



ACMA6013

MAJOR PROJECT

Assessing the feasibility of mobile robot technology for
material transport at Sony UK Technology Centre

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Abstract

Sony UK Technology Centre is an electronics manufacturing centre based in Pencoed Wales. The manufacturing industry is highly competitive, requiring continuous improvement. Mobile robots are a potential method that Sony could utilise to improve the current materials handling process. First, the evolution of mobile robots is illustrated through research, showing the technical advances since the early designs in the 1950s. Today, mobile robot technology has advanced navigation, communication, power, and safety features, making them highly beneficial in various industries. They can be found in the food and manufacturing industries, optimising processes and minimising waste. Challenges involve the high initial costs and complex implementation projects, which can also raise sociological issues such as resistance to change. Regulations and standards are set to ensure the mobile robots are deployed safely into a suitable environment, safeguarding people. The methodology uses a DMADV six sigma structure, first defining the problem using the Raspberry Pi 500 and Monitor products, which Sony manufactures. Current measurements of these processes show that a warehouse operator travels approximately 18.36km each week with a total of 27.6 m² of floor space allocated to kitting. Per annum, this equates to a cost of £5,202. Using the Kepner-Tregoe decision analysis method, the Platform AMR is highlighted as the most suitable. Reeco Automation supplied data on Challenges arising from the high initial costs, which result in a return on investment of 16.3 years when considering only the challenges associated with the high initial costs, giving a return on investment of 16.3 years when considering only two Raspberry Pi Pro processes.

The design simulation created using Arena Software approximates AMR distances travelled, utilisation, and delays where the process is starved of material. The simulation highlights that the utilisation is relatively low, indicating high potential for scalability to another method, which could improve the economic challenges. An initial startup delay of 192 seconds occurs due to the process being starved at the beginning of each shift. Increasing the AMR velocity significantly reduces the delay. However, it can be eliminated by having a buffer at each line at the start of the shift or by starting the AMR delivery before the shift begins. The project objectives, critical-to-quality requirements, and feasibility are verified before concluding the report. The conclusion further highlights that feasibility challenges lie with the project's economics. However, through the simulation, there is room for scalability. Recommendations for further work include expanding the project to further processes and conducting a physical trial site. Further studies on other methods, such as sorting, could also be included in the project, such as an automated sorting robot. To ensure project success, Sony must create a robust project team and contact a variety of suppliers, providing a vast range of data to compare.

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List of Acronyms

AGV – Automated Guided Vehicles

AI – Artificial Intelligence

AMR – Automated Mobile Robot

CAPEX – Capital Expenditure

CTQ – Critical to Quality

DA – Decision Analysis

DES – Discrete-Event Simulation

DMADV – Define, Measure, Analyse, Design, Verify

FMS – Fleet Management System

IPT – Inductive Power Transfer

IoT – Internet of Things

JIT – Just-In-Time

KPI – Key Performance Indicator

KT – Kepner-Tregoe

LFFA - Lewin's Force Field Analysis

LOLER 98 - Lifting Operations and Lifting Equipment Regulations 1998

MR – Mobile Robot

MQTT– Message Queuing Telemetry Transport

MTTR – Mean Time to Repair

OPC UA – Open Platform Communications Unified Architecture

OPEX – Operational Expenditure

P2P – Peer-to-Peer

PUWER 98 – Provision and Use of Work Equipment Regulations 1988

ROI – Return on Investment

RPi – Raspberry Pi

RSI – Repetitive Strain Injury

SLAM – Simultaneous Localisation and Mapping

Sony UKTec – Sony UK Technology Centre

TPM – Time Preventive Maintenance

UWTSD – University of Wales Trinity Saint David

VOC – Voice of the Customer

WIP – Work in Progress

Declaration Statement

This thesis is the result of the author's original research. It has been composed by the author and has not previously been submitted for examination which has led to the award of a degree.

Signed: Nathan Jay Mackechnie

Date: 18/05/2025

1. Introduction

Sony UK Technology Centre (Sony UKTec) traces its origins to 1974, when a new production facility was established in Bridgend by the Prince of Wales, now King Charles III, to meet growing European demand for Sony's iconic Trinitron television sets. The site was relocated to its current Pencoed site, opened by Queen Elizabeth II in 1993 (Sony, 2024). The 30,000m² facility now manufactures a range of electronics from TV broadcast cameras and equipment to third-party businesses such as the Raspberry Pi (RPI). The following section will further detail the report's context, aims, and objectives.

1.1. Context of the Topic

The electronics industry is highly competitive, even requiring competition between other Sony sites for new products. This high level of competition drives the requirement for innovative automation solutions that optimise processes, lowering costs and leading to increased profit. Production processes are typically optimised to achieve the required output and are continuously analysed to identify areas of improvement. However, indirect methods such as material handling are usually ignored because they are not a direct production process.

Current material handling at Sony UKTec is done manually and typically involves transporting pallets of material to and from the line, accumulating manual labour costs and floor space allocation costs. The mobile robot (MR) industry has seen significant advances over the last decade, including improvements in sensor technology, algorithms, and safety features. Both automated guided vehicles (AGV) and automated mobile robots (AMR) are two forms of MRs used across many industries to optimise material transport. An MR is defined as an advanced machine capable of navigating in various environments (Raj and Kos, 2022). MRs present opportunities for reducing manual labour, optimising the material handling process, and reducing costs. They can also improve factory-floor utilisation by introducing smaller, more frequent material deliveries, thereby minimising congestion and freeing up valuable space for additional operations or business expansion. The aims and objectives of the report will be set in the following section.

1.2. Aims and Objectives of the Report

This report aims to provide the reader with a sufficient understanding of MRs before assessing the feasibility of deploying them at Sony UKTec to optimise material handling processes. The objectives include research on MR technology, its historical evolution, key technical features, application in industry, relevant regulations and standards, and the sociological impact of introducing this technology to a manufacturing facility.

Following the research section, the report will then follow a define, measure, analyse, design, and verify (DMADV) structure, aiming to set the project objectives to assess two RPi processes as a case study to understand the feasibility of an MR solution at Sony UKTec. In the define phase, the project objectives will be established, the scope will be clarified, and essential customer requirements will be gathered. The measure phase will then create a data-collection plan for those requirements and record baseline measurements for both RPi. At the same time, the selection criteria for the mobile robot, supplier, and model are defined.

During the analysis phase, the shortlisted robotic solutions will be assessed against these criteria, considering their technical performance, safety, cost implications, and potential for scale. The design phase follows, in which an Arena discrete event simulation will be developed to simulate an MR, collecting data on distance travelled and utilisation implications to the process. The verify phase will review the work, ensuring it is relevant to the aims and objectives, customer requirements, and feasibility assessment. The report will then conclude with recommendations for Sony UKTec to introduce MR technology.

2. Research on Mobile Robots

MRs encompass a range of robotics technologies designed to improve efficiency by reducing manual labour (Fazlollahtabar and Said-mehrabad, 2015). Although similar in their goal of material handling automation, AGVs and AMRs differ in their operational and technical abilities (Patricio and Mendes 2020).

AGVs are guided by pre-defined paths, which may be magnetic strips or wires placed throughout a facility (Wang, 2015). This guidance is most reliable in static environments performing repetitive tasks (Xu et al., 2020). Conversely, Liu et al. (2024) highlight that AMRs have sensors, cameras, and navigation algorithms that enable them to effectively navigate dynamic environments without requiring a fixed guidance system.

The following literature review will explore the evolution, technical considerations, applications, sociological and regulatory impacts of AGVs and AMRs. This analysis aims to understand the factors affecting their feasibility and successful deployment in automated material handling.

2.1. Historical and Future Developments of MRs

Technological advancements have transformed MRs into efficient material handling solutions for various industries. The key developments of MRs will be discussed in the following sections, understanding the origin through the recent and future developments.

2.1.1. Early Developments

AMRs owe their origins to AGVs, dating back to the early 1950s. Initially, AGVs were basic unmanned robots that followed predefined paths to perform repetitive tasks (Kumar et al., 2024). Dutra and Lengerke (2011) highlight that Arthur Barrett of Barrett Electronics invented the first AGV. This tow-type AGV pulled a series of carts along an electrically conductive wire embedded in the floor, as shown in Figure 1.

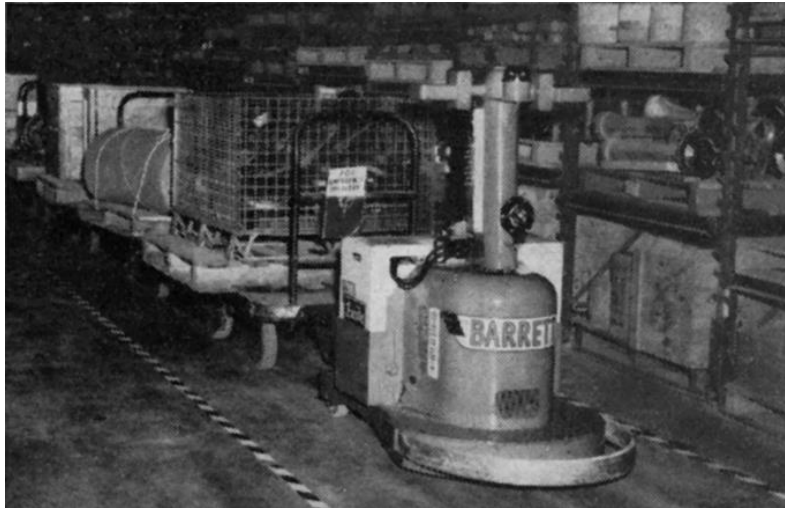


Figure 1– Guide-O-Matic AGV developed by Barrett Electronics

The 'Guide-O-Matic' was initially used to automate material transport within warehouses and industrial facilities, focusing on streamlining the movement of goods and reducing manual labour (Bandyopadhyay, 2017). The safety features would be minimal at this time and likely only consist of an emergency stop button. Although this may pose a risk to a person's safety, the movement of this AGV was highly predictable, reducing the risk of collision.

The automotive industry adopted Barret's innovation, with companies like Volvo and General Motors (GM) pioneering the integration of AGVs into their manufacturing processes during the 1960s and 1970s (Benhabib, 2003). Both companies utilised AGVs to automate material handling along production lines. Materials transported included heavy engines, which benefited from AGVs by reducing the number of operators needed to transport the material and decreasing the risk of repetitive strain injuries for the operators (Ujvari and Hilmola, 2008).

Early technological progression of AGVs included the integration of computer controls to enhance their capabilities and efficiency (McNeil, 2002). These advancements enabled more sophisticated route planning, allowing AGVs to optimise material handling operations by navigating complex layouts and reducing travel time. This was a significant shift from the basic wire-guided systems of the 1950s, as AGVs began to incorporate software-driven decision-making processes that improved their operational flexibility.

Safety features saw notable advancements during this period. Early AGVs primarily relied on emergency stop buttons; however, by the late 1970s, systems began integrating sensors and automatic stop mechanisms. These features enhanced workplace safety by preventing collisions and mitigating risks associated with human-robot interaction. The incorporation of proximity sensors allowed AGVs to detect obstacles and halt their operation when an obstruction was detected (Kim, Naganathan and Dukkipati, 2000).

2.1.2. Recent and Future Developments

Recent developments in MRs include significant advancements in autonomy, connectivity, and intelligence. The AMR represents an evolution from AGVs, eliminating the requirement of fixed pathways using onboard sensors like LiDAR and advanced software for navigation in dynamic environments (Siciliano and Khatib, 2016).

In the 2010s, AMR saw rapid commercialisation, and companies like Amazon saw the potential to use them in their warehouses. Amazon’s acquisition of Kiva Systems in 2012 accelerated the deployment of intelligent robots capable of automating warehouse operations. These robots optimised inventory picking and transportation while improving scalability and reducing labour demands (Groover, 2020). The development timeline of MRs is outlined in Figure 2.

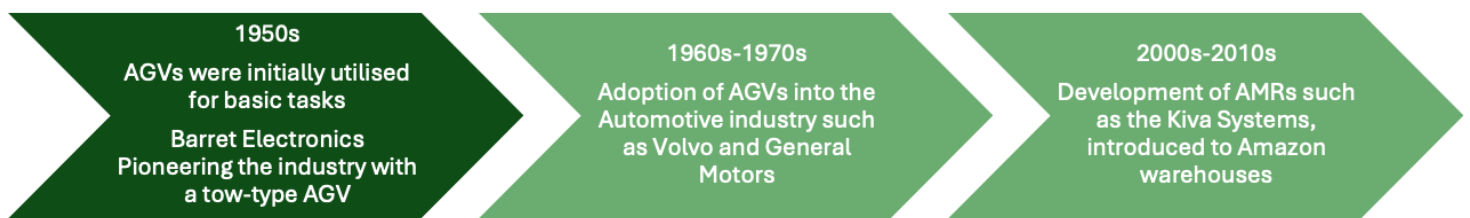


Figure 2 - Summary MRs developments

Future developments include integrating MRs with advanced artificial intelligence (AI) technologies. Industry 4.0 innovations such as the Internet of Things (IoT), will enhance connectivity, providing efficient communication between systems (Ryalat et al., 2024). Advancements in navigation software and hardware will improve precision, allowing the robot to complete complex tasks with high accuracy (Reis, Couto, and Junior, 2023). With the push for sustainability, research also focuses on improving battery life and reducing the energy consumption of a robot (Wu et al., 2023).

The definitions of AI, Industry 4.0, and IoT can be found in Appendix 5

2.2. Technical Aspects of AGVs and AMR

The following section explores the technical aspects of AGVs and AMR, focusing on their fundamental technologies and distinguishing characteristics. By highlighting their operational differences, this discussion provides a deeper understanding of how these systems function and the advancements that set AMR apart from traditional AGVs.

2.2.1. Navigation Systems

As highlighted in section 2.1.2, AGVs navigate using fixed, predefined paths such as magnetic strips, optical markers, laser guidance, and more, as illustrated in Figure 3.

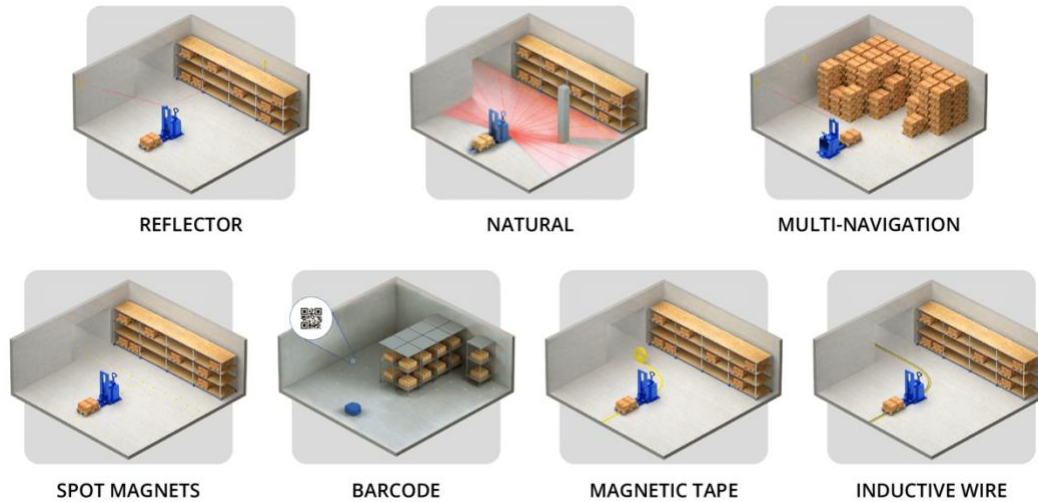


Figure 3 - Types of AGV navigation (Align, 2024)

This type of navigation is often deemed reliable for repetitive tasks where movement is predictable (Wang, Tong, and Xu, 2020). However, Siegfried and Bourafa (2023) highlight that AGV navigation methods often prove unsuitable in dynamic environments due to their reliance on predefined pathways, making them inefficient in adapting to unexpected obstacles or changes in surroundings.

Conversely, AMRs use advanced technologies such as LiDAR and simultaneous localisation and mapping (SLAM) to dynamically map and adapt to their surroundings, enabling flexible navigation around obstacles (Huang and Geng, 2024), as illustrated in Figure 4.



Figure 4 - Illustration of AMR 'Free Navigation' (Pastor, 2023)

Although flexibility is improved through AMR navigation methods, Tolenov and Omarov (2024), highlight that AMR can come at a higher cost than AGVs due to their advanced systems (Charles, 2022). However, improved efficiencies and reduced infrastructure maintenance requirements offset these costs, such as eliminating fixed pathways.

2.2.2 Connectivity and Communication

Reliable connectivity is critical for these robots to ensure efficient operation. More recently, a 5 G connection has been commonly used for communication between the robots and a Fleet Management System (FMS) (Oyekanlu et al., 2020). An FMS is software used to oversee, coordinate, and optimise the operation of multiple robots within a facility, as illustrated in Figure 5.



Figure 5 - Fleet management System (Wiferion, 2024)

5G connectivity appears advantageous due to its low latency and high bandwidth communication (Hazarika and Rahmati, 2023), making it ideal for large-scale environments. Alternative connection types include Wi-Fi or Bluetooth for short-range communication with other equipment. More advanced robots can switch between connection types, ensuring the best and most suited connection is being utilised for the operation (Ohori et al., 2023)

Message Queuing Telemetry Transport (MQTT) and Open Platform Communications Unified Architecture (OPC UA) are a set of rules known as a communication protocol that define how data is exchanged (Silva et al., 2021). For AGVs and AMR, protocols such as these ensure reliable and secure communication between the devices. Peer-to-peer communication allows devices to exchange data directly, bypassing a central server. In robotics, it enhances efficiency by enabling robots to coordinate tasks autonomously.

