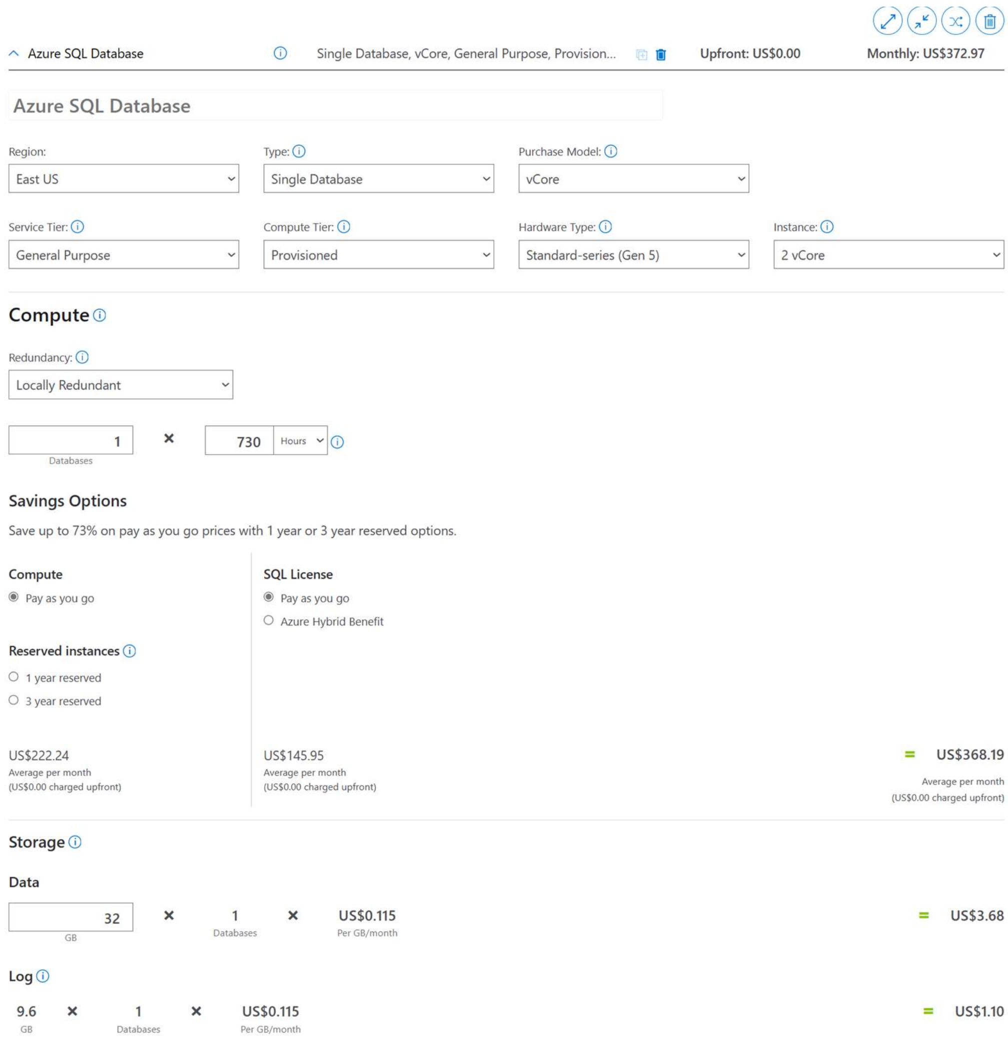


Figure 35: Azure SQL database price estimate.

5.3 MES Core cost breakdown

The development of MES Core is free due to the use of an open-source framework with a local database. However, while this is not necessary for the operation of MES Core, this helps bring about Industry 4.0 to a company. Shopify was picked as an ERP system and with it comes a cost of $99 CAD for the small businesses tier. To communicate with Shopify or any ERP system, an OPC server is needed. Kepware's KEPServerEx was used, and its pricing is largely affected by how many drivers you want to get for the server. The Manufacturing suite was chosen which includes major

PLC manufacturers like Allen-Bradley, Automation Direct, Honeywell, Omron, Siemens, etc. and the inclusion of OPC classic and OPC UA communication. This brings the total cost to implement Industry 4.0 to $2,768 / Yr. CAD as shown in Figure 34.

