Durham University
Department of Engineering

Feasibility Report for Group 19-AIBM4 Autonomous Material Mover



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July 7, 2026

Executive Summary

This feasibility report looks into the development of an Automated Material Mover (AIBM4), which aims to transport materials autonomously within a factory environment. This would eliminate the need for manual handling of goods, improve productivity and ensure a safer and more sustainable working environment.

Through an iterative design process, we chose a three-wheeled automated forklift design that integrates differential steering around a central axle for maximum manoeuvrability and tape sensing technology for precise movement within a factory environment. To make this design contemporary and sustainable, the body and forks will be made out of steel due to its high reconcilability and we will use airless tyres to improve durability and reduce waste.

Engineering calculations validate the design's structural integrity and feasibility as well as ensuring compliance with ISO 3691-4 standards. An in-depth cost analysis demonstrates that automated guided vehicles (AGVs) are financially viable over conventional manual forklifts, due to significant savings in labour and operating costs over time.

An adaptable factory layout design has been included which has been optimised for AGV operation, however the material mover has been designed to fit into the majority of modern-day factories. We have also conducted a risk assessment to mitigate any risks as well as created a Gantt chart which determines that the design process will be finished by the end of March 2025. This report demonstrates the technical, economic and environmental upper hand that an automated material mover can provide in a modern factory setting.

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1. Introduction

1.1 What is the problem that we are attempting to solve?

Efficient material handling is essential in modern manufacturing, but conventional forklifts still require manual operation. This project seeks to eliminate manual dependency by designing an autonomous material mover.

1.2 Issues with Conventional Manual Material Handling

Manual labour and forklifts have several key issues within factory environments:

- **Inefficiency:** Human workers require regular breaks, reducing productivity.
- **Safety concerns:** Human error can lead to an increased likelihood of an accident as well as a higher chance of injuries.
- **Cost:** Cost of labour is very large, and multiple shifts necessitates additional hiring costs.
- **Reliability:** Human error can lead to materials being moved to the wrong locations.

Overall, these issues reduce productivity and compromise workplace safety.

2. Project Scope

Scope Canvas for Project: AIBM4

Cost Magnitude	Staff Magnitude	Duration Magnitude	Start Date: 29/10/24
£50,000	6 staff members	142 days	**End Date: 20/03/25**

Goal

To develop an automated material mover that can reduce the requirement for personnel within manufacturing and supply facilities. Hence it must have a better cost-benefit analysis, have less down time and be more efficient than its nonautomated counterparts. The material mover will be able to carry pallets of goods up to 2 tonnes and will not need any human involvement when running its day-to-day tasks.

Objectives

Design a mapping/navigation system for the automated mover to follow a path around the warehouse.
Design a drive system and wheels/tracks.
Choose appropriate communication technology/signals.
Design a factory/warehouse layout.
Design collision avoidance and emergency protocols – adhering to relevant safety standards and regulations.
Create simulations of the design using appropriate software.
Design a robust solution that complies with industry standards and is capable of future updates to keep it contemporary.

Risks

There may be scope creep due to continuous changes being made because of the ambiguity of the project. Other risks include communication breakdowns within the group and technical issues.
Mitigations include regular group meetings to monitor performance and progress, clear planning and calculations to ensure the mover is reliable. In the Gantt Chart scope creep is mitigated by giving ample time to complete major tasks with firm deadlines.

Quality

Feasibility report, presentation and final report must both be delivered on time, whereas sub-tasks have some flexibility.
Must be compliant with ISO 10218-1, ISO 1028-2 and BS EN ISO 13849-1.
Quality control checks include constant simulation using relevant software e.g. LTSpice, SolidWorks etc.
Must be able to lift and unload pallets (weighing up to 2 tonnes) and move them around an indoor warehouse environment safely, in order to maintain the production line. This must be done efficiently and without human interaction.

Stakeholders & Communication

- Dr Aissa Ikhlef and Mr Bill Maxwell – stakeholders: Regular communication through weekly seminars, shared Microsoft Teams and email.
- Suppliers: Indirect contact by monitoring prices and stock. May have to contact via email for quotes for some industrial parts.

Project Trade-offs

	Fixed	Adjust	Accept
Scope		X	
Schedule	X		
Cost			X

Sponsors - Names

Dr Aissa Ikhlef and Bill Maxwell

Cost / Budget

Labour cost (£15 per hour) ~ £18,000.
Sensor £672.01 for shock resistant model [1].
Magnetic Tape - ($217 per 45 metres) ~ £651 [2].
Motor and controller - £3,495.60 [3].
Steel forks ~ £236 [4].
Battery ~ £6,300 [5].
1 Tonne of Steel per Frame ~ £700.
Charger Per Unit ~ £1,000 (based off home car EV chargers) [6].
Control System Server ~ £2,000 – Powerful GPU, RAM + CPU
Hydraulic system ~ £1,500 [7] [8] [9] [10].
Total costs for material mover parts ~ £16,554.61.
This does not include costs for wiring, wheels and programming.
SolidWorks license - £2,544 a year [11]
MATLAB and Simulink license - £3,250 a year [12].
workers to manufacture) [13].
Contingency funds ~ £5,000.