2.2.3. Power Systems

AGV and AMR typically use rechargeable lithium-ion batteries for their high energy density, lifespan, and charge speed properties (Hanschek et al. 2022). These properties enable these robots to operate for extended periods, minimising downtime.

Charging is often facilitated through docking stations, where a robot autonomously travels to the station and connects to transfer power. (Xue, Wang and Li, 2022). In some instances, robots may charge during scheduled intervals set by an FMS, such as during production downtimes like breaks or shift changes.

An advanced method employed in modern systems is opportunity charging, where robots autonomously charge whenever idle or between tasks. This approach ensures the fleet maintains optimal energy levels throughout operations without impacting productivity. Opportunity charging is particularly advantageous in high-demand environments, as it reduces the need for extended downtime and extends battery lifespan by avoiding deep discharge cycles (Fan and Jiang, 2024).

Additionally, charging through inductive power transfer (IPT) is an alternative method, allowing for in-process charging, minimising downtime, and increasing efficiency (Bohács, Győrvári, and Kluth, 2019), as shown in Figure 6.



Figure 6 - Wireless AGV and AMR charging (Wiferion, 2023)

Having charging locations on the floor minimises the impact on existing production layouts, allowing charging ports to be in key areas, such as next to the production line.

2.2.4 Technical Safety features

MR incorporates a wide range of safety systems to help protect people and equipment. The navigation sensors, LiDAR, and SLAM detect objects surrounding the robot (Sanchez-Cubillo, Del-Ser, and Martin, 2024). Speed control systems also provide an additional layer of safety, monitoring and controlling the robot's speed based on proximity to obstacles, as shown in Figure 7



Figure 7 - Illustration of Proximity Detection (Pastor, 2022)

Typically, a robot's surroundings are zoned by collision risk, with red being high, medium, and low. Based on the object's location, safety algorithms influence the robot's movement (Liaqat et al., 2019). While AGVs are

limited to slowing down or coming to a stop to avoid collisions, Ammour, Orjuela, and Basset (2022) discuss the ability of AMR to manoeuvre around, significantly reducing the risk of collision without slowing or stopping.

More basic yet essential safety features include emergency stop buttons, which allow for physical intervention or intervention via a remote or pendant (Fernandes et al., 2022). Audio and visual alerts, such as alarms and lights, improve safety by alerting anybody nearby of their presence. In some cases, MRs are equipped with laser projectors.



Figure 8 - MR Laser Safety Projectors (Lovell, Milanovic, and Kasturi, 2019)

As illustrated in Figure 8, laser projectors further improve the visibility of the MR and can even display information such as the direction of travel. Advanced algorithms using the FMS allow for area zoning, creating one-way zones, no-robot zones, and even congestion detection, preventing the robot from entering an area if it is too congested (Cheng et al., 2023).

2.2.4 Summary of MR Technology

AGVs and AMRs share core technologies, but their key difference lies in navigation. AMR uses LiDAR and SLAM for flexible movement, avoiding obstacles, while AGVs follow fixed paths and stop when obstructed, making AMR more efficient in dynamic environments.

Communication is achieved via Wi-Fi, Bluetooth, or 5G, with AMR coordinating tasks and movements. Fleet Management Systems (FMS) enhance efficiency by planning routes, jobs, and charging, though they are not essential for robot operation.

Safety features include emergency stop buttons, audiovisual alerts, advanced sensors, and algorithms. While AGVs slow down or stop when detecting obstacles, AMR navigates around them, improving adaptability and reducing congestion.

2.3. Application in Industry

Due to their flexibility to operate in various environments, MRs can be seen in applications that include warehousing, the food industry, and manufacturing. The following sections will discuss their application in these three industries.

2.3.1. Warehousing Industry Applications

As previously highlighted, Amazon is a notable case where AMRs have been introduced as a collaborative solution. They minimise the travel distance of employees by bringing the required storage rack to the operator, as shown in Figure 9.



Figure 9 - Amazon AMR in Operation (Swofford, 2021)

The AMR is used to perform a mundane task, retrieving and transporting a rack from one location to another (Allgor, Cezik and Chen, 2023). Beyond minimising travel, the AMR enhances safety by lowering physical strain on employees. Additionally, their ability to navigate beneath storage racks allows for more efficient warehouse layouts, reducing the required floor space by eliminating the requirement for designated walkways (Loffler, Boysen and Schneider, 2023).

2.3.2. Food Industry Application

Leading online supermarket Ocado significantly benefits from the use of AGVs. Combined with an advanced fleet management system, the fulfilment process is optimised, ensuring the picking sequence, product placement, and routes are efficient (Shaklab et al., 2023). Like Amazon, Ocado can maximise its storage capacity by eliminating walkways required by a human picker, as shown in Figure 10.



Figure 10 - Ocado Automated Warehouse (Sawers, 2020)

The bespoke-built AGVs travel along rails on top of the racking, locate the designated pick-up or drop-off stop, and retrieve or deposit the tote from underneath. By doing this, Ocado has significantly reduced its operational costs by minimising manual labour, allowing for competitive prices, which is crucial for customer satisfaction and profitability (AIRushood, 2023).

2.3.3. Manufacturing Industry Application

In manufacturing, AGVs and AMRs both improve material handling operations. However, AMRs are particularly effective in dynamic environments due to their navigation capabilities. Research by Savci et al. (2022) and Chewu and Manok (2023) further emphasises the advantages of AMR over AGVs in such settings.

The car manufacturer BMW employs AGILOX AMRs to transport material around its Regensburg site in Germany. The initial project began with a pilot phase in 2017, utilising one AMR to transport materials across the site. Following the successful pilot phase, twenty-seven AGILOX AMRs are autonomously supplying assembly lines with raw materials (Agilox, 2024) as shown in Figure 11.



Figure 11- AGILOX AMR at BMW Regensburg Plant (Technische Logistik, 2024)

In combination with an FMS, the MR fleet exchanges key data, enabling optimised autonomous material delivery across the 1.4 million square metre site. The AMR technology is critical to the operation, ensuring the AMR can navigate easily within the dynamic environment (Azangoo et al., 2021). Employees at the site are now redeployed to carry out higher-skilled tasks, improving productivity and likely improving job satisfaction. The following section will further discuss the benefits of MRs, especially in a manufacturing environment.

2.4. Benefits & Limitations of Mobile Robots in a Manufacturing Environment

Integrating MRs in manufacturing promotes lean manufacturing principles, enhances efficiency, and reduces waste. However, implementation also presents limitations regarding cost, scalability, and long-term sustainability. The following sections will address the benefits and limitations of MRs in an industrial environment. The definition for lean manufacturing is stated in Appendix 5.

2.4.1. Benefits of Mobile Robots in a Manufacturing Environment

There are eight wastes in lean manufacturing initially identified by Taiichi Ohno. These wastes have been identified to negatively impact a process's efficiency (Leksic, Stefanic and Veza, 2020). It can be argued that by implementing MRs, there is a reduction in all eight wastes shown in Table 1.

Table 1 - Eight Wastes and how MR Reduces

Waste	Relevance
Transport	Manual material transportation is significantly reduced, and material movement is optimised, reducing unnecessary travel.
Inventory	Deliveries from warehouse to production can be optimised, minimising excess stock, also known as 'Work in progress' (WIP) from the production floor, adopting a just-in-time (JIT) delivery system.
Motion	Human movement is reduced, allowing for workers to focus on more significant tasks.
Waiting	Utilising an FMS to optimise deliveries can reduce waiting times between processes, ensuring material is delivered or removed from the process on time.
Overproduction	Although not directly impacted by MRs, automation of material handling can help plan more efficient production rates, avoiding surplus.
Overprocessing	Redundant manual handling steps are eliminated, simplifying processes.
Defects	Automated handling minimises errors, reducing damage to parts which may be caused through delivery as well as reducing human error to the wrong parts being delivered to production.
Non-utilised Talent	Automating mundane tasks which allows employees to be prioritised for higher value activities.

The deployment of MRs can raise safety concerns and enhance safety in specific areas. For instance, MRs can handle hazardous materials, removing personnel from potentially dangerous situations. Automating

repetitive tasks like transporting boxes significantly reduces the risk of repetitive strain injury (RSI) (D’Souza, Costa, and Pires, 2020).

Capturing real-time data such as item locations, transport, and upcoming tasks enhances operational feasibility. Unlike human operators, who must identify an item's location, collect it, deliver it to production, and return to plan the next task, MRs have immediate access to data. Figure 12 illustrates the flow of both manual and automated material handling.

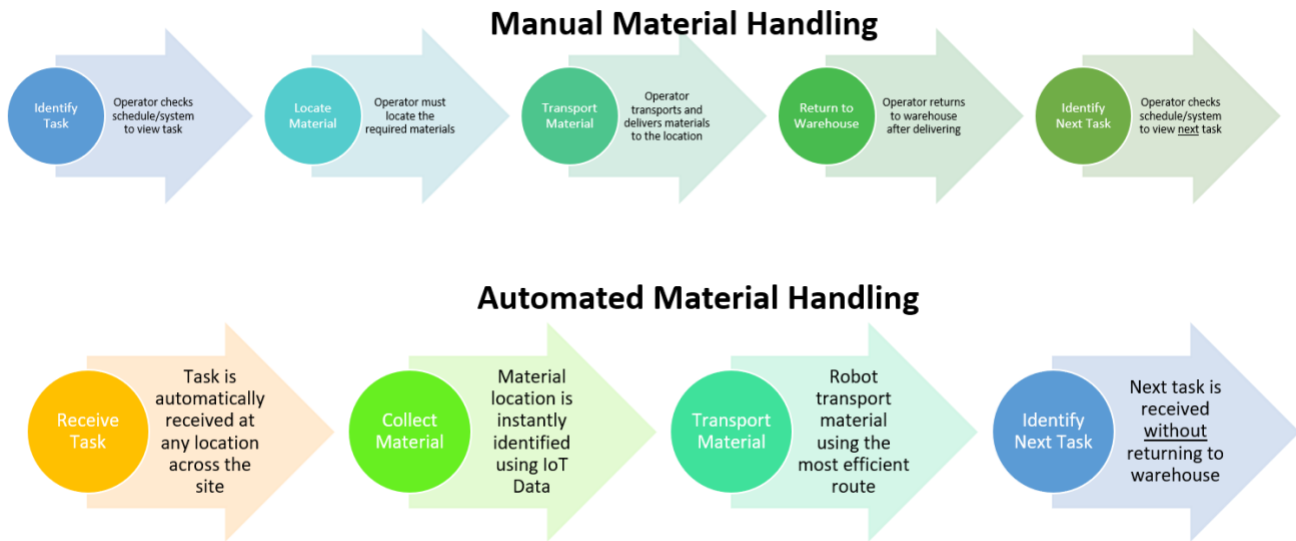


Figure 12 - Overview of manual and automated material handling in manufacturing

With MRs, Items are efficiently transported to production via the optimal route and can seamlessly transition to the next task, potentially located nearby, improving overall workflow and reducing unnecessary movements (Chu et al., 2024).

In manufacturing, production levels fluctuate throughout the year, with unexpected increases or decreases. MRs provide flexibility to adapt to these changes, reducing the need for additional operators during peak periods and minimising idle costs during low production. Unlike new operators who require training, these robots can learn from existing data, allowing quick integration of additional units.

2.4.2. Challenges of MRs in a Manufacturing Environment

A significant challenge with MRs is the high initial investment, including hardware costs for robots, signal boosters, door controls, charging stations, and necessary infrastructure modifications. Software upgrades may also be required to integrate existing warehouse systems with the FMS, demanding significant time and resources (Draganjac et.al., 2016). Ongoing costs include maintenance, such as sensor calibration, software updates, component replacements, annual software subscriptions, and service plans. These expenses

substantially increase upfront costs and extend the return-on-investment (ROI) period (Almeida et al., 2023). Although highly adaptable to changes, AMRs are still limited compared to the flexibility of human workers in terms of movement. For example, a person can physically move an obstruction if it is in their path, whereas a robot will halt or take a less efficient route (Hu et al., 2023).

MRs rely on stable power supply and a network connection. Power outages, software failures, or disruptions to communication can cause delays or downtime, disrupt production schedules, and lead to financial losses for the company (Fazlollahtabar and Akhavan, 2017). Unlike humans who can adapt and find alternative solutions during system failures, MRs will not operate until the failure has been rectified. Additionally, manufacturing facilities typically have many automated systems, often relying on wireless communication, which introduces further risk of disruptions. The benefits and limitations discussed above are summarised in Table 2.

Table 2- Summary of Benefits and Limitations of MRs in a manufacturing environment

Benefits	Limitations
Reduced Transport Waste	High Initial Investment
Optimised Inventory Management	Limited Path Finding Adaptability
Reduce Human Motion	Dependence on Power/Network Stability
Minimised Waiting Time	Maintenance Costs
Controlled Overproduction	Complex Implementation
Reduced Overprocessing	Wireless Inference
Reduced Defects	Longer ROI
Better Workforce Utilisation	
Enhanced Safety (RSI, Hazardous Material)	
Real-Time Data Optimisation	
Adaptable to Production Fluctuations	

Overall, MRs enhance lean principles and improve certain safety factors. However, costs remain a significant challenge. High initial investment and ongoing maintenance extend the ROI period. Human adaptability in certain situations may justify a collaborative approach.

2.5. Environmental Impact and Sustainability of Mobile Robots

As industries seek to make their operators greener, the environmental impact of MRs is a key consideration. Sustainability depends on factors including energy consumption, carbon footprint and end-of-life management.

2.5.1. Energy Consumption

MRs typically use lithium-ion or lead-acid batteries for power. Variables such as travel distance, velocity, and load influence their energy consumption. Longer distances, higher speeds, and heavier loads increase energy demand (Meissner and Massalski, 2020). Design modifications such as positioning load and unload areas at the start of walkways, regulating speeds, and implementing towing mechanisms rather than carrying payloads can minimise energy consumption.

2.5.2. Long-Term Sustainability

Consideration must be made towards the long-term sustainability of MRs. These robots comprise various materials, including metals, plastics, and electronic components, each requiring varying end-of-life processing. Electronic waste poses the most significant challenge due to hazardous materials and the additional costs associated with specialised recycling (Fawole et al., 2023). Improper battery disposal presents substantial ecological risks. However, repurposing used batteries for secondary applications, such as in the automotive industry, offers a good solution to minimise the environmental impact.

Regular maintenance, through implementing preventative maintenance (PM) strategies, extends the operational life span of the MR. Li and Zhang (2022) highlight the importance of TPM schedules in reducing wear-related failures, minimising downtime, and extending the equipment's life cycle.

2.5.3. Environmental Benefits.

MRs can offer environmental advantages over traditional material handling methods. For instance, Ocado operates with minimal on-site staff, significantly reducing the carbon footprint associated with employee commuting (Zheng, Gao and Tong, 2023). Facility energy savings can also be made by lowering lighting and HVAC requirements in specific areas without compromising productivity. Improvements to lean principles such as reducing defects, reduces material waste, decreasing the environmental impact of disposing or replacing the defective component. The following section will cover the regulations and standards applicable to MRs.

2.6. UK Regulations and Standards for Mobile Robots

The deployment of MRs in the workplace must comply with UK regulations and standards to ensure safe operation. This section outlines key regulations and standards relevant to their use in manufacturing.

2.6.1. Regulations

Regulations are legally binding and set by the government or regulatory bodies. Organisations must comply with them to ensure safety, environmental protection, and legal accountability (Mishra and Kumar, 2023). Table 3 presents a selection of regulations relevant to the use of MRs in manufacturing.

Table 3 - Regulations relevant to the use of MRs in manufacturing

Regulation	Description
Health and Safety at Work Act 1974	Ensures that employers must protect the health, safety, and welfare of employees. Risk assessments must be conducted, with adequate training with safe systems of work (Mogotlane and Pilusa, 2018).
Provision and Use of Work Equipment Regulations 1998 (PUWER 98)	All equipment, including MRs, must be safe, maintained, and only used by trained staff. Safety features like emergency stops and alerts must be present (Health and Safety Executive, 1998).
Supply of Machinery (Safety) Regulations 2008	The supplier must ensure that the MR must meet essential health and safety standards before supply to the customer (The Stationery Office Limited, 2008).
UKCA Marking	MRs must have UKCA marking to show they meet UK safety laws (GOV.UK, 2023).
Lifting Operations and Lifting Equipment Regulations 1998 (LOLER 98)	If MRs are used to lift loads, they must comply with LOLER. Requiring regular inspections and maintenance to ensure lifting operations remain safe (Health and Safety Executive, 2023).
Management of Health and Safety at Work Regulations 1999	Employers must carry out risk assessments and put controls in place. This supports safe MR use around people (Health and Safety Executive, 2022).

2.6.2. Standards

The most relevant standards for MRs used in manufacturing environments include those listed in Table 4.