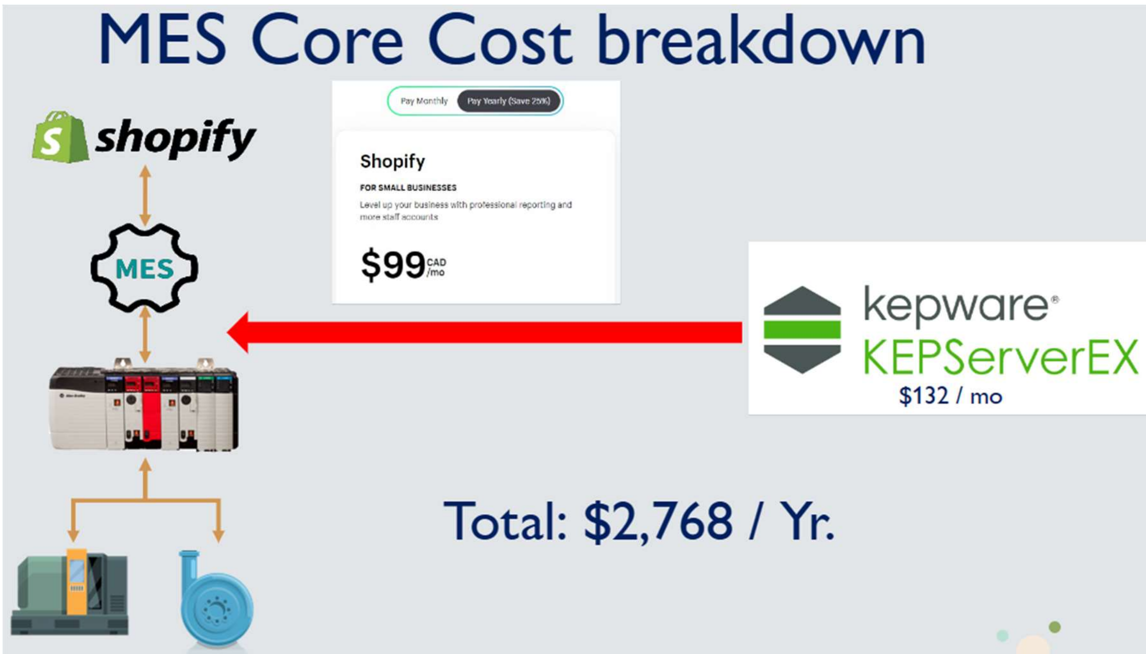


Figure 36: MES Core cost breakdown.

Overall, comparing with some of the MES vendors, MES Core costs less than 5% of the total operation cost of current MES solutions making it a compelling choice for businesses aiming to optimize their manufacturing processes. By leveraging an open-source approach, MES Core not only minimizes upfront investment but also provides long-term benefits such as scalability, flexibility, and freedom from vendor lock-in.

Chapter 6. Conclusion and Future Work

This research focused on developing an open-source Manufacturing Execution System. A literature review was conducted to determine the current landscape of MES and the challenges hindering its adoption by SMEs, notably cost and a lack of standardized MES functionalities. Drawing insights from the McMaster Learning Factory's needs and existing MES vendor solutions, MES Core was developed to specifically tackle these major concerns faced by SMEs.

The major concerns MES Core solves include:

- Cost-effectiveness: MES Core is largely free with the web application developed using open-source code with limited cost due to 3rd party software like deploying on Microsoft Azure, OPC Server and connection, and an ERP system.
- Standardization: MES Core encompasses the requirements of what an ideal starter MES system should have. Manufacturing Execution, production monitoring, inventory management, Master data management, and integration between ERP and shop floor.

Despite being an open-source solution, MES Core is relatively new, and comprehensive testing is required to validate its ability to deliver essential benefits. This validation process will occur through deployment and rigorous testing within the Learning Factory environment.

6.2 Future Work

The result of this thesis showed that a manufacturing execution System can be developed using minimal resources for companies however this only provides essential functionality to enable Industry 4.0. Prospects of this study include:

1. Investigating additional Industry 4.0 features such as integrating AI for predictive maintenance in machine health monitoring and optimizing production by anticipating breakdowns.
2. Conducting a comprehensive analysis of MES Core's implementation in the Learning Factory, assessing its effectiveness through the use of KPIs.
3. Strengthening MES Core by implementing cybersecurity measures to ensure data is protected and released to the appropriate user.