Not in Scope:

Developing the magnetic tape technology.
Developing other autonomous machines that work in the warehouse environment.

Parking Lot:

Assumptions made:
Smooth warehouse flooring, the material mover does not have to go outside, it will not be working in an environment with humans, and the material mover travels along a fixed U-shaped path (goods in at one end and goods out the other) with machines on each side.
A factory/warehouse design, charging mechanisms, and communications signals need to be considered to complete this project.

Gain / Revenue
Toyota quotes return on investment ~ 2 years (we will aim for similar).
Save in labour costs for customer of £64,648.80 per annum (based on driver pay of £11.07 per hour)
Roughly £1.25/hour in electricity costs for the customer – based on £0.25/kWh and a power consumption of roughly 5kW [15].
Also reduced downtime, a person can drive a forklift for a maximum of 8 hours per day.
Shifts human labour into more high-value jobs e.g. technicians, equipment operators.
No need for the customer to pay for operator training as it is automated.
Less chance of injury due to no human interaction, creating a safer working environment.
Cash flow in:
Market size is expected to reach USD 126.20 billion by 2029. CAGR ~ 12.4%.[16]
Automated forklifts ~ 20-30% of the market [17].
2025 AGV market size ~ £62,341,468,560.00
2025 Automated forklift market size ~ £12.47 billion (assuming 20% of market)

Figure 1: Scope Canvas

3. User-Requirement-Specification

Core requirements	General Requirements	Future Enhancements
• Operate completely autonomously in predefined zones, performing tasks of moving materials • Be able to adapt to and cope with various payloads and operational environments • Include certain safety mechanisms to act safely within its environment • Have an emergency stop function which can be operated at any time • Be more efficient than a manual worker and a conventional forklift, i.e. must have a higher uptime	• Autonomous operation – Capable of navigating, loading and unloading without any manual intervention • Load Capacity – Will transport palleted goods of up to 2 tonnes in weight • Environment – Able to operate in a warehouse setting with smooth and even flooring • Power supply – Will operate on rechargeable batteries • Functional requirements; Navigation and obstacle detection, material handling and speed control • Safety requirements: Emergency stop, collision avoidance and alarm/error detection system • Usability requirements: User interface, diagnostics and maintenance • Environmental requirements: Temperature and humidity, and durability • Compliance Requirements: Safety standards (e.g. ISO 3691-4 on Driverless Industrial Trucks • Reliability – 99% uptime over a 1-year period • Error Tolerance – less than 1% failure rate for loading/unloading of goods • Navigation accuracy – Reaches the location within 50mm	• An advanced obstacle detection and avoidance system • Remote Monitoring and Control – Potentially over the internet • Dynamic speed – dependent on load and surrounding conditions • Data logging – Used to improve performance analysis • Intelligent task scheduling - Algorithm to sort tasks, i.e. machine does tasks near each other in one go • Energy efficient mode – For example when dealing with light loads • 3D Mapping – Using LiDAR to produce a visualisation of the material mover's currently location and route which can be viewed remotely.

Figure 2: URS – Automated Material Mover Project

4. Concepts

4.1 Initial Concepts

1. A three-wheeled mover with magnetic tape sensors. This design utilises a compact three wheeled configuration to allow for maximum manoeuvrability in tight spaces. Due to its magnetic tape sensing technology it can accurately navigate predefined paths within a factory setting and be easily integrated and changed within factories.

2. A four-wheeled mover on a monorail. This design uses a monorail to ensure extremely precise movement as well as a four wheel base which makes it very sturdy for lifting goods and transporting them quickly and efficiently. An advantage of the design was that there was no down-time due to the material mover being constantly connected to a power source.

3. A six-wheeled mover with line-following sensors. Six wheels allows for superior stability and load-bearing capabilities as well as maximum manoeuvrability. It would use differential steering for its central axis, with the other four wheels being caster wheels, to allow it to spin on the spot making it highly manoeuvrable and versatile.