Table 4 - Standards for MRs in manufacturing

Regulation	Description
ISO 10218-1:2025	Safe-design requirements, protective measures and information for use of industrial robots on mobile platforms in production environments (ISO, 2025a)
ISO 10218-2:2025	Safety requirements for integration of industrial robot systems into manufacturing lines, covering risk assessment and safeguarding (ISO, 2025b)
ISO 9283:1998	Performance criteria and test methods for navigation accuracy, repeatability and path-following of automated industrial robots (ISO, 1998).
IEC 60204-1:2016	Defines general requirements for the electrical equipment of machines, referencing control circuits, operator interfaces, EMC and protective bonding (IEC, 2018).
ISO 13850:2015	Outlines functional requirements and principles for the emergency-stop function on machinery (ISO, 2015).
ISO/TS 15066:2016	safety requirements for collaborative robot operation, covering speed/force limits and monitoring (ISO, 2016).

Table 4 lists just some of the standards relevant to the application of MRs. When implementing these robots, it is critical to involve compliance experts to ensure conformity with all applicable standards.

2.7. Sociological Impacts of Mobile Robots

Implementing MRs in manufacturing impacts many processes, creating significant change across a site. Resistance to change can occur, often caused by people being accustomed to original processes and the uncertainty of the change, as addressed by Kopp et al. (2023). Concerns regarding job security are a prominent reason for resistance. Fears may arise that MRs could threaten their roles, leading to increased anxiety about their future within the organisation. Safety concerns may arise regarding employees operating in

proximity to the MR. These concerns can negatively impact the workplace culture, leading to further issues such as employees leaving the company (Cunningham et al., 2013).

On the other hand, eliminating low-skilled roles can promote workplace development. Upskilling employees and investing in high-skilled roles such as engineers and technicians will be essential for successfully implementing MRs (Stareček et al., 2018).

Lewin's force field analysis (LFFA), developed by Kurt Lewin, is a valuable tool for understanding the dynamics of implementing change in an organisation (Lewin, 1951). LFFA aims to list the driving forces that push an organisation toward implementing MRs and the restraining forces that limit the organisation, as shown in Table 5. Each force is weighted from weakest to strongest (1-10), providing a total score for both sides (Swanson and Creed, 2014). The quantitative summary aims to guide management on what specific forces to reinforce. In this case, the proposed change is to minimise manual material transport by deploying MRs to transport materials autonomously material.

Table 5 - Lewin's Force Field Analysis

Driving Forces	Score (1-10)	Restraining Forces	Score (1-10)
Lean-waste elimination and efficiency improvements	10	High initial investment	9
Ergonomic and safety improvements	8	Job security concerns	7
Real-time data collection	7	Reliable on stable power and network	3
Environmental Improvements	5	Regulatory and standards compliance	3
Workforce up-skilling	6	Limited adaptability compared to human	4
Total	36	Total	26

The driving forces outweigh the total restraining forces by a score of ten. Consequently, the organisational climate favors replacing manual material transport with an automated solution. High capital expenditure is the

most significant restraining force. An organisation should focus on strategies that improve the projected ROI, such as phased implementation, leasing options, or multi-line deployment, to reduce the impact of this barrier.

Overall, the literature discussed above provides a foundational understanding of the capabilities, benefits, and limitations of MR technology. Research shows that MR technology is a potential solution for Sony UKTec, with a focus on AMR technology due to its ability to navigate effectively in dynamic environments. The following section outlines the methodical approach to evaluating the suitability of MR systems at Sony UKTec.

3. Define – Autonomous Material Handling

This project is structured around the DMADV methodology, a Design-for-Six-Sigma approach suited to developing new processes or major redesigns rather than incrementally improving an existing one (Antony, 2014). DMADV guides the work from problem definition through data collection, option generation, and simulation to a validated feasibility proposal (Cronemyr, 2007). The Define phase introduces the problem statement, stakeholder requirements, and project objectives, setting a clear foundation for assessing AMR feasibility.

3.1. Problem Statement

Material delivery at Sony UKTec is essential for maintaining efficient operations, ensuring that materials are delivered to the production line on time and finished goods are promptly removed to minimise congestion and optimise workflow. Material handling is manual and involves an operator delivering and collecting material to and from the process. Manual material handling leads to inefficiencies such as increased labour costs, delays and further waste as addressed in section 2.4.1. The Raspberry Pi 500 and Monitor products shown in Figure 13 are two products recently introduced to the Pencoed Site.



Figure 13 - Pi Monitor and Pi 500 Products

These are the two largest products that Sony UKTec manufactures for RPi. The kitting area allocated for a week's production of these models spans approximately 12 metres by 1.2 metres on both sides of the central walkway, as illustrated in Figure 14.



Figure 14 - Pi Monitor (Left) and Pi 500 (Right) Production Floor Kitting

With Sony UKTec actively pursuing new business opportunities, optimising floor space has become increasingly important. The current layout and manual handling methods strain available space, highlighting the need to explore automated material handling solutions. The following section will present the concerns and requirements raised by Sony UKTec employees.

3.2. Voice of the customer

The Voice of the Customer (VOC) was gathered to ensure that the project objectives for the automated solution align with the expectations and requirements of the key stakeholders at Sony UKTec. These requirements and concerns were converted into Critical to Quality (CTQ) characteristics, summarised in Table 6.

Table 6 - Voice of the Customer and Critical to Quality

Stakeholder / Customer	Requirement / Concern	Critical to Quality
Warehouse Operators	Easy load and unload Helps reduce workload Concern of losing job	Load and unload times Records of Personal Development (RPD)
Line Operators	No delays Concerns may obstruct workflow	On time deliveries
Production Managers	No delays – Achieve targets	On time deliveries
Senior Management	Improve process efficiency Reduced manual labour Saves floorspace by reducing kitting size ROI Concerns	Space saved Manual labour reduction Initial and on-going investment costs
Compliance (H&S)	Safe human-robot interaction Compliant with H&S regs and standards	Compliance with standards
Production Engineering	Optimised routes to minimise component wear Support Availability	Travel Distances Speed of support
Business Development	Selling point for new business Help reduce labour costs and quotes to win business	Reduction in labour costs Robot Utilisation for expansion
HR / Academy	Upskilling people	Records of Personal Development
Facilities Management	Energy management data	Energy consumption
Warehouse Management	No delays Visibility of inventory Minimises impact to Warehouse workload	On time deliveries Inventory visibility Queued jobs visibility

3.3. Project Aims and Objectives

As stated in the research phase, AMR technology is most suited to Sony UKTec's production environment and will be the type of technology analysed. The Pi Monitor and Pi 500 production lines will be used as case

studies, as they are the largest RPi products currently manufactured at the site and demand significant manual handling and floor space.

This project aims to determine the feasibility of deploying MR technology within two RPi processes at Sony UKTec. The study also seeks to build the foundations required for further viable rollout, setting selection criteria, assessing cost implications and developing a simulation to generate the data regarding MR material handling. Key objectives will include:

- 1. Analysing the current material handling process
- 2. Analysing AMR feasibility
- 3. Estimating total costs and potential savings
- 4. Simulating AMR material handling for the Pi lines to understand the impact on layout and variation of key parameters
- 5. Assessing scalability for wider rollout

The project will conclude with a feasibility analysis of a specific type of AMR for operations at Sony UKtec. The following section outlines what is in and out of this project's scope.

3.4. Project Scope

The scope of the project is highlighted in Table 7.

Table 7 - Project Scope

In Scope	Out of Scope
- Analyse current material handling for RPi Monitor and 500 production lines - Define requirements (Wants and Musts) - Contact suppliers for specifications and cost estimates - Simulation of robotic material handling - Evaluation of technology, safety and operational requirements - Cost analysis - Feasibility conclusion - Recommendations	- Implementation or purchase of AGVs/AMR - Physical trials or integration into live production lines - Evaluation of other production areas or departments beyond the two Pi lines - Detailed IT or infrastructure design for integration - Final procurement decisions or supplier evaluation

It is understood that a study on MR technology could be vast, intensively exploring many aspects. While a thorough assessment will be required, this study aims to serve as an initial study, providing useful discussions on key areas.

3.5. Project Timeline

The project timeline is shown in the Gantt chart in Figure 15.

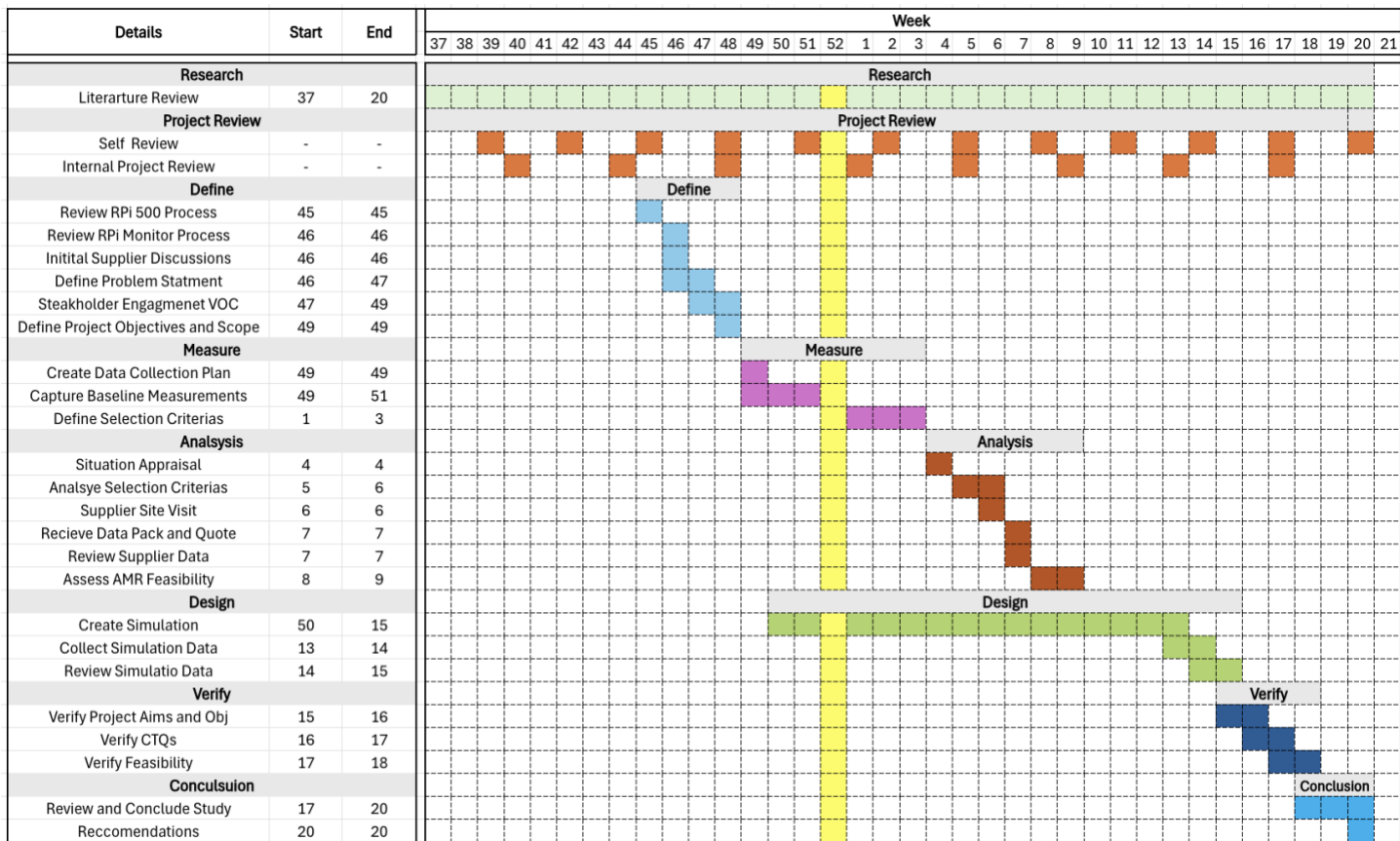


Figure 15 - Project Timeline

The project timeline outlines a clear and logical flow, beginning with the research phase in Week 37 (2024) and concluding in Week 20 (2025). Each stage is scheduled to follow on from the previous, allowing for a smooth transition between phases. The yellow section in the middle highlights the Christmas shutdown period, during which no project work will occur. The following section will be the measure phase, starting with creating a data collection plan following the CTQs captured from the VOC.

4. Measure

The Measure phase aims to collect and quantify baseline data from the current material handling process at Sony UKTec. This section establishes a data collection plan and sets key criteria for further assessments. The data collected will be used as a benchmark to evaluate the feasibility and impact of introducing AGVs or AMR.

4.2. Data collection plan

The data collection plan is presented in Table 8.

Table 8 - Data collection plan

Critical to Quality	Metric	Collection Method	Collection Period
Load and unload times	Average time per kit	Time-motion Study	During Pilot Phase
On-time deliveries	Time waiting for delivery / collection	Process Simulation	During study
Space saved	Area saved	Pre / post layout measurements	During study
Manual labour reduction	Seconds manual labour saved	Pre / post labour calculations Time spent travelling	During study
Initial and ongoing investment costs	CAPEX and OPEX	Supplier quotes	During study
Compliance with standards	Conforms with ISO/UKCA/HSE	Supplier documentation	During study
Travel Distances	Metres travelled	Physical Measurements	During study
Support Availability	MTTR	Maintenance Contracts	During Pilot Phase
Labour cost reduction	Yearly savings through automation	HR Finance data modelling pre / post	During study
Robot utilisation	% utilisation for operation	Process Simulation	During study
Records of personal Development	Number of submitted RPDs	Training system log	During pilot phase
Energy consumption	Power Consumption (W)	Supplier data	During study
Inventory visibility	Real-time inventory accuracy	Supplier packages	During study
Queued jobs visibility	Real-time job accuracy	Supplier packages	During study

The table outlines the key CTQ metrics for evaluating the material handling process. It includes measures such as load and unload times, on-time deliveries, space savings, manual labour reduction, compliance with

standards, MTTR, labour cost reduction, robot utilisation, travel distances, records of personal development, energy consumption, inventory visibility, and queued jobs visibility. AMR data will be gathered once the most suitable AMR type has been selected, ensuring that subsequent supplier evaluations are based on relevant performance benchmarks and operational requirements.

4.3. Baseline Measurements

Baseline measurements have been collected for the current material handling process. Both RPi models typically operate on a day shift within a 4.5-day week, with flexibility to scale to two or three shifts. The following sections will present travel distances and estimated time spent travelling.

4.3.1. Raspberry Pi 500 Process

The RPi 500 line is located 85 m from the warehouse and requires five raw material deliveries and one finished goods collection per day shift, outputting an average of 121 units per hour. Each delivery supports approximately 1,000 units, while each finished goods pallet contains 840 units. Table 9 summarises the weekly handling data for this process.

Table 9 - Summary of the current Pi 500 material handling data

Operation	Frequency	Warehouse to line distance (m)	Distance Per Day (m)	Distance Per Week (m)	Time spent travelling Per Week (s)
Material Delivery	5	85	850	3825	2899
Finished goods	1	85	170	765	579.5

Over a 4.5-day working week, the total travel distance is 4,590 m. Based on an average walking speed of 1.32 m/s (Song, Choi and Collins, 2020), this equates to 3,478.5 seconds (approximately 0.97 hours) of travel time. The current layout of RPi 500 is shown in Figure 16.

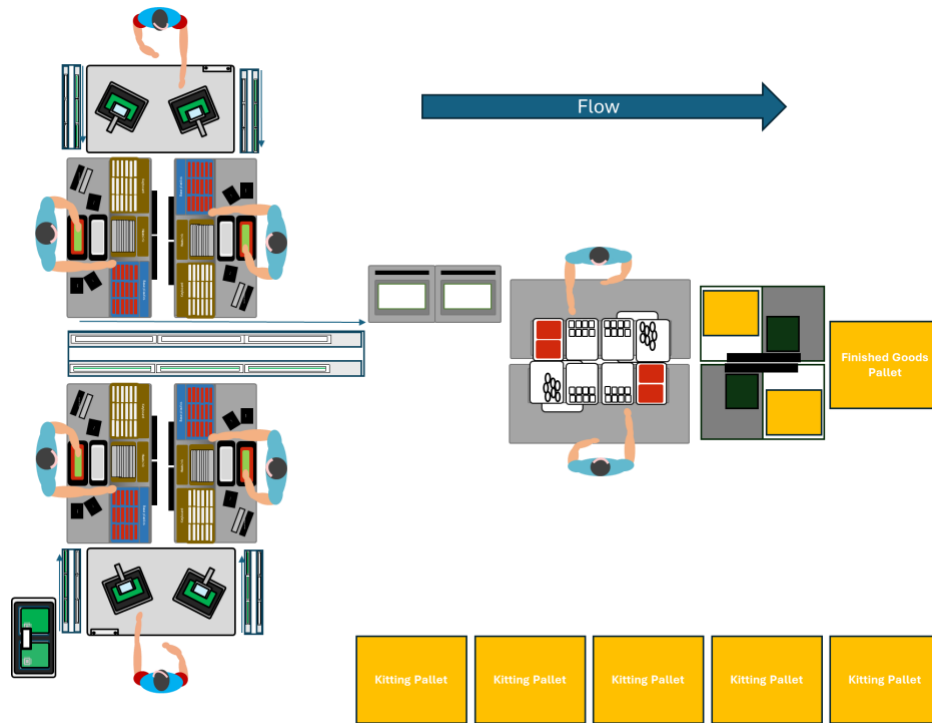


Figure 16 - RPi 500 Current Layout

Pallet storage for the RPi 500 line occupies approximately 7.2 m², based on a standard pallet footprint of 1.2 m².

4.3.2. Raspberry Pi Monitor Process

The RPi Monitor line is slightly further from the warehouse at 90 m, and outputs an average of 104 units per hour. Due to component size and packaging format, ten pallets of raw material are required to build 900 units per day shift. Seven collections of finished goods are needed, each transporting 120 units per pallet, totalling 840 units per shift. Table 10 summarises this.