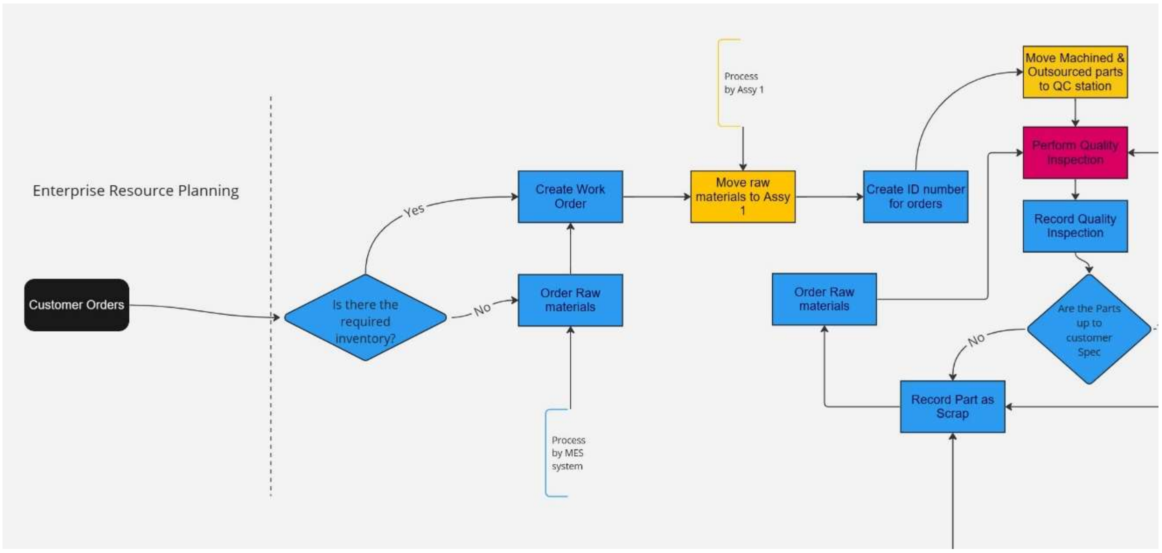
These endeavors would strengthen MES Core, aligning it more with Industry 4.0 and bolstering its value for SMEs seeking efficient manufacturing solutions.

Appendix-A MES Core Models

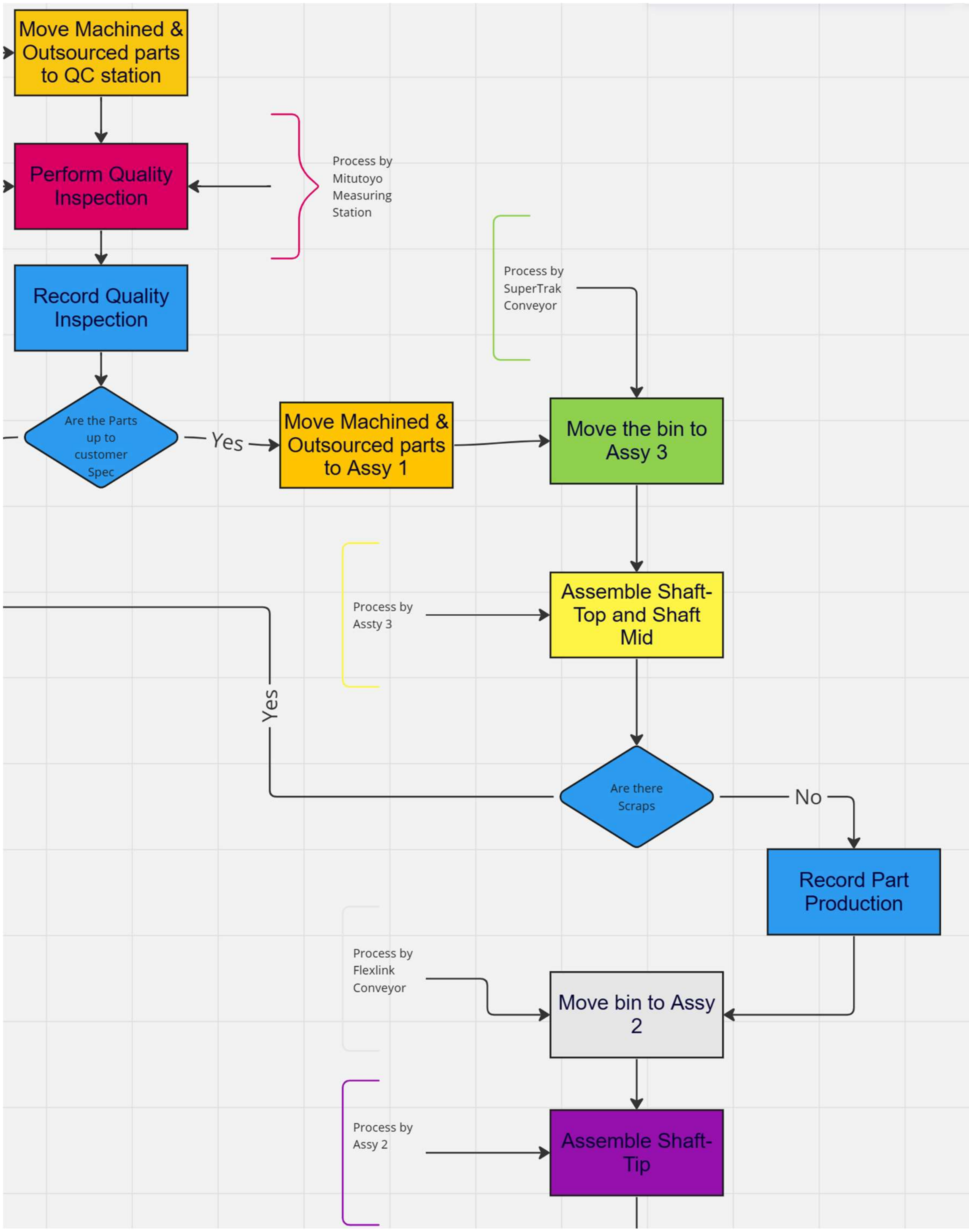
#	Model	Description
1.	AppUser	This Model represents a user in MES Core and is distinguished using the User roles.
2.	CurrentProduction	This model handles the current production for each specified Work center
3.	FulfillmentOrder	This model handles fulfilling Shopify orders
4.	HistoricalProduction	This model is responsible for all Production performed for each specified Work center
5.	Inventory	This model handles all inventory for each specified Product
6.	LineItem	This model defines specific information about the Shopify Order
7.	LineItemProperties	This model defines specific customizations to Line Items
8.	OpcConnection	This model is responsible for all required information needed to connect the Work center to their respective physical stations.
9.	OPCSubscription	This model handles all OPC configurations used to connect to the PLCs