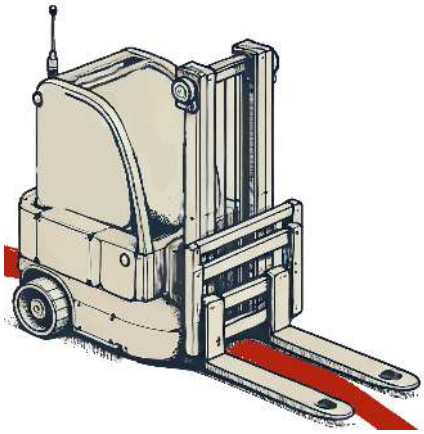

Figure 3: Concept 1: Three-wheel magnetic tape following design

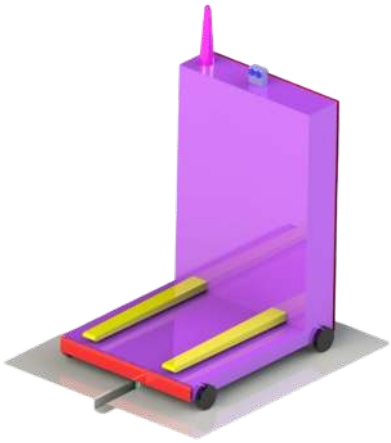

Figure 4: Concept 2: Four-wheel monorail design

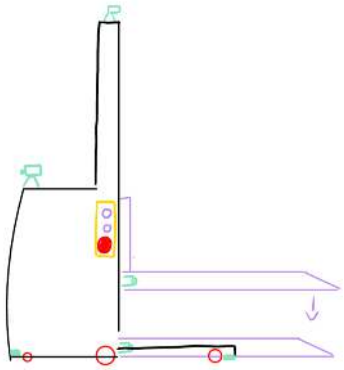

Figure 5: Concept 3: Six-wheel line following design

4.2 Strengths and Weaknesses

Each concept was evaluated against the URS using a design decision matrix. A summary of this is provided in Table 1 below.

Table 1: Concept Evaluation Matrix

Criteria	Concept 1	Concept 2	Concept 3
Load Capacity	High	Medium	Medium
Navigation Efficiency	Medium	High	High
Cost	Low	Medium	Medium
Ease of Maintenance	High	Low	Low

5. Chosen Solution

Initially, the pooling of design ideas resulted in Figure 6. However, it was then decided that the lifter ought to pick items off the floor, leading to a redesign resulting in the counterbalance forklift in figure 7. The wheels were placed in a tadpole configuration to give better manoeuvrability and dynamic stability. The vehicle will be guided by magnetic tape on the factory floor detected by sensors on the undercarriage. The forks make use of a hydraulic lifting system, and will be charged using a wireless charging system which is adjacent to the main path.



Figure 6: Initial Pooled Design



Figure 7: Final Design

5.1 Sustainability

In order to make the design sustainable, the body and forks are likely to be made from steel because it has the highest recycling rate among all materials used in construction and engineering [17]. The castor wheels can be made of high-quality pre-consumer nylon (from the waste of polyester production) [18] and the drive wheels can be airless tires, as this would reduce the amount of rubber that goes into landfill and improve fuel efficiency [19]. For lithium-ion batteries, a hydrometallurgical process can be used, where 80% of the battery can be recycled and 95% of the valuable materials can be recovered and used for new batteries [20].

5.2 Engineering Calculations

Assuming the fork is a beam of uniform cross section fixed at the left end to the forklift, it can be modelled as shown in Figure 14. This calculation uses a factor of safety of three for the maximum load, as specified by ISO 2330 for the prototyping of forklift forks [21].

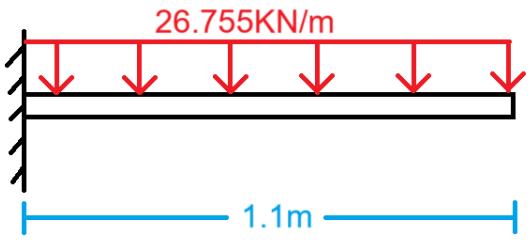

Figure 8: Diagram showing the force diagram of a singular fork.

Using Macaulay's method, the equation for the deflection of an EN19 steel fork with $E = 200\,\text{GPa}$, height $h = 40\,\text{mm}$, and width $b = 100\text{mm}$ [22] is given by:

$$\nu = \frac{3}{320000}\left(\frac{-16186.5}{2}x^2 + \frac{29430}{6}x^3 - \frac{26755}{24}x^4\right) \tag{1}$$

Therefore the maximum deflection, at the furthest point from the fork's support, $x = 1.1\,\text{m}$, is $\nu = -45.9mm\,\text{mm}$. For fatigue, following ISO-2330 standards a cyclic stress amplitude of 1.655MPa was obtained using equation (2).

$$\text{Cyclic Stress Amplitude} = \left(\frac{Force}{Area}\right) \tag{2}$$

The obtained value is smaller than the minimum fatigue limit of 175MPa so no cracking due to fatigue will occur.