Table 10 - Summary of the current RPi Monitor material handling data

Operation	Frequency	Warehouse to line distance (m)	Distance Per Day (m)	Distance Per Week (m)	Time spent travelling Per Week (s)
Material Delivery	10	90	1800	8100	6136
Finished goods	7	90	1260	5670	4295.5

The total weekly travel distance is 13,770 m, significantly more than the RPi 500 line. At 1.32 m/s, this equates to 10,431.5 seconds (approximately 2.9 hours) of walking time. Figure 17 shows the current layout for the RPi Monitor production line.

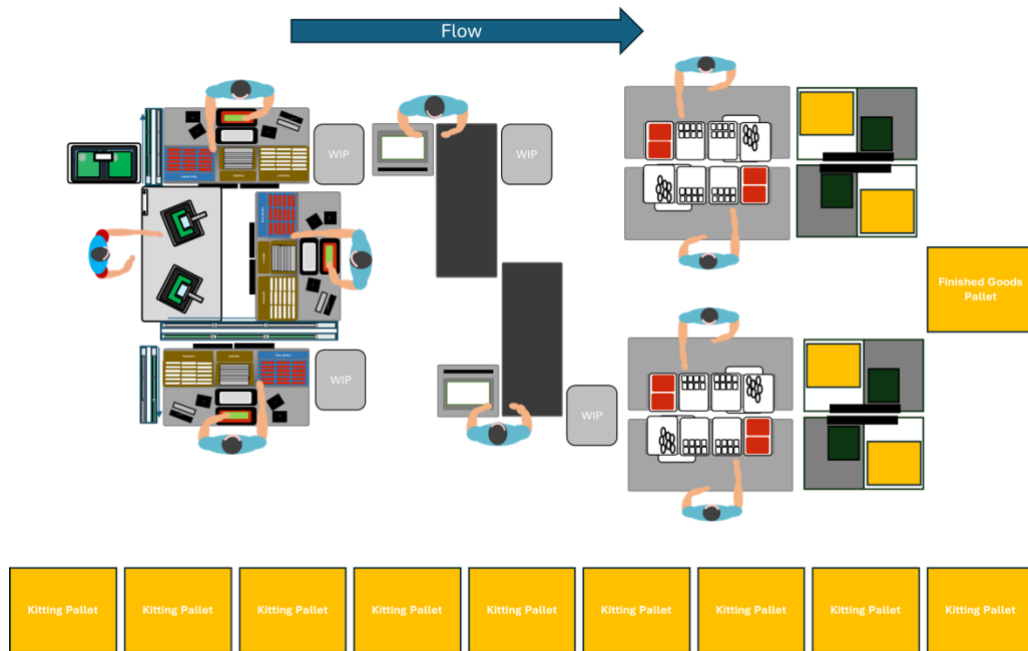


Figure 17 - RPi Monitor Current Layout

Seventeen pallets are required on the line at any one time, totalling 20.4 m² of occupied floor space.

4.4. Setting the Selection Criteria

The Kepner-Tregoe (KT) method for decision analysis (DA) (Quick, 1980) adopts a structured approach to making decisions. In the following sections, process objectives will be set and defined as wants or musts.

4.4.1. AMR Type Selection Criteria

Table 11 shows the selection criteria for the type of AMR used at Sony UKTec.

Table 11 - KT Objectives and Wants and Musts for AMR Type

Objectives	Must/Want (1-10)
Operates safely around people	M
Can move materials between locations	M
Operate within factory environment	M
Can follow pre-defined paths	M
Adaptable in dynamic environments, autonomously navigate	M
Can navigate in walkways 1.2m width	M
Reduces kitting and finished goods floor space by 65%	10
Scalable to variety of models at Sony UKTec	9
Adaptable with other accessories, e.g., different mounts etc	8
Can navigate in walkways minimum 0.8m Width	8
Capable of transporting a variety of equipment (Totes, stations, single boxes etc)	7
Minimal disruption to current operations, does not cause congestion	7
Minimal disruption to current layouts	6
Can carry multiple kits if required (2 or more)	5
Simple load and unload	5
Energy efficient transport method	4

These objectives have been selected to reflect the operational challenges identified in the problem statement and align with the overall project goals of improving efficiency, reducing manual handling, and optimising floor space.

4.4.1.1. Types of AMR to be Evaluated

Alfredo Pastor Tella is an expert in mobile robotics who has devoted over ten years of his career to helping companies improve their logistics by automating their material handling processes. Through online discussions, Alfredo provided his expert knowledge on what types of AMR Sony UKTec should evaluate, which is summarised in Table 12.

Table 12 - Types of AMR to be evaluated for Sony UK Technology Centre

AMR Type	Picture	Description	Use Cases
Platform		Flat, low-profile robot designed to transport a variety of payloads placed directly on its surface. Often used with carts, racks, or bins.	Moving general-purpose equipment, parts, or containers between warehouse and production lines.
Pallet Jack		Automated version of a manual pallet jack, capable of lifting and transporting standard pallets directly.	Transporting raw material or finished goods on pallets, especially in warehousing operations.
Pallet Platform		Similar to a platform AMR but specifically designed to carry full pallets. Larger in size, travelling under a raised pallet to lift and transport.	Moving static pallet loads, ideal for fixed pick-up/drop-off points
Cobot		A mobile robot equipped with a collaborative robotic arm. Performs transport tasks and light assembly or pick-and-place tasks autonomously.	Performing both material delivery and light tasks (e.g. picking) near production lines.
Cart Pull		Towing robot designed to autonomously pull one or more carts along defined routes. Suited for transporting multiple loads in one trip.	Efficient movement of kitted materials or reusable containers across multiple production areas.

The types of AMR above will be assessed to identify the most suitable option for Sony UKTec. The following section will define the selection criteria for the specific supplier and model.

4.4.2. Supplier and Model Selection Criteria

Table 13 presents the selection criteria for the specific supplier and model.

Table 13 - KT Objectives and Wants and Musts for AMR Type

Objectives	Must/Want (1-10)
Operates safely around people	M
UKCA/CE Certification	M
Integration Service	M
Fleet management system	M
On site support available within 2 working days	M
Capable of loads of up to 50 Kg	M
Availability of spare parts	M
Training plans	M
Servicing plans	M
Capable of operating in 1.2m walkways	M
In process charging	M
Maximise range of load capacity	10
Adaptable with a variety of accessories	9
Fast support available e.g >1day	9
Maximise capability to operate in narrow walkways	8
Easily maintained	8
Supplier with proven track record	7
Maximum travel speed (m/s)	6
Energy efficient	5
Easily scalable	5
Compact footprint	4

As defined in the project scope, suppliers will not be evaluated against the above selection criteria within this study. Instead, the requirements have been established to provide a structured foundation for supplier assessment should the project proceed to implementation.

5. Analysis

During the analysis phase, the current material handling process will be evaluated, along with the AMR options, against the defined criteria. The overall purpose is to highlight the causes of inefficiencies and determine the most suitable AMR solution to meet the site requirements.

5.1. Situation Appraisal of the Current Material Handling Process

The current material handling processes across both lines present multiple challenges, impacting operational efficiency, manual labour, and business scalability.

5.1.1. Non-Value-Added Labour

Manual material transport is essential. However, it requires skilled labour on non-value-adding tasks, contributing directly to motion and talent waste (Thürer, Tomašević, and Stevenson, 2017). At current volumes, operators travel 18.36 km weekly between both models, equating to 3.86 hours and an annual operational expenditure (OPEX) of £2,938.54 per operative based on an hourly cost of £15.66. Scalability is limited, additional staff are often required during peak demand, introducing training overheads, reduced early productivity, and recruitment fees. Rising labour costs, driven by UK wage growth, further inflate this. Inflexibility and dependence on labour-intensive handling increase the price per unit produced, reducing profitability and inflating customer quotations. Over time, this can limit competitiveness and risk the loss of future business.

Overall, the current method negatively impacts operational efficiency, contributes to lean manufacturing wastes, and limits strategic growth. It highlights the need to reduce manual labour requirements, which automation could address.

5.1.2. Inefficient Use of Floor Space

Combined, both models occupy 27.6m² of floor space for kitting and finished goods, annually costing £2,263.20 based on a rate of £82/m². While reducing kit sizes could decrease this footprint, it would require more frequent deliveries, increasing manual handling demands. In a facility with rising production volumes and no physical room for expansion, this limits layout optimisation and the ability to onboard new products. Space constraints also cause congestion, creating additional safety and flow difficulties that impact daily operations.

Overall, excessive floor space usage restricts operational flexibility, adds to overhead costs, and constrains the site's capacity to grow and adapt. Reducing space dependency through automation would support a leaner, more scalable layout.

5.1.3. Lack of Process Control

Manufacturing processes require consistency to ensure efficiency (Li, 2015). The material handling process lacks the control and predictability necessary for efficient operations. Manual material handling relies heavily on operator availability, timing and judgment, leading to inconsistent deliveries and collections. Delays result in unutilised labour, waiting for material to be delivered, one of the eight wastes in manufacturing.

Digital traceability is limited, with material visibility only existing when the material is located within the warehouse. Key performance indicators (KPI) such as delivery accuracy, transport cycle times, or operator efficiency are not captured, limiting opportunities for continuous improvement.

Overall, the lack of control reduces production reliability, hides performance issues, and limits the business's ability to adapt, scale, or improve internal logistics processes. Automation would create a consistent, measurable, and traceable process supporting standardisation, real-time oversight, and proactive decision-making.

5.2. Analysis of Selection Criteria

The following sections evaluate the selected AMR types, suppliers, and models against the objectives defined in Section 4.4. Input has been gathered from key stakeholders, including warehouse management, production management, production engineering, and a representative from HR. Including an HR team member ensures impartiality in the scoring process, as they hold no direct involvement in the project.

5.2.1. Evaluation of AMR Type

Each AMR type was evaluated using the KT method against the weighted selection criteria defined in Section 4.4. All five options satisfied the mandatory requirements and were scored according to their performance against prioritised objectives. The complete scoring table is provided in Appendix A and is summarised in Table 14.

Table 14 - AMR KT Evaluation Summary

AMR Type	KT Score	Key Benefits	Key Limitations
Platform	655	Compact, highly adaptable, supports varied load types, ideal for tight spaces	Process that uses pallets will require adaption, increasing initial costs and project complexity
Cart Pull	486	Energy efficient, minimal infrastructure change, easy integration	Limited to cart-based loads, reduced crossline flexibility
Cobot	415	Ideal for collaborative tasks, strong in human-robot interaction scenarios	Low payload capacity, slower cycle times, complex integration
Pallet Jack	309	Suitable for heavy pallet handling	Large footprint, poor manoeuvrability, limited scalability
Pallet Platform	286	High load capacity	High layout disruption, minimal adaptability, unsuitable for lean/hybrid operations

Overall, the Platform AMR offers the most balanced and scalable solution as it aligns with the site's current operational challenges while supporting broader strategic objectives such as process flexibility, lean, and scalable automation.

5.2.2. Analysis of Supplier and Model Selection Criteria

The supplier and model selection criteria reflect the site's requirements for a solution that integrates seamlessly and delivers long-term reliability, safety, and scalability. The main objectives are to ensure that all solutions meet the minimum safety, regulatory, and functional requirements. When setting the objectives, the requirement for the supplier to be an integrator was highlighted due to the lack of specialist knowledge of AMR on-site. Another essential requirement that the members in the KT meeting agreed upon was the requirement for an FMS. Although likely unnecessary for just two models, an FMS will be essential when expanding the project to wider processes, ensuring the AMR is automatically managed and processes are fully optimised. The weighted wants aim to establish differentiation between the suppliers based on operational flexibility and long-term value. The ability to transport a wide range of loads, interchange accessories, connect connections, and navigate down narrow aisles is a key evaluation point ensuring the scalability of other factory processes. Breakdowns of the AMR or systems would cause severe disruption to the associated processes, making the responsiveness of support a key selection factor. While the minimum requirement is to receive onsite technical support within two working days, a high-priority want is to access same-day support in urgent scenarios. This reflects the operational need for rapid fault recovery and minimal downtime, particularly in high-throughput or time-sensitive environments. Ease of maintenance is critical in ensuring timely repairs, as it also ensures that the maintenance workload does not substantially increase.

Overall, the criteria have been set to ensure technical compliance, operational suitability, flexibility, and long-term scalability. Suppliers with a proven track record in AMR integration who can respond quickly when required support will be prioritised. This may justify selecting a UK-based supplier to ensure service responsiveness. The chosen supplier must also be capable of integrating a fleet management system and providing comprehensive maintenance contracts and training plans to support sustained deployment. Additional considerations include the supplier's ability to support future expansion, offer software flexibility for integration with existing systems, and demonstrate a clear roadmap for upgrades or system enhancements.

5.4. Supplier Data – Reeco Automation

Due to the variety of AMR, costs, or technical data were not collected during the measure phase to avoid collecting unnecessary data on AMR that do not meet the project requirements. As Jordan Jenkins of UWTSD recommended, Reeco Automation is an integrator and supplier of Omron AMR and has a close relationship with the university. Sony and Barry Graham from Reeco organised a site visit, which provided an understanding of Sony UKTec's facilities and processes.

During the visit to Sony UKTec, Graham reviewed the facilities and agreed that a platform-type AMR is the most suitable for the operation (Graham, 2025). The robot recommended is the LD90 Omron AMR, as shown in Figure 18.



Figure 18 - LD90 Omron Platform AMR

The supplier data sheet for the LD90 is available in Appendix B. The following sections will assess the data to understand its operational, safety, technical, and economic feasibility. By determining this specific AMR, a clearer understanding of the critical features, key advantages, and potential limitations relevant to the application will be gained.

5.4.1. Technical Feasibility

Wi-Fi is used for communication between the AMR and the FMS; this will require additional infrastructure of signal boosters throughout the site. Production test pods on site also use Wi-Fi as a means of communication, which can disrupt AMR communication and cause downtime. For the Pi 500 and Monitor processes, disruption may be minimal as the number of AMRs required is likely to be small; however, increasing the size of the fleet will result in further signals, increasing the risk of disruption and requiring additional infrastructure, such as signal boosters.

The LD90 uses a lithium-ion battery, a standard energy storage system across most industrial AMR due to its high energy density and long service life (Chen et.al., 2020). Data indicates a battery life of approximately 2000 full charge cycles. Charging from 20% to 80% takes around two hours and ten minutes, emphasising the need for opportunity charging during idle periods to avoid extended operational downtime. Effective integration of charging points into the layout will be essential to maintain high AMR utilisation, particularly during multi-shift operations. The charging stations draw 800 W each, which is manageable at low volumes, but expanding to additional processes may require upgrades to the facility's electrical infrastructure.

The LD90 has LiDAR sensors with 240 degrees of coverage, low-level lasers, sonar, and a standard vision camera. These sensors allow the AMR to move precisely and safely in a dynamic environment. Considerations must be made for maintaining these components, which will involve specialist training and a stock of spare components if a replacement is required.

5.4.2. Operational Feasibility

The maximum payload at Sony UKTec is 50kg, within the LD90's 90kg maximum payload capability. At a full payload, the LD90 can run for approximately twelve hours. Graham stated that the run time will be further enhanced if a cart transport method is utilised, as the payload is minimised. For single-shift operations of eight hours, the LD90 can operate without downtime. However, its run time is limited during two or three-shift operations without opportunity charging. Figure 19 shows the dimensions of the LD90.

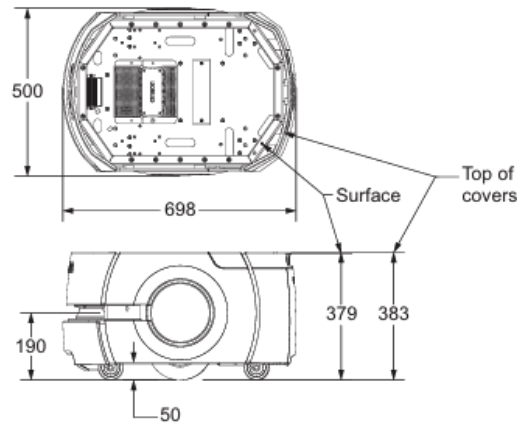


Figure 19 - Dimensions of the LD90 Omron AMR

The LD90 measures 0.5m by 0.7m, giving 0.35m clearance on either side when travelling down a 1.2m walkway, allowing the maximum travel speed of 1.35 m/s. The minimum walkway at Sony UKTec is 0.8m, which gives little clearance, limiting the robot to a reduced travel speed of 0.8 m/s, as confirmed by Graham. The stop position accuracy is ± 12 mm, allowing for accurate pick-up and deposits of material, ensuring consistency.

The data sheet highlights that the floor must meet the minimum ACI 117 FF-25 standard, which relates to the floor's flatness (Olson, 2020). The maximum traversable step is 15mm, which is not an issue with the current layout at Sony UKTec.

The FMS is a highly beneficial option, minimising manual interaction by autonomously managing AMR movement, live inventory visibility, and real-time schedule visibility. Deliveries are optimised in real time, reducing human error and congestion and ensuring efficient, scalable operations as production demands grow. Charging stations require dedicated floor space, which must be carefully considered during layout design. It is essential to take a long-term view and strategically position charging points to support current operations while allowing for future expansion of AMR fleets.