10.	OperationType	This model handles the different types of operations that can be performed for each process route
11.	Order	This model handles all incoming Shopify Orders made by the Customer
12.	PartsPerHour	This model records parts produced each hour for each Work center
13.	ProcessRoute	This model defines all sequential steps needed to manufacture a specified product
14.	Product	This model defines the information for each product that a company produces
15.	Scrap	This model records all scraps accrued during production
16.	SubParts	This model defines the information for each part needed in the production of a specified product
17.	WCProduction	This model defines key details needed for production in each Work center
18.	Work center	This model represents a physical Work center on a Company's production Line

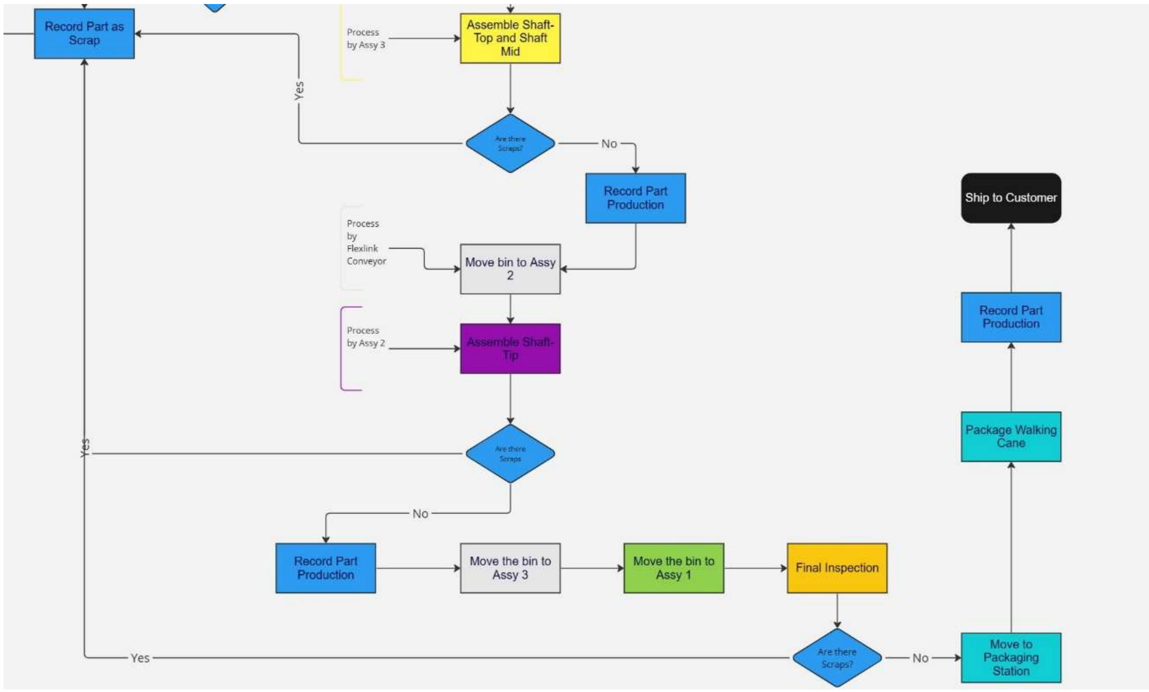
Appendix-B Learning Factory Process Flow



Appendix Figure 1: Learning Factory Process Flow Part 1.



Appendix Figure 2: Learning Factory Process Flow Part 2.



Appendix Figure 3: Learning Factory Process Flow Part 3.

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