In a counterbalance forklift design, tipping is avoided by using a counterbalance to shift the centre of mass behind the drive wheels. The mover will tip about the drive wheel when the force through the the load moment is greater than the counterbalance moment. The wheelbase is the distance between the drive and rear wheel, and Y shows the distance from the drive wheel to the centre of mass of the forklift.

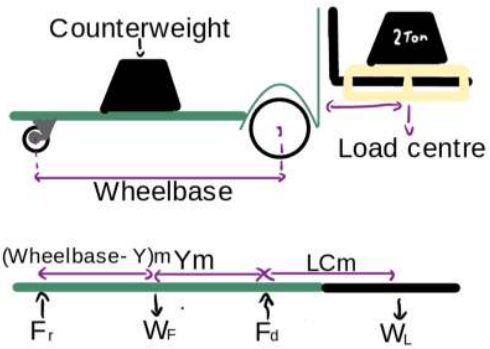

Figure 9: Diagram of forklift mass distribution, and free body diagram

The weight of the whole forklift is shown as W_F and the weight of the load is W_L acting at a distance equal to the load centre LC from the drive wheel. Knowing that at the point of tipping, $F_r = 0N$ and taking the moments about the drive wheel:

$$W_{\mathrm{F}} Y = W_{\mathrm{L(tip)}} LC \tag{3}$$

The Toyota 06-8FG20F [23] offers an example of a similar manual forklift with the same load ratings as our design. In this model, the counterweight has a mass of 4318kg, which gives a load tipping weight of 3750 kg, and a factor of safety against tipping of 1.875. Our design takes LC as $0.967m$, Y as $1m$, W_L as $3750gN$ (a 2 tonne load multiplied by the 1.875 factor of safety), and so determines that:

$$W_{\mathrm{F}} = \frac{W_{\mathrm{L(tip)}} LC}{Y} = \frac{3750g \times 0.967}{1} = 3626.25gN \tag{4}$$

This means a counterweight of 3626kg - similar to the value Toyota use. For the sake of saftey and simplicity in further calculations, this value will be rounded up to 4000kg. This gives us an aim for a value that ensures our forklift is safe, but does not compromise efficiency through unnecessary added weight. Shifting the counterweight further back would be a good way of reducing the necessary counterweight mass. Integrating load sensors would ensure that the 2 tonne limit is not exceeded, preventing damage to the forklift.

The weight of the forklift is an important factor in the driving force that it requires. The total drive force the vehicle needs is the sum of rolling resistance, air resistance, other smaller resistive forces such as resistance in the bearings and motor, and accelerating force. For the purposes of these calculations, the vehicle is assumed to need to reach a top speed of $10mph$ ($4.47ms^{-1}$), in a time of up to $4s$, similar other forklifts [24], and since the speed is relativity low, air resistance is assumed to be negligible. Rolling resistance, F_{rr}, is given by [25]:

$$F_{rr} = C_{rr} mg = 0.015 \times 6000 \times 9.81 = 882.9\,\mathrm{N} \tag{5}$$

accWhere C_{rr} = Coefficient of Rolling Resistance, taken for tyres on concrete of average condition to be 0.015 [26], m = Mass of the vehicle, taken to be 6000 kg as previously calculated plus the load weight, and g = Acceleration due to gravity, taken to be $9.81\,\mathrm{ms}^{-2}$. The accelerating force, F_a, is given by:

$$F_a = m\frac{\Delta v}{\Delta t} = 6000 \times \frac{4.47}{4} = 6705\,\mathrm{N} \tag{6}$$

Where Δv = Required change in speed, taken as the top speed of $3.58ms^{-1}$, and Δt = Time to execute required speed change, taken as $5s$. And so the total drive force required is the sum of these forces,

$$F_d = F_{rr} + F_a = 882.9 + 6705 = 7587.9\,\mathrm{N} \tag{7}$$

The motor torque required to produce this force, T_m, is given by:

$$T_m = F_d \times R_w \times RF = 7587.9 \times 0.289 \times 1.15 = 2.521\,\mathrm{kNm} \tag{8}$$

Where R_w = Wheel radius, valued at $0.289m$, and RF = Resistance Factor, which accounts for

smaller resistances such as those in the bearing and the motor, and is taken as 1.15 [27]. Therefore, if each motor is picked to have 2.5kNm of torque, the total drive torque will be 5kNm - roughly twice what is required, ensuring that the vehicle has sufficient torque.

5.3 Expected Cost

The estimated cost of the product is £50,000, and this covers:

- All the hardware for the autonomous material mover
- All of the software acquisition and development for navigation, and task automation.
- The implementation of the system into a conventional factory; however, this will likely differ on a site-to-site basis.