Overall, LD90 meets Sony UKTec's load, runtime, and navigation requirements, operating within payload limits and completing day shifts without downtime. It navigates 1.2 m walkways at full speed and 0.8m at reduced speed, with ± 12 mm positioning accuracy. Floor conditions meet ACI 117 FF-25 requirements. FMS integration enables scalable, automated fleet control, and charging stations must be strategically planned for future expansion.

5.4.3. Safety Feasibility

The LD90 uses a Class 1 laser scanner to detect obstacles and avoid collisions. Class 1 lasers are considered eye-safe, ensuring minimal risk to personnel (Hasselbach et al., 2019). Graham confirmed that Omron AMR

are equipped with collision avoidance algorithms, enabling the robot to predict the movement of surrounding objects and dynamically adjust its path to prevent impact. In addition to the laser scanner, Figure 20 shows additional safety features of the LD90.

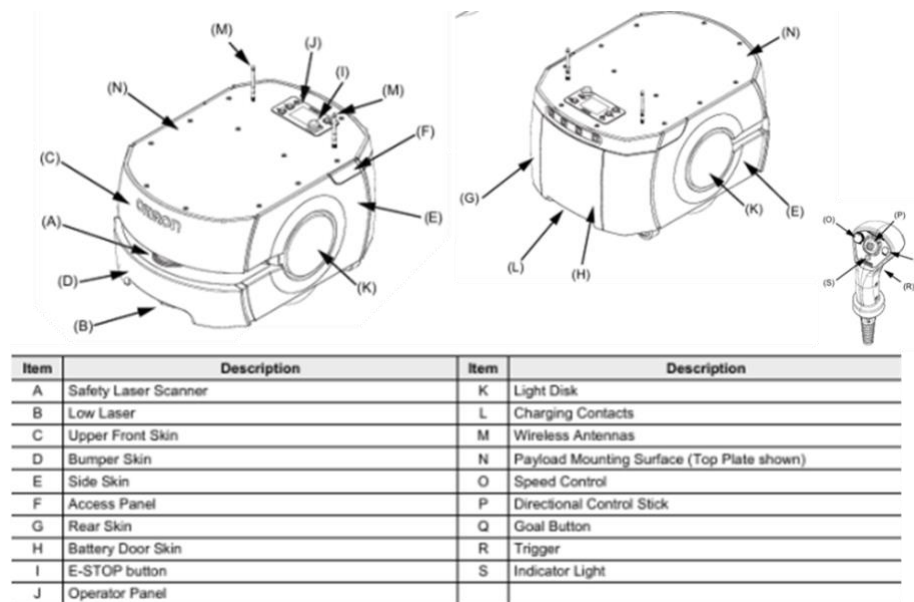


Figure 20 - LD90 Features Diagram

Contact bumper sensors located at the front add an additional layer of protection, causing the AMR to stop if activated. E-Stops allow for manual interaction, as well as audible and visual indicators. The data sheet also shows that a sonar sensor is located on the rear of the AMR, improving collision detection in the blind spot of the primary safety laser.

Safety zoning is also possible via the FMS, allowing the creation of AMR exclusion zones and variable speed zones. For example, speeds could be reduced in high-traffic areas, and exclusion zones near equipment could be created. Table 15 shows the summary of safety-related standards for the LD90.

Table 15 - Summary of safety-related standards for the LD90.

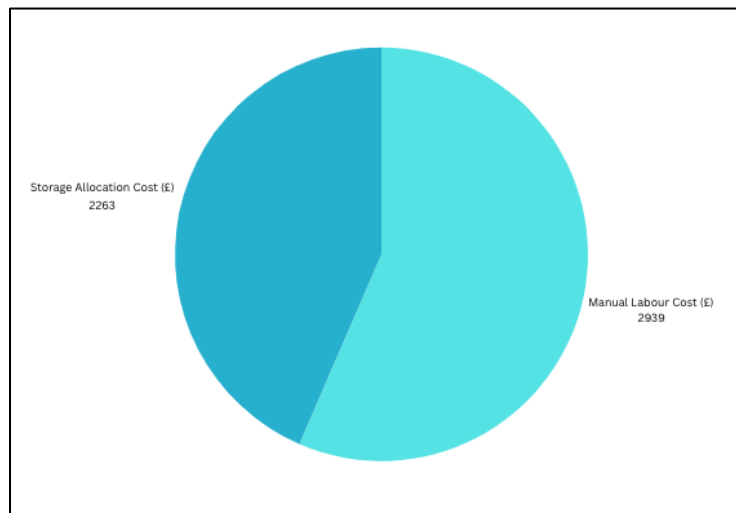
Standard	Relevance
EN ISO 12100	Ensures the AMR is fundamentally designed to eliminate or reduce risks to operators (ISO, 2010).
EN ISO 13849-1	Ensures the reliability and performance of critical safety functions like E-Stops and collision avoidance (ISO, 2015).
EN 60204-1	Guarantees electrical safety, covering wiring, grounding, and fault protection (IEC, 2018).
EN 1525	Defines operational safety requirements specifically for AMR and AGVs in shared human environments (CEN, 1997).
ANSI B56.5	Provides international validation of operational safety systems, supporting compliance beyond the UK (ANSI/ITSDF, 2019).

Collectively, these standards show the robot can operate on the shop floor without extra guarding, supporting safety feasibility at Sony UKTec.

Overall, the LD90's integrated safety systems, supported by the standards listed in Table # make it well-suited for safe, collaborative operation on Sony UKTec's production floor. A key risk is that sensor performance can degrade without regular maintenance and calibration, or if elevated dust and glare levels interfere with laser and sonar detection.

5.4.4. Economic Feasibility

The current material handling costs have been calculated in section 5.1. and is summarised in Graph 1.



Graph 1 – RPi 500 and Monitor Total Material Handling Costs

Manual transportation accounts for the highest OPEX, with floorspace allocation contributing 43% of the total OPEX. Graham provided a budgetary quote, including the price of an AMR starter kit and additional AMR, shown in Figure 21.

Item	Description	Qty.	Price £
1	LD90 – Mobile Robot Starter Kit (ESD) & Battery - LD90 Starter Kit (ESD Version) - o Charging Station - o Top Plate - o Joystick - LD Series Battery - Cell Alignment Positioning System (CAPS)	1	£46,171.00
2	Mobile Robot I/O Box & Power Supply – (Door Call)	1	£ 1,232.85
3	Fleet Management & Control Cabinet - Industrial PC - 19" Touchscreen Monitor - Fleet operations License for 5 x AMR maximum (3 Years) - Logic controller & Data enable network (POC-UA)	1	£31,200.59

Figure 21 - Budgetary quote by Reeco Automation

This quote includes an LD90 AMR with essential controls to program the robot, a door control required for the AMR to travel between the warehouse and production, and an FMS with a three-year operational license for up to five AMRs. Additionally, material transport will require trolleys, costing approximately £325 each. An estimate of three per process is necessary for kit preparation, while one is utilised at the lineside.

At this stage, it is anticipated that a single AMR will be sufficient to service both production lines; this assumption will be validated through simulation in the following section. Preliminary analysis suggests that the AMR could eliminate 100% of the OPEX currently attributed to manual material transport. Additionally, adopting an AMR system is expected to reduce floor space requirements significantly. With trolleys measuring 1.2 m by 0.6 m and accommodating incoming raw materials and outgoing finished goods, the total space required for material handling is estimated at approximately 3m² (1.5 m² per model). This represents an 89% reduction in floor space compared to the current layout, reducing the associated annual cost to just £246. The capital expenditure (CAPEX) is summarised in Table 16.

Table 16 - Summary of AMR costs and savings

Item	Quantity	Cost
LD90 AMR and Controls Starter Kit	1	£46,171.00
I/O Door control	1	£1,232.82
Fleet Management System and Control Cabinet	1	£31,200.59
Transport Trolley (1.2mx0.6m)	6	£1,950.00

Therefore, the total estimated CAPEX is £80,554.41. It is also important to note that this does not include installation fees, maintenance, servicing contracts, spare parts, or annual licence renewals. Assuming that manual transport is mitigated, floor space is reduced, and allocation is reduced by 81%, the total annual saving is £4,966.74, giving a 6.17% yearly return and a total ROI in 16.3 years.

Additional costs not yet accounted for would extend this payback period further, making the solution economically unviable if limited solely to the Pi 500 and Monitor processes. This underscores the importance of wider scalability across additional production lines to maximise the return and justify the investment.

Implementing a modular AMR system that supports future process areas would improve overall cost efficiency and strengthen the business case for adoption.

In contrast, additional savings could be considered. Projected rises in wage rates and employers' National Insurance contributions would magnify the labour-cost savings delivered by automation, thereby shortening the ROI. However, it is also essential to consider that expenditure, such as supplier and energy costs, could lengthen the ROI.

Overall, implementing an AMR is feasible from a practical perspective. However, the ROI is extremely high and would be difficult to justify based on a single deployment. The AMR must be rolled out across additional facility areas to make the investment viable. Further considerations, such as increasing employee and supplier costs, should also be factored into the ROI. A simulation will therefore be used to analyse the utilisation of a single AMR, addressing scalability and providing insight into the impact of varying key parameters on system performance and operational efficiency.

6. Design – Simulation

In this phase, Arena Simulation software develops a discrete-event simulation (DES) of the RPi 500 and Monitor processes. Cycle-time data gathered during the Measure phase defines each processing node, while AMR tasks are represented as transport entities. The simulation aims to understand the approximate travel distances and robot utilisation while minimising material delay time for both processes.

6.1. Arena Simulation of the Pi 500 and Monitor Process

The model in Figure 22 was created to represent both RPi processes.

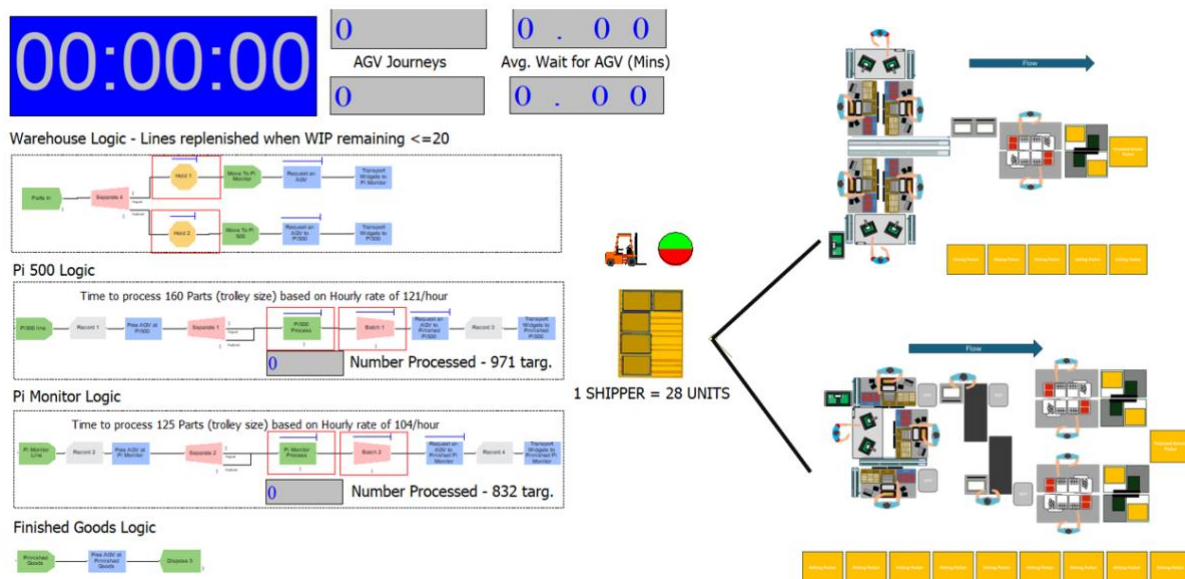


Figure 22 - Arena Simulation Model

DES models a system as a time-ordered sequence of instantaneous events (Karnon et al., 2012). In this case, each kit delivery and collection enables efficient evaluation of delays, utilisation, and flow. Assumptions have been made to minimise the complexity of the model, focusing on variables that directly impact material flow, which are detailed in the next section.

6.1.1. Model Assumptions

Table 17 presents each assumption, its effect on the model, and the expected impact should the assumption be altered.

Table 17 - Model assumptions and Impact

Assumption	Expected effect on model	Impact if modified
Line buffer threshold <=10% of process hourly rate RPI 500 = 12 RPI Monitor = 11	Impacts the frequency of delivery, AMR is triggered when line is <=10% of process hourly. Impacting AMR utilisation and distances travelled	Increasing this threshold will result in fewer deliveries, more material lineside. Lowering the threshold will increase the frequency of deliveries, less material stored lineside but a great risk of delays.
Inventory is always available	No delays on warehouse end of process, kit is instantly ready for transport.	If shortages are introduced, waiting time increased, potentially starving a process of raw material
Cycle time is fixed	No variance in process time	Higher cycle time decreases AMR demand while lower increases.
AMR load capacity is fixed for deliveries and collection	Load capacity fixed based on maximum trolley capacity Determines AMR utilisation.	Larger capacity reduces utilisation. Lower capacity raises utilisation
AMR follows a fixed, interruption-free path	Provides best-case travel time with no routing conflict	Adding human or truck interference lengthens travel time and delays
Constant AMR velocity of 1.35 m/s	Establishes baseline transport time	Higher speed shortens delays. Lower speed lengthens queues and waiting time
AMR returns to inventory after every delivery	Simplifies routing but increases empty travel distance	Multi-stop routing would reduce empty kilometres and battery draw
Dayshift operation only	Omits second- or third-shift battery and labour effects	Adding extra shifts requires opportunity charging and may reveal capacity shortfalls
Battery recharge not modelled	Assumes full availability and zero charge downtime	Including recharge windows reduces effective utilisation and may require an additional AMR
Docking and undocking delay ignored	Underestimates cycle time by a small constant per trip	Modelling docking and undocking will increase travel time, potentially leading to delays
No equipment failure or Wi-Fi dropout	Assumes perfect reliability with no unplanned downtime	Introducing mean-time-between-failure and repair time decreases overall equipment effectiveness
AMR delivers to the closest Process first	Impacts total delay time	If material delivered to the furthest process first, delay time would increase

The assumptions in the table above establish the model's baseline and highlight how each simplification impacts the simulation

At the start of the simulation, there is expected to be an initial fixed delay due to both processes having no initial material. This is illustrated in Figure 23, using the distances measure from the warehouse to each process and the assumed AMR velocity of 1.35m/s

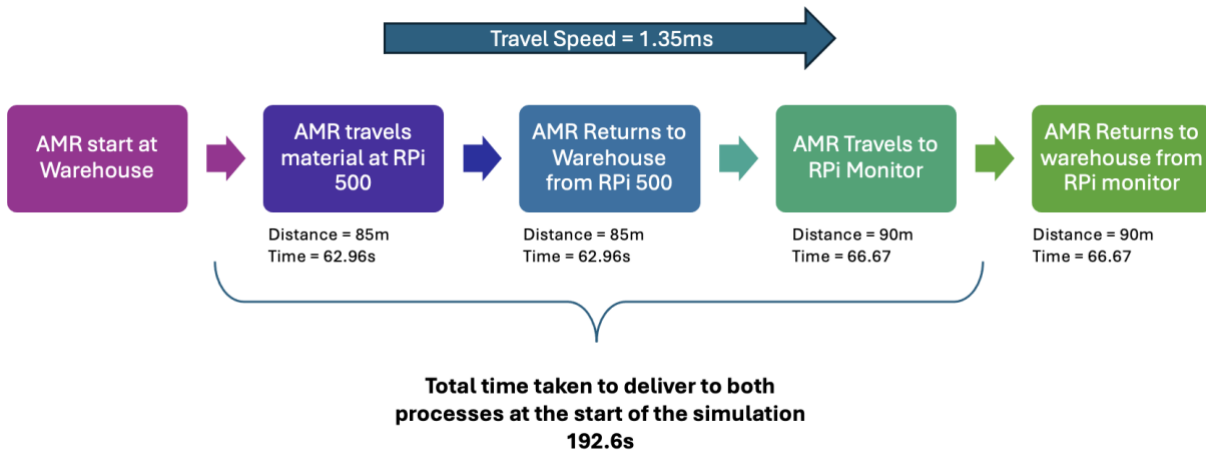


Figure 22 - Process flow of initial simulation delay

With the AMR travelling to RPi 500 first, it must return to the warehouse before delivering material to the RPi Monitor process, creating an initial fixed delay of approximately 192 seconds. The following sections will display results from the simulation, starting with a baseline measurement with all assumptions listed in Table 16

6.1.2. Simulation Baseline Measurements

In this section, the simulation will be run with the assumptions listed, a 10% buffer threshold for each process, a fixed AMR travel speed of 1.35m/s and a maximum load capacity of 160 units worth of material for RPi 500 and 125 for RPi Monitor. The load capacity of finished goods will be set at twenty-eight units, equating to one full shipper in both processes. The simulation is run for eight hours of production. Data is captured for the total distance travelled by the AMR, the percentage of AMR utilisation, and the total delays during which a process was waiting for material delivery. The results are displayed in Table 18 and are available in full in Appendix 3.

Table 18 - Simulation Baseline Results

Simulation Run	AMR Distance Travelled (m)	AMR Utilisation (%)	Total delay (s)
1	6725	32%	192

The total distance travelled per day is relatively high due to the AMR returning to the warehouse after each delivery. In reality, an FMS will have a better overview of upcoming tasks, holding the AMR in the area where the next task is, reducing the number of journeys. AMR utilisation is 32%, meaning the AMR spends approximately 5.5 hours idle. While this shows that a single AMR is not efficiently used for this operation, it highlights the opportunity for scalability to other processes. The total delay time observed is 192 seconds, which is expected. To mitigate this initial delay, a condition could be made that the processes must start with a small material buffer at the start of each day.