Cost Item	**Amount (£)**
Labour Costs	18,000
Material Costs	25,617
Manufacturing Costs	2,500
Software and Simulation	2,544
Contingency	1,339
Total Estimated Cost	**50,000.00**

Table 2: Breakdown of Expected Costs for the Autonomous Material Mover

5.4 Cost Comparison for a Customer

Whilst this product may seem expensive at first to potential customers, it has distinct financial and logistical advantages over manual forklifts. It should be considered that automated forklifts do, on average, move slower than regular manually driven forklifts.

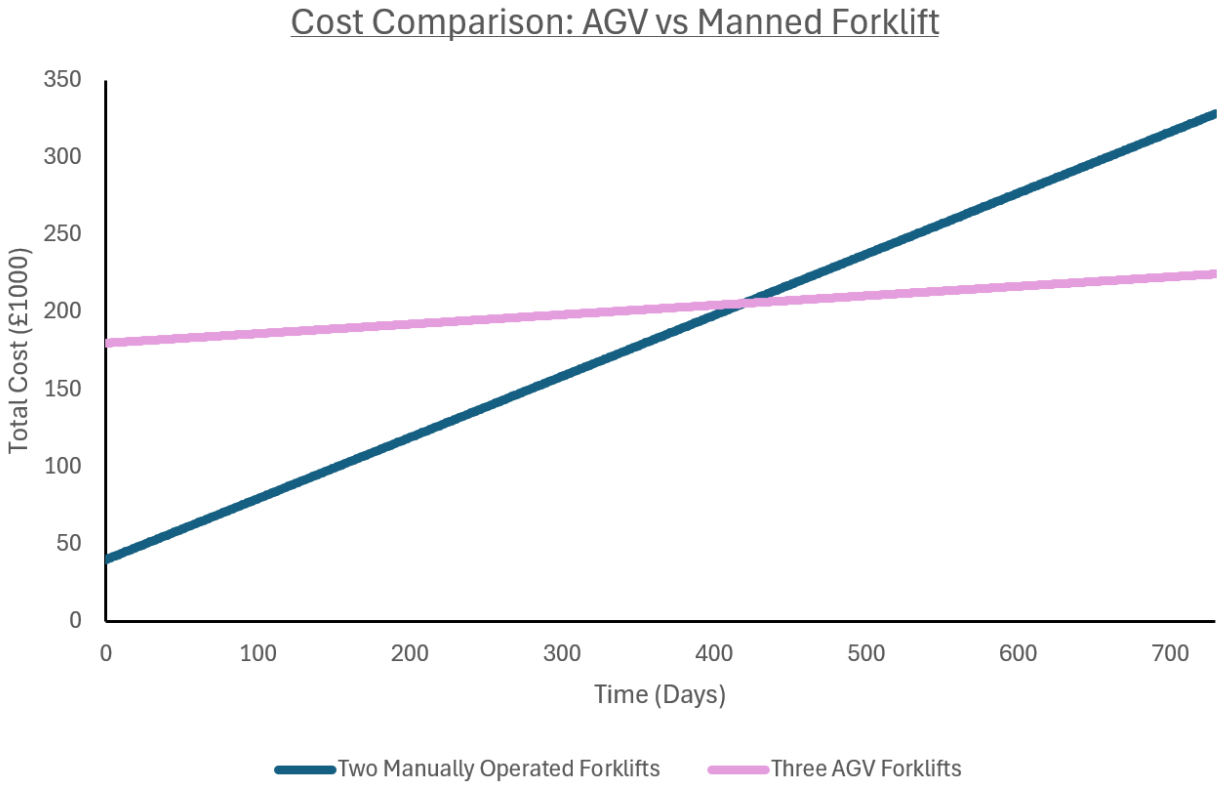

Figure 10: Cost Comparison: AGVs vs Manned Forklift

This means that it takes around 1.3-1.5 automated forklifts to do the same work as a single manned truck [28]. Taking these things into consideration, the following table assumes a factory using two manned forklifts, and how these costs would compare to three AGVs.

Cost per unit taken as £60,000 for an AGV, compared with £20,000 for a manual forklift. From the graph in Figure 8 we can see that after 420 days of operation the three AGV forklifts become more economical in comparison to the two manually operated forklifts.