On the other hand, in practice, the AMR could be scheduled to deliver the material before the process starts, eliminating the initial delay time. In addition, the initial delay time could be reduced if the AMR velocity is increased. The following section will demonstrate the impact of varying AMR velocity.

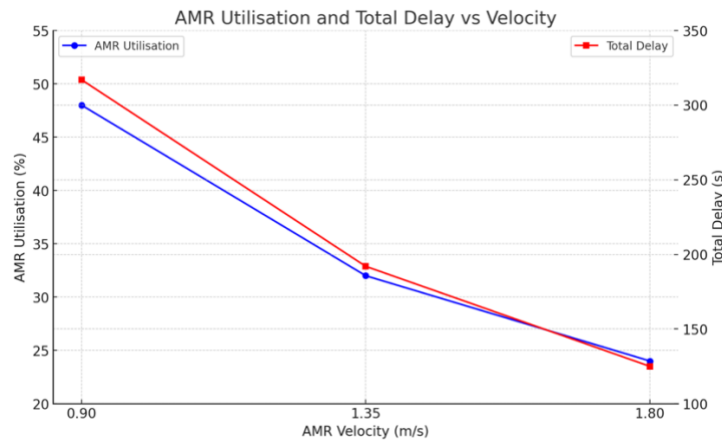
6.1.3. Impact of Varying AMR Velocity

Since delay occurs solely at the start of the simulation, the AMR's travel speed is the only parameter that influences total delay. Appendix 2 quotes speeds of 1.8 m/s for the LD60 model and 0.9 m/s for the larger LD90X. By updating the simulation with these velocity values, the effects on delay are presented in Table 19, and the full results are available in Appendix 4.

Table 19 - Simulation Varying AMR Velocity

AMR	AMR Velocity (m/s)	AMR Distance Travelled (m)	AMR Utilisation (%)	Total delay (s)
LD90X	0.9	6725	48	317
LD90	1.35	6725	32	192
LD60	1.8	6725	24	125

AMR distance remains constant as expected for all velocities. The relationship between AMR utilisation and total delay time is captured in Graph 2.



Graph 2 - Varying AMR velocity vs Utilisation vs Delay

Graph 2 demonstrates that increasing the AMR's travel speed reduces delay and the overall utilisation percentage. This highlights that choosing an AMR with a faster velocity will allow for better scalability and improved adherence to the production schedule. Therefore, although the LD90 was initially recommended, an AMR like the LD60 may be a better option.

Overall, this simulation has a series of assumptions to minimise the complexity of the model. The simulation provides valuable data regarding transportation, such as distance travelled, utilisation, and total delay time. In this instance, the simulation was used to give a basic understanding of how the assumed variables impact these parameters. The total distance the AMR covers per shift is relatively large compared to the current manual method. One reason is that the AMR routing is not optimised and returns to the warehouse after each delivery, when sometimes this may be a wasted movement. AMR utilisation indicates significant room for expansion, even with just one AMR. The delay time only accumulates as expected at the beginning of the process. Increasing the AMR velocity is one method of reducing the delay time, but it does not eliminate it. Two methods to eliminate this delay are to either have the AMR deliver material autonomously before the shift begins or have a small buffer of raw material left lineside.

7. Verify

This verification phase is a review of the work carried out, confirming whether the project has met the aims and objectives, addressed the CTQ requirements, and determined the feasibility and impact of an MR solution.

7.1. Verify Project Aims and Objectives

The project aimed to assess the feasibility of deploying MRs for material handling at Sony UKTec, using the RPi 500 and Pi Monitor production processes as case studies. By analysing performance data, CTQ metrics and supplier options, it laid the foundations, defining selection criteria, cost estimates and simulation models to support a future rollout.

A situation appraisal of the RPi processes was used to set the baseline measurements of the current material handling processes, understanding their implications and costs. Using KT, project objectives were set for both specific AMR type and the specific supplier and model. Five AMR types were evaluated, determining the platform AMR to be the most suitable against the objectives. Supplier and model requirements were analysed without vendor scoring, laying the groundwork for identifying suitable suppliers in a potential full-scale rollout. Reeco Automation was contacted to provide data and a budgetary quotation on one of their platform AMRs and add-ons to assess the technical, operational, safety, and economic feasibility. Although this may not be the exact AMR that will be used, this analysis provides a benchmark for assessing other AMRs in the future. The Arena simulation model quantified spatial requirements and evaluated the effects of parameters such as buffer thresholds, AMR speed, and load capacity. Analysis of the simulation outputs revealed utilisation patterns and demonstrated the solution's scalability to additional processes.

Overall, adherence to the DMADV methodology ensured that all aims and objectives were fulfilled, culminating in a comprehensive feasibility assessment and validated simulation for MR deployment at Sony UKTec. The following section will review the CTQs captured during the measure phase.

7.2. Verify Critical-to-Quality Requirements

The CTQs are pivotal to the project's success. By addressing them, stakeholder commitment to the project is gained, increasing the likelihood of a successful implementation. Table 20 lists the CTQs identified in the define section, highlighting if they have been addressed in the study, relevant section and reasoning.

Table 20 - Verifying VTQ requirements

Critical-to-Quality	Answered	Section	Details
Kit load and Unload times	No	-	Live measurements to be taken during pilot phase
On-time deliveries	Yes	6.1	Delays analysed during simulation
Space saved	Yes	5.4.4 & 6.1	Space saving estimated in 5.4.4 and confirmed with simulation results in section 6.1
Manual Labour reduction	Yes	5.4.4	Labour reduction summarised with cost benefits
CAPEX and OPEX	Yes	5.4.4	CAPEX estimated from supplier quotes, further details required to understand OPEX
Compliance with Standards	Yes	5.3.3	Relevant standards listed in Reeco Automation quote, involvement with compliance team to review in pilot phase is recommended
Travel distances	Yes	4.3	Baseline travel distances of both RPi process collected through physical measurements
Support Availability	No	-	Varies depending on supplier, will be analysed during supplier selection stage
Labour Cost Reduction	Yes	5.4.4	Labour cost savings estimated from baseline measurements vs CAPEX
Robot Utilisation	Yes	6.1	Robot utilisation was calculated using Arena simulation
RPDs	No	-	No training conducted during study phase
Energy Consumption	Yes	5.4.1 & App.2	Discussed in section 5.4.1 and further details available in appendix 2.
Inventory Visibility	Yes	5.4.2 & App.2	Inventory visibility available with an FMS as discussed i section 5.4.2 and highlighted in appendix 2
Queued Jobs Visibility	Yes	5.4.2 & App.2	Queued jobs visibility available with an FMS as discussed i section 5.4.2 and highlighted in appendix 2

Overall, Table 19 shows that eleven of the fourteen CTQs have been addressed in this study. Should the project proceed, the remaining three, load and unload times, support availability, and RPD submissions, are

planned for measurement during the next phase. Although the current CTQs have been addressed, a further review incorporating detailed data from the selected suppliers will be necessary.

7.3. Verify Feasibility of a mobile robot for Material Transport

In this section, the deployment of an MR for autonomous material transport will be verified, and previous sections within this DMADV study will be reviewed. For an MR solution to be considered feasible, the solution must have sufficient technical and safety features allowing for safe and efficient operation within Sony UKTec's dynamic environment.

Quotation data from Reeco Automation for the LD90 AMR demonstrates that its advanced technical capabilities, including LiDAR, sonar, and low-level sensors, allow for reliable and effective task completions. AMR technology enables the robot to navigate in dynamic environments, a critical requirement for the process. Operationally, a single LD90 can run with a minimum charging requirement. However, issues may arise during two- or three-shift operations, particularly where the AMR utilisation is high, minimising opportunity charging. Minor changes will be required regarding the production layout due to insufficient floor and walkways for AMR travel. Minor operations can be run without an FMS at the expense of efficiency. Without an FMS, process visibility is reduced, risking delays. In this case, for feasibility, an FMS is required to ensure optimal process efficiency.

From a safety perspective, the LD90 has sufficient safety features to operate effectively amongst employees, avoiding collisions with the suitable technical features. An FMS also allows for robot zoning, allowing engineers to create defined one-way zones and more, further strengthening the requirement of an FMS. Economic feasibility is where complications arise.

Based solely on the two RPi processes, the ROI is 16.3 years and does not include all associated costs, which will further increase the ROI. Projects typically require a two-year ROI for budget approval at Sony. Therefore, approval is extremely unlikely based on this study alone. The economic feasibility study could be further strengthened by performing a sensitivity analysis on factors affecting ROI, as shown in Table 21.

Table 21 - Sensitivity analysis on ROI

Scenario	Floor Space Saving (£)	Employee Saving (£)	Project CAPEX (£)	ROI (Years)
Baseline	2,017.20	2,938.54	80,544.41	16.3
A – Employer costs increase by 5%	2,017.20	3,085.47	80,544.41	15.8
B – Supplier Costs Increase by 5%	2,017.20	2,938.54	84,571.63	16.9
C – Project expanded to 4 lines total	8068.80	11,754.16	80,544.41	4.1
D – All Scenarios	8068.80	12,341.88	84,571.63	4.1

The most significant improvement to ROI is to expand the project to a total of 4 production lines. In this case, the costs associated with RPi 500 and the Monitor are doubled to give an approximation. This data further strengthens the case that expanding the project could provide a more realistic ROI.

Overall, using data supplied from Reeco Automation, an AMR will be feasible for operations at Sony UKTec. However, the high initial costs of introducing this solution pose challenges, necessitating the need to expand the study further to understand true economic feasibility.

8. Conclusion

The research section of this report aimed to provide the reader with a sufficient understanding of MR technology to study whether MR technology is a feasible material handling solution for Sony UKTec. The research first looked at the evolution of MR technology and presented its origin and key technological advancements to the reader. The technical aspects of MR technology were shown, highlighting the key features that make MRs suitable for safe and efficient operation in various industries.

It is highlighted that the two types of MRs are AGVs and AMRs. With advancements, AMRs are typically the choice due to their ability to navigate freely when obstructed. Amazon, Ocado, and BMW are three companies that have utilised MRs for material transport. These companies have improved process efficiency, reduced manual labour, and optimised floor space. The benefits of MRs in manufacturing are specifically highlighted, highlighting the benefits of reducing waste and building lean processes. The limitations are also presented and mainly concern the initial and ongoing costs associated with MRs. This section is critical to the report, highlighting some benefits and limitations Sony UKtec may encounter if MRs are introduced.

Environmental performance is an increasingly essential criterion. MRs can reduce a company's carbon footprint by minimising workforce size and allowing HVAC and lighting loads to be reduced. However, the long-term sustainability of onboard batteries, electronics, and sensors must also be considered. Compliance with standards, UKCA marking, and Health and Safety Executive guidance is essential to safeguard personnel. Sociological factors, such as workforce acceptance, skills development, and ergonomic impact, must be addressed alongside the technical and regulatory requirements. Lewin's model highlights key driving and restraining forces for implementing changes. Conducting a basic study on the application of introducing MRs in organisations shows that the driving factors outweigh the restraining factors, showing that the project should go ahead, but should consider how to reinforce the strengths further while minimising the impact of the restraining factors.

The DMADV structure was applied to map the existing system, quantify its limitations, compare alternative MR options against clearly defined CTQs, build a simulation to predict performance, and verify that the recommended solution satisfies Sony UKTec's technical, operational, safety and economic requirements, laying the groundwork for a future site-wide rollout.

The measure phase addressed the CTQs, a critical step in ensuring the remainder of the project aligns with the requirements and concerns raised by the stakeholders. RPi 500 and Monitor were chosen due to the relatively high-quality material storage and manual transport required. The data collected allowed for the analysis of the processes in the analysis phase, emphasising the costs of the current manual labour and floor space allocation methods, amounting to £5201.74 per year. On top of this, the current process also lacks control, with minimal performance visibility, making process optimisation difficult.

Using the KT DA structure, a selection criterion was created for the specific AMR type, followed by a further detailed criterion for the supplier and model. Five variations of AMR were assessed against the requirements, showing that the platform AMR is the most suitable against the set objectives by scoring the highest. For this study, the supplier and model KT were not conducted to maintain focus on the key objectives. Instead, this section was analysed to indicate the type of suppliers and models that will be suitable if the project moves ahead.

The information provided by Reeco Automation on their LD90 model provided relevant data to assess feasibility. Technical, operational, safety, and economic feasibility are analysed using the LD90 as an example of a typical AMR. Economic feasibility remains the primary challenge, whereas technical, operational, and safety evaluations all indicate favourable viability. Based on the quote supplied by Reeco Automation, the ROI is significant, at 16.3 years before breaking even. While this is a challenge, extending the study to encompass other processes may provide the scale required for a suitable ROI. A multi-process approach could offer more savings. However, increasing project size can result in further CAPEX and OPEX. While economic feasibility uses actual quote data to provide an overview of costs, additional considerations such as the increasing labour costs, energy costs, and supplier costs impact the ROI.

Through the input process and AMR data captured in the previous sections, a DES is created using Arena Simulation. To minimise the complexity of the model, several assumptions were applied that reduce real-world fidelity but still offer a valid approximation of expected performance. The simulation revealed that the AMR distance travelled per shift is relatively high compared to the current daily travel distances. While it is scheduled for increased travel distance due to the lower kit sizes, the condition that the AMR returns to the warehouse after each delivery adds to this. In practice, an FMS would optimise travel, reducing the distance travelled by predicting upcoming tasks. The results revealed that the total delay time is relative to the time the AMR takes to deliver material to both processes at the start of the shift. By increasing the AMR speed, this delay and utilisation are reduced. Ensuring the AMR starts material delivery before the shift begins is essential to mitigate the delay completely. An alternative method is to provide the process finishes with a daily buffer. The Verify phase confirms that the project met its aims, addressed the CTQs, and validated the feasibility findings, demonstrating how the work aligns with the original objectives. During the verification of the economic feasibility, a sensitivity analysis further highlighted the purpose of increasing the project to include more processes, significantly reducing the ROI.

Overall, the study has provided a suitable understanding of MR and its surrounding technology and evaluated the feasibility of its application at Sony UKTec. The following section discusses recommendations for further work to enhance the project in preparation for wider rollout.

9. Recommendations for Further work

Further expanding the simulation to understand the impact on some variables, such as buffer threshold and load capacity, will help better understand how processes can be optimised. Following this, a physical pilot using an AMR with an FMS on both RPi processes will provide a more accurate representation of its use. A physical trial will introduce challenges such as obstructions and variations in process cycle times. The impact on other processes should also be validated here, for example, understanding the impact on the warehouse operators, what materials are involved in unloading and loading, and how finished goods will be sorted. It is recommended to understand what other technologies could enhance this process, such as a sorting robot located within the warehouse, as shown in Figure 24.



Figure 23 - Automated Sorting Robot (Loudin, 2022)

Expanding the project to encompass the material handling process may further strengthen the feasibility and economic benefit. Incorporating AI vision systems should also be explored to monitor material levels, serving as an indicator for material deliveries and collections. It is highly recommended that these additional improvement scenarios are captured within a sensitivity analysis, highlighting how they impact the ROI. Contacting a large variety of suppliers that align with the selection criteria will be beneficial in providing a thorough understanding of capabilities and costings. This should be done to maintain competitive tension between suppliers, which will help Sony secure the most favourable terms.

It is highly recommended that key members from different departments be involved as the project advances. For example, involving the production engineering team will allow them to understand the project further, raise important questions, and secure buy-in for their involvement, improving the likelihood of success. Further participation of other departments will also allow for more rigorous use of tools such as value-stream-mapping or LFFA, specifically analysing the project at Sony UKTec with the known figures.

Overall, this study establishes a foundational framework for deploying MRs at Sony UKTec's material-handling processes. The recommendations outlined will reinforce this framework, providing a broader perspective across additional material-handling processes.