Cost Factor	**Manual Forklifts**	**AGVs**
Initial Cost per Unit	£20,000	£60,000
Number of Units	2	3
Total Initial Cost	2 × £20,000 = £40,000	£180,000
Annual Labour Cost per Forklift	£11.44 × 16 × 365 = £66,810	£0
Total Annual Labour Cost (16 hours a day)	2 × £66,810 = £129,297.6	£0
Electricity Cost per Year (25.46p per kWh)	£14,868	£22,302
Total Annual Operating Cost	£148,487	£22,302

Figure 11: Cost Breakdown for Manual and Automated Forklifts [14]

5.5 Factory Layout

A CAD factory layout has been produced using information from EG Propertylink listing for Unit 5, Hurworth Road, Aycliffe Business Park [29] as an example. This layout makes use of a U-shaped path for the movers, with machines along either side of the path. The path is marked with magnetic tape which the movers can detect and follow using sensors. At each end of the path will be the goods-in and goods-out areas, where the movers will collect supplies for the machines and deposit finished products respectively. In these areas, there will also be charging stations, positioned out of the way to prevent disruption.

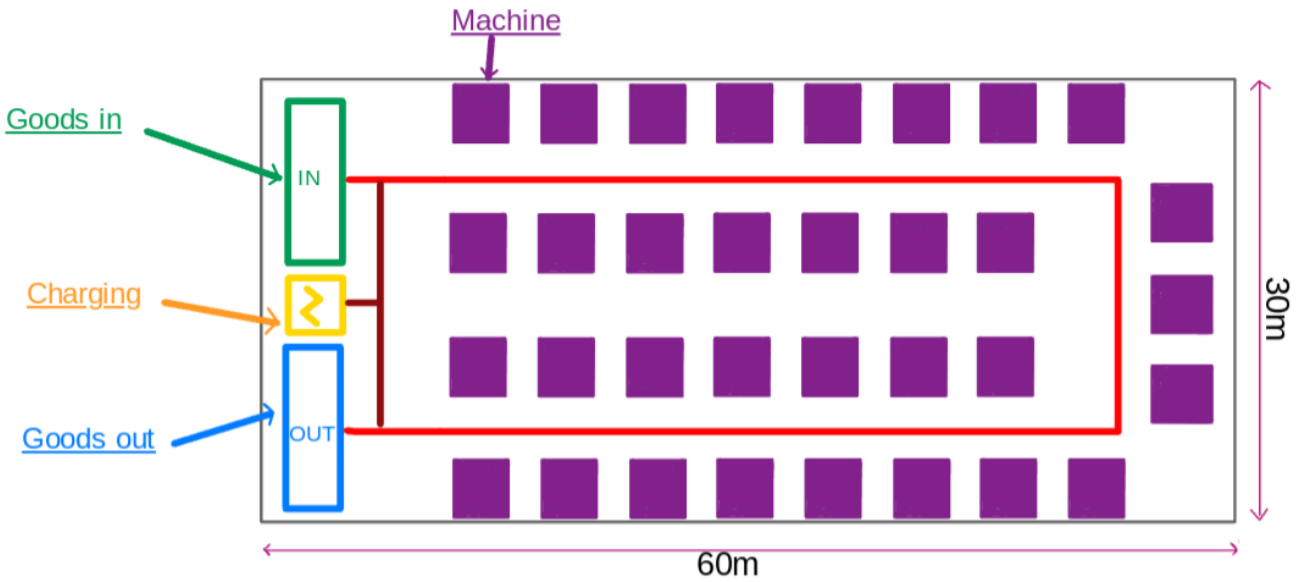

Figure 12: Factory design layout

6. Risk assessment

AIBM4Risk Assessment – Automated Material Mover Project

Location: Where will the activity take place?	Description of Activity: To include enough information to establish the foreseeable hazards
Factory and warehouse environments where the automated material mover will operate.	This risk assessment addresses the design, operation, and maintenance of an automated material mover. The mover is designed to transport up to two tons of load within a controlled factory environment. The scope includes integration with the factory layout, compliance with safety standards, and coordination with existing automated systems and personnel to minimise risks.

Hazards (Things with the potential to cause harm)	Those at risk	What is the nature of the risk? (injuries, damage that could result)	Uncontrolled risk level	Required controls (how the risk can be removed or reduced by engineered methods, safe systems, etc.)	Controlled risk level
Collision with Obstacles/Personnel	Factory staff, material mover	Injury to staff, damage to equipment or mover	Severity = 5 Likelihood = 4	Implement collision avoidance sensors (LiDAR); clearly mark mover paths and emergency stop systems	Severity = 2 Likelihood = 2
System Malfunction or Navigation Failure	Material mover, operations	Delays, incorrect routing, potential collisions	Severity = 4 Likelihood = 4	Redundant navigation systems, continuous monitoring, and automatic rerouting	Severity = 2 Likelihood = 2
Power Failure	Material mover, factory operations	Disruption in operations, risk of incomplete tasks	Severity = 3 Likelihood = 3	Smart charging stations and power monitoring for minimal downtime	Severity = 2 Likelihood = 2
Component Overheating	Mover equipment, factory	Risk of fire, damage to mover, potential for injury	Severity = 4 Likelihood = 3	Install temperature sensors on motors/battery with automatic shutdown if overheated	Severity = 2 Likelihood = 2
Handling Fragile/Hazardous Materials	Factory staff, mover	Potential for spills, contamination, or damage	Severity = 5 Likelihood = 3	Adapt navigation and handling protocols for fragile/hazardous loads; emergency containment	Severity = 2 Likelihood = 2
Communication Failure	Factory network, mover operation	Loss of control, miscommunication leading to incorrect navigation	Severity = 4 Likelihood = 3	Reliable communication protocols (5G/Wi-Fi), with fallback options and monitoring	Severity = 2 Likelihood = 1
Obstacle and Traffic Congestion	Material mover, other systems	Delays, collision risk, navigation inefficiency	Severity = 4 Likelihood = 4	Predictive traffic management, real-time coordination with automated systems	Severity = 2 Likelihood = 2
Environmental Conditions	Material mover, equipment	Damage from humidity, dust, temperature fluctuations	Severity = 4 Likelihood = 3	Insulation, protective casings, and monitoring for specific environmental limits	Severity = 2 Likelihood = 2
Load Stability	Mover, nearby equipment, goods	Potential for load tipping or imbalance	Severity = 5 Likelihood = 3	Real-time load monitoring, dynamic suspension for uneven loads	Severity = 2 Likelihood = 2

Health and Safety Risk Matrix

This matrix shows the probability and severity levels to help assess risks. For detailed guidance, please refer to the university's health and safety documentation.

Assessment Prepared by	Supervisor/Manager acceptance	Signature	Date
Name: Jiaxi Wang Signature: Jiaxi Wang Date: 10 Nov 2024	Name: Aissa Ikhleff, Bill Maxwell	Jiaxi Wang	Nov 14 2024

Figure 13: Automated Material Mover Project Risk Assessment

7. Project Schedule

In order to plan out the schedule throughout the project Gantt Charts were created, this ensures no tasks are ignored and gives ample time for them to be completed. The excerpt of the Dynamic Gantt Chart in figure 14, made using Microsoft Excel, shows the major tasks to be completed in order to succeed with the remainder of the project.