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Appendix 1– AMR Type Selection Scoring (KT Analysis)

Insert New Objective		Sort Objectives		importance of each WANT? (most important WANT = 10; Others = 1-10, relative to the 10th)		= Indicate final choice		Total = 655		= Indicate final choice		Total = 309	
				Alternative 1				Alternative 2					
Objectives				Platform AMR		Score		Pallet Jack AMR		Score		score	
Operates safely around people				M		GO				GO			
Can move materials between locations				M		GO				GO			
Operate within factory environment				M		GO				GO			
Can follow pre-defined paths				M		GO				GO			
Adaptable in dynamic environments, autonomously navigate				M		GO				GO			
Can navigate in walkways 1.2m Width				M		GO				GO			
Reduces kitting and finished goods floor space by 65%				10	Possible to remove pallets from shop floor	10	100	Constrained to pallet sizes		6	60		
Scalable to variety of models at Sony UKTec				9	Can be applied to a variety of processes	10	90	Only operations with pallets		3	27		
Adaptable with other accessories, e.g different mounts etc				8	Able to autonomously change top mount	10	80	Only operations with pallets		1	8		
Can navigate in walkways minimum 0.8m Width				8	Typically compact	10	80	Typically large, may be an issue		4	32		
Capable of transporting a variety of equipment (Totes, stations, single boxes etc)				7	Can be applied to a variety of processes	10	70	Only operations with pallets		4	28		
Minimal disruption to current operations, does not cause congestion				7	Change required but flexible	8	56	Typically large, must move slower, pallets only		7	49		
Minimal disruption to current layouts				6	Compact, will have minimal impact on layout	9	54	Typically large, will require large docking area		7	42		
Can carry multiple kits if required (2 or more)				5	Possible towing carts / racking	7	35	Constrained to pallet		4	20		
Simple load and unload				5	No major change	10	50	Pallets low, may cause RSI		7	35		
Energy efficient transport method				4	Can use trolleys where weight is distributed	10	40	Takes full weight of load		2	8		

= Indicate final choice		286		= Indicate final choice		Total = 415		= Indicate final choice		Total = 486	
Alternative 3				Alternative 4				Alternative 5			
Pallet Platform AMR				Cobot AMR				Cart Pull AMR			
Score		score		Score		score		Score		score	
GO				GO				GO			
GO				GO				GO			
GO				GO				GO			
GO				GO				GO			
GO				GO				GO			
GO				GO				GO			
GO				GO				GO			
6		60		10		100		10		100	
3		27		7		63		7		63	
1		8		7		56		1		8	
4		32		8		64		10		80	
4		28		1		7		1		7	
7		49		3		21		7		49	
4		24		6		36		9		54	
4		20		2		10		7		35	
6		30		10		50		10		50	
2		8		2		8		10		40	

Appendix 2– Reeco Automation Supplier Data

Section 1: Equipment

1.1: Omron LD90 ESD - Autonomous Mobile Robot

Our Autonomous mobile robots (AMRs) are designed to dramatically increase productivity in manufacturing and logistics operations. Allowing employees to focus on tasks that require complex human skills, whilst increasing throughput, eliminating errors and improving material traceability.

Unlike Autonomous Guided Vehicles (AGV) navigation is performed by the natural features of the facility with no expensive facility modification, allowing for rapid deployment, easy modification, flexibility and system expansion. With intelligent obstacle avoidance they can select to use alternate routing where available and are completely safe to operate alongside humans

The LD Series Autonomous Mobile Robots (AMR) have a payload capacity of 60-250Kg which can be increased to 500Kg when deploying a cart system, they can work independently or as a fully integrated fleet, co-ordinating material movements between the manufacturing lines and the warehouse.

Omron LD90 Features:

- 90 Kg payload capacity.
- LIDAR Navigation and Safety with 240° coverage
- Low level laser, Rear Sonar & Front Bumper
- Natural Navigation
- Up to 13-hour runtime
- Top speed 1.35 m/s.
- ESD



CAPS – Cell Alignment Positioning System:

CAPS is a positioning system that uses real world features of the environment, to effectively create a final position reference (target). This allows for highly accurate and repeatable alignment of the AMR's at pick up and drop off locations

Reeco Automation Supplier Data Continued

1.2: Fleet Management & Control Station

The Fleet Management & Control Station incorporates an Industrial PC hosting the Virtual Fleet Management system.

This is licensed for fleet operations, in this scenario for a maximum fleet size of 5 x AMR's (3 Year updates*). A 19" touchscreen monitor is incorporated, providing fleet operation information and used interface, and the means to provide full data integration

*Licenses provide free system updates for the period and can be renewed at 3 years, alternatively the system can continue operation on the current operating system, additionally they can be expanded to allow bigger fleet sizes to operate.



1.2.1: Fleet Management – Key Features

Intelligent Job Assignment:

Enterprise manager continually looks ahead to anticipate which robots are the best positioned for upcoming tasks. The system will also delegate jobs based on the most efficient option.



Managed Motion:

Ensures smooth operations in a busy environment by coordinating traffic flows and efficiently sequencing pick up and drop offs.

Traffic Control:

Notifies converging robots of their predicted paths, allowing them to recalculate and avoid collisions in the most efficient way.



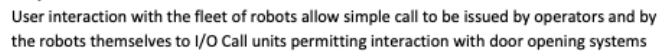
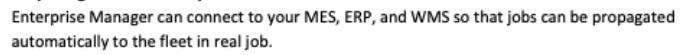
Automatic Updates:

Performs automatic updates such as changes to goals or floor plan.

Charge Management:

Tracks battery power of the entire fleet, directing robots to their nearest available or preferred docking station on a schedule that ensures continuous fleet operation.





Reeco Automation Supplier Data Continued

Section 4: Equipment Specifications

4.1: Omron LD Series Autonomous Mobile Robot

Specifications

LD-60, LD-90, LD-90x, LD-60 ESD, LD-90 ESD, and LD-90x ESD				
Item		LD-60	LD-90	LD-90x
Weight (with Battery)		62 kg		
Environment	Ambient temperature	5 to 40°C		
	Ambient humidity	5 to 95% (non-condensing)		
	Operating Environment	Indoor usage only, no excessive dust, no corrosive gas or liquid. Floor must be free of water, oil, dirt, and debris. Direct sunlight may cause safety laser false positives.		
	Dust / Smoke	Airborne particle size: > 37 µm Floor accumulation: < 10 mg / m ² Avoid smoky areas		
	Ingress Protection Class	IP20		
Altitude		1000 m above mean sea level maximum		
Floor Conditions	Minimum floor flatness	Fr25 (ACI 117 standard)		
	Traversable step	15 mm max. ¹⁾	10 mm max. ¹⁾	
	Traversable gap	15 mm max. ²⁾		
	Maximum Slope	Up to 60 kg: 4.8° / 8.3% incline Over 60 kg: Level floor only		
Minimum floor compressive strength		2.6 Mpa	3.27 Mpa	
Navigation	Routing	Autonomous routing by localizing with safety scanning laser based on environment mapping		
	Environmental map making method	Scan by walking the AMR through the environment, and upload the scan data to the MobilePlanner software		
	Low Front Laser	One Class 1 laser at front of AMR with a 126° field of view		
	Side Laser (optional)	Two Class 1 lasers with a 270° field of view on the sides of payload structure, user-mounted		
Visual Indicators		Light discs are located on the sides of the AMR. Additional indicators can be added.		
Payload		Maximum Weight	60 kg	90 kg
Mobility	Run Time (no payload)	15 h approx.		20 h approx.
	Run Time (full payload)	12 h approx.		15 h approx.
	Maximum Speed	1800 mm/s	1350 mm/s	900 mm/s
	Maximum Rotation Speed	180 °/s		
	Stop Position Repeatability (single AMR) ³⁾	- To a position: ±65 mm - To standard target: ±25 mm, ±2° - With CAPS: ±8 mm, ±0.5° - With HAPS: ±8 mm, ±0.4°		
	Stop Position Repeatability (Fleet) ³⁾	- To a position: ±85 mm - To standard target: ±35 mm, ±2° - With CAPS: ±12 mm, ±0.5° - With HAPS: ±10 mm, ±0.5°		
Drive wheels	Materials	Solid aluminum with non-marking, non-conductive, foam-filled rubber tread		
Passive casters	Materials	Conductive thermoplastic rubber on polyolefin		
Auxiliary Power		5 VDC±5%, 1 A switched Aux power 12 VDC±5%, 1 A switched Aux power 20 VDC±5%, 1 A switched Aux power 22 to 30 VDC (25.6 VDC nominal), 4 A switched 22 to 30 VDC (25.6 VDC nominal), 10 A switched 22 to 30 VDC (25.6 VDC nominal), 10 A safe, switched 10 A switched and 10 A safe switched are from the same source and pass through the same 10 A fuse, so the sum of their current must be less than 10 A.		
Standards	AMR	EN ISO 12100, EN ISO 13849-1, EN 60204-1, EN 1525, ANSI B56.5, EN 61000-6-2, EN 61000-6-4		
	Battery	UN 38.3, UL 2271		
	Docking Station	UL1012/CISA C22.2.107.2		
	Wireless	IEEE 802.11 a/b/g		
	Cleanroom Rating	ISO 5 / Class 100 (AMR, Battery and Docking Station)		

Reeco Automation Supplier Data Continued

4.1: Omron LD Series Autonomous Mobile Robot (Continued)

	Item	LD-60	LD-90	LD-90x
Safety Features	Safety Scanning Laser	One at front of AMR Class 1 PLd safety per ISO13849-1 240° field of view		
	E-STOP Buttons	One on Operator Panel, additional E-STOP buttons can be added to the payload structure		
	Rear Sonar	Two at rear of AMR, 2 m range. Each pair includes one emitter and one receiver working together.		
	Front Bumper	Two pairs of sensors at the front of the AMR		
	Audible Indicators	Two speakers are included. Additional buzzers can be added.		
Operator Interface	Display	8.89 cm diagonal TFT, 320 x 240 pixels, color screen		
	Button	ON button, OFF button, Brake-release button, and keyed mode selection		
User Interface	Wireless	802.11 a/b/g		
	Ethernet	One general purpose, shielded, Auto-MDIX Ethernet port.		
	Serial	Two serial communication interfaces		
	Digital I/O	16 inputs, 16 outputs		
	Audio	Digital audio in / out		

*1 A speed of 250 mm/s is recommended for traversing steps, and routine driving over steps should be avoided. Lower speeds may not traverse the step. Faster or frequent driving over steps will shorten the lifespan of the drivetrain components. All steps should have smooth, rounded profiles.

*2 AMR maximum speed is recommended for traversing gaps, and routine driving over gaps should be avoided. Lower speeds may not traverse the gap. Faster or frequent driving over gaps will shorten the lifespan of the drivetrain components.

*3 Stop position repeatability values were obtained using default AMR parameters and a map created by the LD-series AMR.

Reeco Automation Supplier Data Continued

4.1: Omron LD Series Autonomous Mobile Robot (Continued)

Virtual Fleet Manager Software Minimum Hardware Requirements

Fleet Size / AMR Count	Small ≤ 5	Medium ≤ 15	Large ≤ 30	X-Large ≤ 100
Virtual CPU	2 cores			
Clockspeed	4GHz	8 GHz	12 GHz	16 GHz
Virtual RAM	8 GB	16 GB	24 GB	32 GB
Virtual Disk	512 GB			1 TB
FLOW software version	Minimum FLOW Core 4.0			

Note: The PC/IPC/Server is supplied by the user.

High Accuracy Positioning System (HAPS)

Sensor	Depth	30 mm
	Width	160 mm
	Ingress Protection Class	IP64
	Environment	-40 to 85°C
	LEDs	Power, tape present, left marker, right marker
Magnetic Tape	Width	25 mm
	Orientation	South up
Markers (Magnetic Tape)	Width	25 mm
	Length	300 mm min. for 500 mm/s drive speed
	Orientation	North up
	Separation From Tape	15 to 30 mm
Connections	Front Sensor	RS232-1 (/dev/ttyUSB9) on the core
	Rear Sensor	RS232-2 (/dev/ttyUSB10) on the core
	Power, Both Sensors	Aux power using the included splitter cable
Stop Position Repeatability, LD-60, LD-90*	Single AMR	±8 mm position, 0.4° rotation
	Fleet	±10 mm position, 0.5° rotation
Stop Position Repeatability, LD-250*	Single AMR	±8 mm position, 0.4° rotation
	Fleet	±10 mm position, 0.6° rotation

* Stop position repeatability values were obtained using default AMR parameters and a map created by the LD-series AMR.

Cell Alignment Positioning System (CAPS)

Stop Position Repeatability, LD-60, LD-90, LD-90x*	Single AMR	±8 mm position, 0.5° rotation
	Fleet	±12 mm position, 0.5° rotation
Stop Position Repeatability, LD-250*	Single AMR	±8 mm position, 0.5° rotation
	Fleet	±14 mm position, 0.6° rotation
Type	Software license	

*3 Stop position repeatability values were obtained using default AMR parameters and a map created by the LD-series AMR.

Battery

Type	Lithium-Ion (LiFePO4)
Weight	19 kg
Voltage	22 to 30 VDC (25.6 VDC nominal)
Capacity	72 Ah (battery cell nominal)
Recharge Time	2 hrs. 10 min. for 20% to 80% charge
Ingress Protection Class	IP20
Recharge Cycles	Approximately 2000 cycles*
Charging Method	Automatic or manual

* Approximately 80% of nominal battery capacity will be available after using the battery at 100% depth of discharge at temperatures between 15°C to 35°C.

Docking Station

Current	8 A*
Power	100 to 240 VAC, 50 to 60 Hz
Power Consumption	800 W
Humidity	5 to 95%, non-condensing
Temperature	5 to 40° C
Dimensions (W * D * H)	349 * 369 * 315 mm 495 * 495.5 * 317 mm (with floor plate)
Weight	8.2 kg
Mounting	Wall bracket, directly to floor, or on floor with floor plate
Indicators	Power on: blue Charging: yellow
Connector	For out-of-AMR battery charging

* Circuit breaker built into AC power switch

Joystick (Pendant)

Weight	0.55 kg
IP Rating	IP56

Acuity Camera Specifications

Field of View	140°
Power Input	12 VDC (±10%) supplied from AMR through power connector
Power Consumption	3.3 W maximum

MobilePlanner Software

CPU	1.5 GHz dual-core CPU recommended
Main Memory	1.5 GB min. (4 GB min. recommended)
Hard Disk	At least 200 MB of available space
Video Memory	256 MB min.
Display	XGA 1024 * 768, 16 million colors
Supported Languages	English, Japanese, German, French, Italian, Korean, Spanish, Polish, Simplified Chinese, Traditional Chinese

4.1: Omron LD Series Autonomous Mobile Robot (Continued)

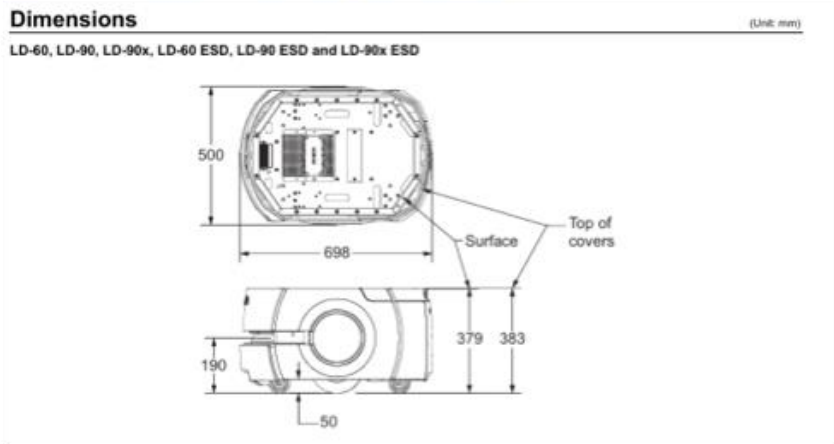
Features and Components

LD-60, LD-90, LD-90x, LD-60 ESD, LD-90 ESD, and LD-90x ESD

The diagram shows an exploded view of the Omron LD Series Autonomous Mobile Robot. The main components are labeled with letters in parentheses: (A) Upper Front Skin, (B) Bumper Skin, (C) Side Skin, (D) Access Panel, (E) Rear Skin, (F) Battery Door Skin, (G) E-STOP button, (H) Operator Panel, (I) Safety Laser Scanner, (J) Low Laser, (K) Charging Contacts, (L) Wireless Antennas, (M) Payload Mounting Surface (Top Plate shown), (N) Speed Control, (O) Directional Control Stick, (P) Goof Button, (Q) Trigger, (R) Indicator Light, and (S) Light Disk. A detailed view of the control stick assembly is shown at the bottom left, with labels (O), (P), (Q), (R), and (S).