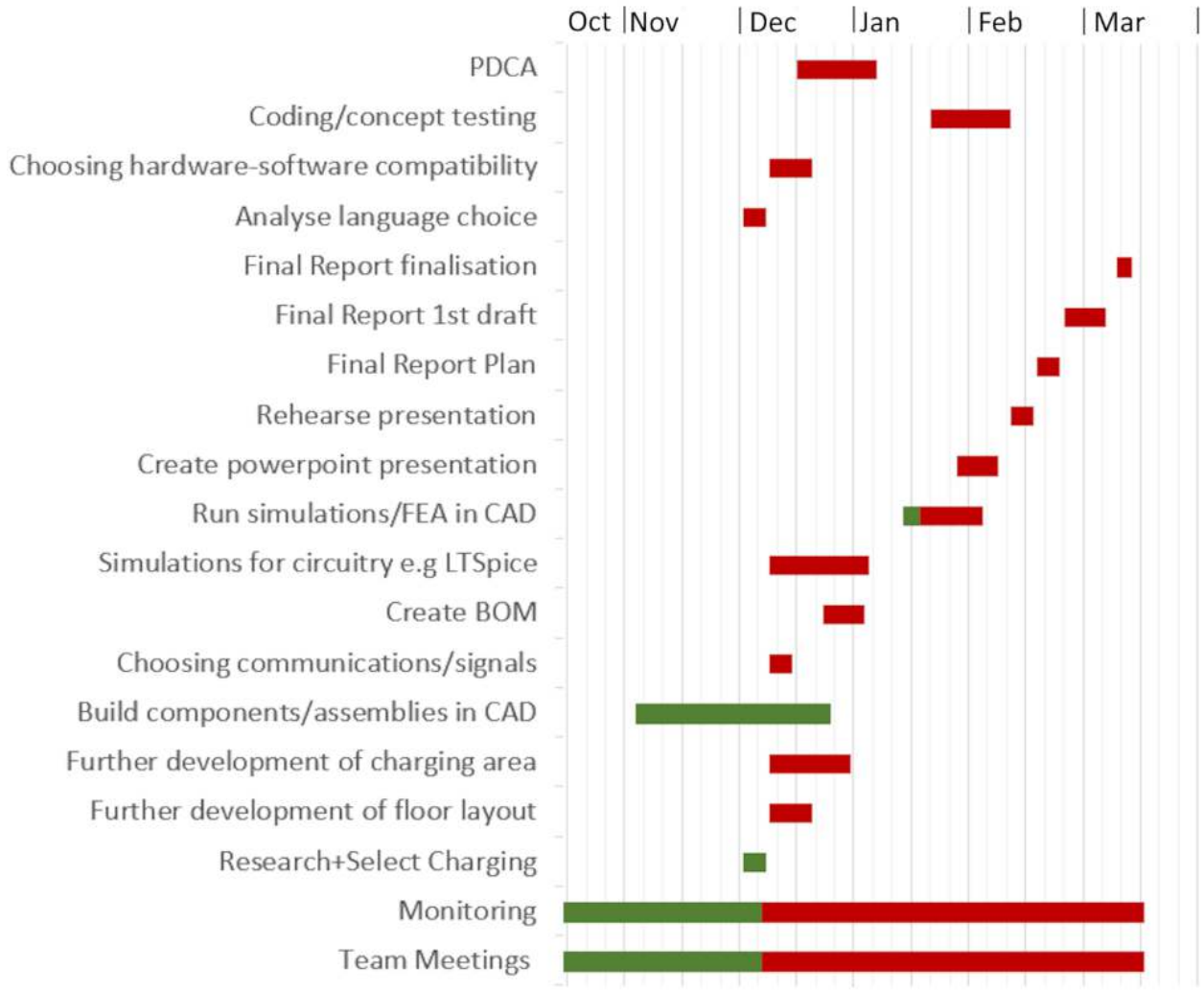

Figure 14: Dynamic Gantt Chart for the remainder of the project

To support the Dynamic Gantt Chart, a Planning Gantt chart was also created. It gives foresight for deadlines and other departmental commitments so that the workload can be planned around these accordingly. The work completed so far provides a strong basis for the remainder of the project which focuses on CAD, software proof of concept and other simulations. Additionally, the chart has 135 contingency hours which caters for scope creep and any drastic changes that need to be made whilst also giving flexibility to change tasks and the hours put into them.

7.1 Meeting Minutes

During every meeting, minutes are taken to ensure all team members have a clear idea of tasks for the week, and allows absent members to catch up. They also serve as a record of progress.

Meeting Date	Present	Absent	Agenda		Talking Points	
31/10/2024	Louis		Create/discuss + download Gantt chart and scope canvas		Project tasks examples:	CAD
	Anna		Present research assigned on 24/10/24			Example Factory Map
	Abi		Decide on plans for the next week (6 bullet points)			Script to analyse map and create task pathways
	Alison		Discuss warehouse layout			Risk Assessment
	Henry		Discuss interface system			Cost analysis
	Will		Look into specs of forklift			Sustainabilty and life cycle analysis
			Propose new Tuesday morning meeting before the seminars			Deadline management
Action Items	Owner	Assigned Persons	Details	Deadline		Look into regenerative braking
Look into mapping	Louis	Louis	Using matlab to process SVGs	12.11.24		Bill of materials
Meet at 12:00 pm in Engineering	Anna	All		5.11.24		Presentation
Gantt Chart	Anna	Anna	Adjust as required	5.11.24		Research into materials
Project Scope	Anna	Anna	For feasibility report	5.11.24		Rails?
Pairs - Initial Designs	All	Abi+Alison, Henry+	Present a rough initial design with justification	5.11.24	Discussion: Wheels vs Tracks	Tracks eliminate need for Lidar
User Requirement Spec	Anna	Henry	For feasibility report	5.11.24		Wheels simplify pickup/dropoff, movement - other units
Risk assess	Anna	Alison	For feasibility report	5.11.24		U shaped, goods in, distribute to machines
Decision Matrix	Abi	Abi	To compare initial designs	12.11.24		Definitely stacking
Add hours to gantt chart + other	Anna	Anna		12.11.24		More interested in the mover design
						90% mover 10% factory
Next Meeting Agenda						
Present initial designs						
Ask Supervisors:	Do we need the code for Lidar/bought in products					
	Does it need to stack shelves?					
	Tracks/Wheels					

Figure 15: Meeting minutes from 31/10/24

8. Conclusion

Our analysis confirms that the autonomous mamover will be able to provide not only an economical but also a sustainable solution for warehouse operations in the future, with a breakeven point compared to conventional forklifts of only 420 days after implementation. This design effectively balances performance, cost and sustainability making it the prefect choice for modern industrial automation needs.

9. Recommendations

This project should proceed as planned based off the information given in this report covering technical feasibility, cost effectiveness and environmental advantages of the proposed three-wheeled automated forklift. Based off our initial studies, the URS created seems to be largely appropriate for this project. We may need to make some minor refinements to better align it with the enhanced manoeuvrability and sustainability focus of our chosen design.

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