Item	Description	Item	Description
A	Safety Laser Scanner	K	Light Disk
B	Low Laser	L	Charging Contacts
C	Upper Front Skin	M	Wireless Antennas
D	Bumper Skin	N	Payload Mounting Surface (Top Plate shown)
E	Side Skin	O	Speed Control
F	Access Panel	P	Directional Control Stick
G	Rear Skin	Q	Goof Button
H	Battery Door Skin	R	Trigger
I	E-STOP button	S	Indicator Light
J	Operator Panel		

4.1: Omron LD Series Autonomous Mobile Robot (Continued)



Appendix 3 – Arena Simulation Process Results

TALLY VARIABLES					
Identifier	Average	Half Width	Minimum	Maximum	Observations
Pi Monitor Process.TotalTimePerEntity	40.046	6.4237	.57600	78.438	831
Pi500 Process.WaitTimePerEntity	42.848	8.5342	.00000	83.533	963
Pi Monitor Process.VATimePerEntity	.57600	(Conn)	.57600	.57600	831
Pi500 Process.VATimePerEntity	.49500	(Conn)	.49500	.49500	963
Pi500 Process.TotalTimePerEntity	43.343	8.5342	.49500	84.028	963
Pi Monitor Process.WaitTimePerEntity	39.470	6.4237	.00000	77.862	831
Widgets.VATime	14.904	(Insuf)	13.860	16.128	63
Widgets.WAITime	.00000	(Insuf)	.00000	.00000	63
Widgets.WaitTime	1394.1	(Insuf)	375.26	2391.6	63
Widgets.TransTime	2.3868	(Insuf)	1.0493	4.2592	63
Widgets.OtherTime	.00000	(Insuf)	.00000	.00000	63
Widgets.TotalTime	85.871	(Insuf)	18.188	438.60	63
Batch 2.Queue.WaitingTime	7.7760	.23847	.00000	15.552	812
Request an AGV to Finished Pi Monitor.Queue	.07958	(Insuf)	.00000	1.0036	29
Request an AGV to Pi500.Queue.WaitingTime	.00000	(Insuf)	.00000	.00000	7
Batch 1.Queue.WaitingTime	6.6825	.19542	.00000	13.365	952
Hold 2.Queue.WaitingTime	235.76	(Insuf)	1.0493	472.46	7
Hold 1.Queue.WaitingTime	210.93	(Insuf)	.00000	425.56	7
Pi Monitor Process.Queue.WaitingTime	39.486	6.1717	.00000	77.862	832
Request an AGV to Finished Pi500.Queue.Wai	.18725	(Insuf)	.00000	2.3093	34
Request an AGV.Queue.WaitingTime	.00000	(Insuf)	.00000	.00000	7
Pi500 Process.Queue.WaitingTime	42.810	8.5342	.00000	83.533	964
DISCRETE-CHANGE VARIABLES					
Identifier	Average	Half Width	Minimum	Maximum	Final Value
Widgets.MIP	211.21	(Insuf)	.00000	335.00	237.00
Pi500 Resource.NumberBusy	.99331	(Insuf)	.00000	1.0000	1.0000
Pi500 Resource.NumberScheduled	1.0000	(Insuf)	1.0000	1.0000	1.0000
Pi500 Resource.Utilization	.99331	(Insuf)	.00000	1.0000	1.0000
Machine.NumberBusy	.00000	(Insuf)	.00000	.00000	.00000
Machine.NumberScheduled	1.0000	(Insuf)	1.0000	1.0000	1.0000
Machine.Utilization	.00000	(Insuf)	.00000	.00000	.00000
Pi Monitor Resource.NumberBusy	.99781	(Insuf)	.00000	1.0000	1.0000
Pi Monitor Resource.NumberScheduled	1.0000	(Insuf)	1.0000	1.0000	1.0000
Pi Monitor Resource.Utilization	.99781	(Insuf)	.00000	1.0000	1.0000
Batch 2.Queue.NumberInQueue	13.371	(Conn)	.00000	28.000	19.000
Request an AGV to Finished Pi Monitor.Queue	.00481	(Insuf)	.00000	1.0000	.00000
Request an AGV to Pi500.Queue.NumberInQueue	.00000	(Insuf)	.00000	.00000	.00000
Batch 1.Queue.NumberInQueue	13.312	(Conn)	.00000	28.000	11.000
Hold 2.Queue.NumberInQueue	6.4381	(Insuf)	.00000	10.000	3.0000
Hold 1.Queue.NumberInQueue	6.0761	(Insuf)	.00000	9.0000	3.0000
Pi Monitor Process.Queue.NumberInQueue	73.226	10.092	.00000	136.00	43.000
Request an AGV to Finished Pi500.Queue.Num	.01326	(Insuf)	.00000	1.0000	.00000
Request an AGV.Queue.NumberInQueue	.00000	(Insuf)	.00000	.00000	.00000
Pi500 Process.Queue.NumberInQueue	88.064	13.523	.00000	169.00	156.00
AGV.NumberBusy	.31559	(Insuf)	.00000	1.0000	.00000
AGV.NumberScheduled	1.0000	(Insuf)	1.0000	1.0000	1.0000
AGV.Utilization	.31559	(Insuf)	.00000	1.0000	.00000
Finished Goods.NumEntTrans	.14210	(Insuf)	.00000	1.0000	.00000
To Pi 500.NumEntTrans	.00000	(Insuf)	.00000	.00000	.00000
Pi500.NumEntTrans	.01620	(Insuf)	.00000	1.0000	.00000
Pi Monitor.NumEntTrans	.01530	(Insuf)	.00000	1.0000	.00000
Pallet Station.NumEntTrans	.00000	(Insuf)	.00000	.00000	.00000
To Pi Monitor.NumEntTrans	.00000	(Insuf)	.00000	.00000	.00000
COUNTERS					
Identifier	Count	Limit			
Num Journeys	77	Infinite			
AGV Distance	6725	Infinite			
OUTPUTS					
Identifier	Value				
Pi Monitor Process Accum VA Time	478.65				
Pi500 Process Accum Wait Time	41263.				
Pi Monitor Process Number In	875.00				
Pi Monitor Process Accum Wait Time	32799.				
Pi Monitor Process Number Out	831.00				
Pi500 Process Number Out	963.00				
Pi500 Process Number In	1120.0				
Pi500 Process Accum VA Time	476.68				
Widgets.NumberIn	2064.0				
Widgets.NumberOut	1827.0				
Pi500 Resource.NumberSeized	964.00				
Pi500 Resource.ScheduledUtilization	.99331				
Machine.NumberSeized	.00000				
Machine.ScheduledUtilization	.00000				
Pi Monitor Resource.NumberSeized	832.00				
Pi Monitor Resource.ScheduledUtilization	.99781				
System.NumberOut	63.000				

Appendix 4 – Arena Simulation Varying AMR Speeds

LD90X 0.9m/s Results

Replication ended at time : 480.0 Minutes					
Base Time Units: Minutes					
TALLY VARIABLES					
Identifier	Average	Half Width	Minimum	Maximum	Observations
Pi Monitor Process.TotalTimePerEntity	38.914	6.4160	.57600	77.913	830
Pi500 Process.WaitTimePerEntity	41.933	8.5266	.00000	82.978	959
Pi Monitor Process.VATimePerEntity	.57600	(Conn)	.57600	.57600	830
Pi500 Process.VATimePerEntity	.48500	(Conn)	.48500	.48500	959
Pi500 Process.TotalTimePerEntity	42.428	8.5266	.48500	83.473	959
Pi Monitor Process.WaitTimePerEntity	38.338	6.4160	.00000	77.337	830
Widgets.VATime	14.904	(Insuf)	13.860	16.128	63
Widgets.WAITime	.00000	(Insuf)	.00000	.00000	63
Widgets.WaitTime	1365.6	(Insuf)	379.63	2377.7	63
Widgets.TranTime	3.6331	(Insuf)	1.5740	6.5740	63
Widgets.OtherTime	.00000	(Insuf)	.00000	.00000	63
Widgets.TotalTime	86.622	(Insuf)	22.516	442.53	63
Batch 2.Queue.WaitingTime	7.7760	.23847	.00000	15.552	812
Request an AGV to Finished Pi Monitor.Queue	.54866	(Insuf)	.00000	3.0460	29
Request an AGV to Pi500.Queue.WaitingTime	.00000	(Insuf)	.00000	.00000	7
Batch 1.Queue.WaitingTime	6.6825	.19542	.00000	13.365	952
Hold 2.Queue.WaitingTime	237.66	(Insuf)	1.5740	474.07	7
Hold 1.Queue.WaitingTime	212.07	(Insuf)	.00000	427.09	7
Pi Monitor Process.Queue.WaitingTime	38.353	6.4160	.00000	77.337	831
Request an AGV to Finished Pi500.Queue.Wai	.30995	(Insuf)	.00000	3.8420	34
Request an AGV.Queue.WaitingTime	.00000	(Insuf)	.00000	.00000	7
Pi500 Process.Queue.WaitingTime	41.974	8.5289	.00000	82.978	960
DISCRETE-CHANGE VARIABLES					
Identifier	Average	Half Width	Minimum	Maximum	Final Value
Widgets.WIP	211.76	(Insuf)	.00000	335.00	237.00
Pi500 Resource.NumberBusy	.98997	(Insuf)	.00000	1.0000	1.0000
Pi500 Resource.NumberScheduled	1.0000	(Insuf)	1.0000	1.0000	1.0000
Pi500 Resource.Utilization	.98997	(Insuf)	.00000	1.0000	1.0000
Machine.NumberBusy	.00000	(Insuf)	.00000	.00000	.00000
Machine.NumberScheduled	1.0000	(Insuf)	1.0000	1.0000	1.0000
Machine.Utilization	.00000	(Insuf)	.00000	.00000	.00000
Pi Monitor Resource.NumberBusy	.99672	(Insuf)	.00000	1.0000	1.0000
Pi Monitor Resource.NumberScheduled	1.0000	(Insuf)	1.0000	1.0000	1.0000
Pi Monitor Resource.Utilization	.99672	(Insuf)	.00000	1.0000	1.0000
Batch 2.Queue.NumberInQueue	19.350	(Conn)	.00000	28.000	18.000
Request an AGV to Finished Pi Monitor.Queue	.03321	(Insuf)	.00000	1.0000	.00000
Request an AGV to Pi500.Queue.NumberInQue	.00000	(Insuf)	.00000	.00000	.00000
Batch 1.Queue.NumberInQueue	19.282	.59328	.00000	28.000	7.0000
Hold 2.Queue.NumberInQueue	6.4659	(Insuf)	.00000	10.000	3.0000
Hold 1.Queue.NumberInQueue	6.0927	(Insuf)	.00000	9.0000	3.0000
Pi Monitor Process.Queue.NumberInQueue	71.105	10.340	.00000	135.00	44.000
Request an AGV to Finished Pi500.Queue.Num	.02135	(Insuf)	.00000	1.0000	.00000
Request an AGV.Queue.NumberInQueue	.00000	(Insuf)	.00000	.00000	.00000
Pi500 Process.Queue.NumberInQueue	85.368	14.540	.00000	168.00	168.00
AGV.NumberBusy	.48932	(Insuf)	.00000	1.0000	.00000
AGV.NumberScheduled	1.0000	(Insuf)	1.0000	1.0000	1.0000
AGV.Utilization	.48932	(Insuf)	.00000	1.0000	.00000
Finished Goods.NumEntTrans	.21316	(Insuf)	.00000	1.0000	.00000
To Pi 500.NumEntTrans	.00000	(Insuf)	.00000	.00000	.00000
Pi500.NumEntTrans	.02431	(Insuf)	.00000	1.0000	.00000
Pi Monitor.NumEntTrans	.02296	(Insuf)	.00000	1.0000	.00000
Pallet Station.NumEntTrans	.00000	(Insuf)	.00000	.00000	.00000
To Pi Monitor.NumEntTrans	.00000	(Insuf)	.00000	.00000	.00000
COUNTERS					
Identifier	Count	Limit			
Num Journeys	77	Infinite			
AGV Distance	6725	Infinite			
OUTPUTS					
Identifier	Value				
Pi Monitor Process Accum VA Time	478.08				
Pi500 Process Accum Wait Time	40213.				
Pi Monitor Process Number In	875.00				
Pi Monitor Process Accum Wait Time	31821.				
Pi Monitor Process Number Out	830.00				
Pi500 Process Number Out	959.00				
Pi500 Process Number In	1120.0				
Pi500 Process Accum VA Time	474.70				
Widgets.NumberIn	2064.0				
Widgets.NumberOut	1827.0				
Pi500 Resource.NumberSeized	960.00				
Pi500 Resource.ScheduledUtilization	.98997				
Machine.NumberSeized	.00000				
Machine.ScheduledUtilization	.00000				
Pi Monitor Resource.NumberSeized	831.00				
Pi Monitor Resource.ScheduledUtilization	.99672				
System.NumberOut	63.000				

LD60 1.8m/s Results

Replication ended at time : 488.0 Minutes					
Base Time Units: Minutes					
TALLY VARIABLES					
Identifier	Average	Half Width	Minimum	Maximum	Observations
Pi Monitor Process.TotalTimePerEntity	40.509	6.4384	.57600	78.700	831
P1500 Process.WaitTimePerEntity	43.174	8.5366	.00000	83.811	964
Pi Monitor Process.VATimePerEntity	.57600	(Corr)	.57600	.57600	831
P1500 Process.VATimePerEntity	.48500	(Corr)	.48500	.48500	964
P1500 Process.TotalTimePerEntity	43.669	8.5366	.48500	84.306	964
Pi Monitor Process.WaitTimePerEntity	39.933	6.4384	.00000	78.124	831
Widgets.VATime	14.904	(Insuf)	13.860	16.128	63
Widgets.WATime	.00000	(Insuf)	.00000	.00000	63
Widgets.WaitTime	1405.5	(Insuf)	375.00	2398.6	63
Widgets.TranTime	1.8151	(Insuf)	.78704	3.1844	63
Widgets.OtherTime	.00000	(Insuf)	.00000	.00000	63
Widgets.TotalTime	85.572	(Insuf)	17.100	437.81	63
Batch 2.Queue.WaitingTime	7.7760	.23847	.00000	15.552	812
Request an AGV to Finished Pi Monitor.Queue	.12989	(Insuf)	.00000	2.3100	29
Request an AGV to P1500.Queue.WaitingTime	.00000	(Insuf)	.00000	.00000	7
Batch 1.Queue.WaitingTime	6.6825	.19542	.00000	13.365	952
Hold 2.Queue.WaitingTime	234.92	(Insuf)	.78704	471.66	7
Hold 1.Queue.WaitingTime	210.48	(Insuf)	.00000	425.29	7
Pi Monitor Process.Queue.WaitingTime	39.948	6.1848	.00000	78.124	832
Request an AGV to Finished P1500.Queue.Wait	.10332	(Insuf)	.00000	2.0470	34
Request an AGV.Queue.WaitingTime	.00000	(Insuf)	.00000	.00000	7
P1500 Process.Queue.WaitingTime	43.137	8.5366	.00000	83.811	965
DISCRETE-CHANGE VARIABLES					
Identifier	Average	Half Width	Minimum	Maximum	Final Value
Widgets.WIP	211.11	(Insuf)	.00000	335.00	237.00
P1500 Resource.NumberBusy	.99489	(Insuf)	.00000	1.0000	1.0000
P1500 Resource.NumberScheduled	1.0000	(Insuf)	1.0000	1.0000	1.0000
P1500 Resource.Utilization	.99489	(Insuf)	.00000	1.0000	1.0000
Machine.NumberBusy	.00000	(Insuf)	.00000	.00000	.00000
Machine.NumberScheduled	1.0000	(Insuf)	1.0000	1.0000	1.0000
Machine.Utilization	.00000	(Insuf)	.00000	.00000	.00000
Pi Monitor Resource.NumberBusy	.99836	(Insuf)	.00000	1.0000	1.0000
Pi Monitor Resource.NumberScheduled	1.0000	(Insuf)	1.0000	1.0000	1.0000
Pi Monitor Resource.Utilization	.99836	(Insuf)	.00000	1.0000	1.0000
Batch 2.Queue.NumberInQueue	13.381	(Corr)	.00000	28.000	19.000
Request an AGV to Finished Pi Monitor.Queue	.00785	(Insuf)	.00000	1.0000	.00000
Request an AGV to P1500.Queue.NumberInQueue	.00000	(Insuf)	.00000	.00000	.00000
Batch 1.Queue.NumberInQueue	13.332	(Corr)	.00000	28.000	12.000
Hold 2.Queue.NumberInQueue	6.4259	(Insuf)	.00000	10.000	3.0000
Hold 1.Queue.NumberInQueue	6.0695	(Insuf)	.00000	9.0000	3.0000
Pi Monitor Process.Queue.NumberInQueue	74.075	10.165	.00000	136.00	43.000
Request an AGV to Finished P1500.Queue.Num	.00732	(Insuf)	.00000	1.0000	.00000
Request an AGV.Queue.NumberInQueue	.00000	(Insuf)	.00000	.00000	.00000
P1500 Process.Queue.NumberInQueue	89.145	12.868	.00000	170.00	155.00
AGV.NumberBusy	.23997	(Insuf)	.00000	1.0000	.00000
AGV.NumberScheduled	1.0000	(Insuf)	1.0000	1.0000	1.0000
AGV.Utilization	.23997	(Insuf)	.00000	1.0000	.00000
Finished Goods.NumEntTrans	.10658	(Insuf)	.00000	1.0000	.00000
To Pi 500.NumEntTrans	.00000	(Insuf)	.00000	.00000	.00000
P1500.NumEntTrans	.01215	(Insuf)	.00000	1.0000	.00000
Pi Monitor.NumEntTrans	.01148	(Insuf)	.00000	1.0000	.00000
Pallet Station.NumEntTrans	.00000	(Insuf)	.00000	.00000	.00000
To Pi Monitor.NumEntTrans	.00000	(Insuf)	.00000	.00000	.00000
COUNTERS					
Identifier	Count	Limit			
Num Journeys	77	Infinite			
AGV Distance	6725	Infinite			
OUTPUTS					
Identifier	Value				
Pi Monitor Process Accum VA Time	478.65				
P1500 Process Accum Wait Time	41620.				
Pi Monitor Process Number In	875.00				
Pi Monitor Process Accum Wait Time	33184.				
Pi Monitor Process Number Out	831.00				
P1500 Process Number Out	964.00				
P1500 Process Number In	1120.0				
P1500 Process Accum VA Time	477.18				
Widgets.NumberIn	2064.0				
Widgets.NumberOut	1827.0				
P1500 Resource.NumberSeized	965.00				
P1500 Resource.ScheduledUtilization	.99489				
Machine.NumberSeized	.00000				
Machine.ScheduledUtilization	.00000				
Pi Monitor Resource.NumberSeized	832.00				
Pi Monitor Resource.ScheduledUtilization	.99836				
System.NumberOut	63.000				

Appendix 5 – Definitions

Artificial Intelligence (AI): The simulation of human intelligence processes by machines, particularly computer systems, including learning, reasoning, and self-correction (Russell & Norvig, 2021).

Industry 4.0: A modern industrial transformation characterised by cyber-physical systems, IoT, and data-driven manufacturing, enabling smart factories (Lasi et al., 2014).

Internet of Things (IoT): A system of interconnected devices that collect and exchange data via the internet using embedded sensors and software (Ashton, 2009).

Lean Manufacturing - A systematic approach aimed at enhancing productivity, quality, and customer satisfaction by minimizing waste and maximising value (Singh, et.al.,2018)