SINERGI Vol. 29, No. 2, June 2025: 301-316
http://publikasi.mercubuana.ac.id/index.php/sinergi
http://doi.org/10.22441/sinergi.2025.2.004

Evaluating the impact of autonomous material handling on the performance of production system: a simulation approach

Ratna Purwaningsih[1]*, Annisa Rahma Shintyastuti[1], Ary Arvianto[1], Chaterine Alvina Prima Hapsari[1], Ade Aisyah Arifna Putri[2], Rifki Daris Dzulfikar[3]
[1]Industrial Engineering Department, Faculty of Engineering, Diponegoro University, Indonesia
[2]Industrial Engineering Department, Faculty of Engineering, Sebelas Maret University, Indonesia
[3]Electrical Engineering Department, College of Electrical Engineering and Computer Science, National Taiwan University of Science and Technology, Taiwan

Abstract
In developing countries, low employment rates lead to manual material handling due to low labor costs. This article analyzes the impact of transitioning from semi-manual to fully automatic material handling systems by replacing the hand pallet system with AGV for transporting materials on the production floor. A simulation model was created to evaluate the impact of the transition on cost and quality. The model focuses on production lines with predetermined pathways and fixed working hours for workstations. The discrete event simulation was developed using ExtendSim. Queuing theory model is employed to assess the utilization of resources within the system. Three scenarios are developed: a human system, systems with 2 AGVs, and 3 AGVs.The findings suggest that systems with AGVs surpass human-operated systems in terms of system reliability, cost-effectiveness, and product excellence. The findings provide essential insights for management decision-making, specifically for deterministic production lines. The research findings emphasize the possibility of significant enhancements in production system performance by implementing autonomous material handling.

Keywords:
AGV;
Automation Impact;
Material Handling;
Modeling & Simulation;

Article History:
Received: May 24, 2024
Revised: August 22, 2024
Accepted: September 12, 2024
Published: May 1, 2025

Corresponding Author:
Ratna Purwaningsih
Industrial Engineering Department, Diponegoro University, Indonesia
Email:
ratna.purwaningsih@ft.undip.ac.id

INTRODUCTION

Pickup and delivery are the most expensive operations in a warehouse, accounting for 55% of the inventory's operating costs [1]. Developing countries struggle with low employment rates, resulting in predominantly manual material handling practices due to low labor costs. Unfortunately, this raises a safety problem because it exceeds the limit of the load index. Despite a standard operating procedure, manual tasks increase faulty products, such as packaging damage, compared to robots that adhere to standard working methods. Furthermore, robots outperform humans in terms of speed due to their consistent speed.

Using robots in companies enhances competitiveness in production and delivery services [2]. Robots can improve efficiency and effectiveness in warehouse operations such as receiving, placing, storing, retrieving, and shipping [3][4]. The decisive factors for robot implementation are incorporating operating systems, integrated drive systems, sensors, communication systems, artificial intelligence (AI), and user interfaces [5]. The robots' development can significantly impact the design and engineering of warehouses [4]. The applications of warehouse robots nowadays are robotic mobile fulfillment systems (RMFSs), picking robots, Automatic Guided Vehicles (AGVs), drones, and other autonomous mobile robots (AMRs) [6].

Although robots have surpassed humans in speed, consistency, and power, the debate over whether to use human labor or robots remains unresolved [7]. The industry in developing countries needs a solid justification to replace human labor with robots, especially in material handling. Therefore, evaluating the performance of manual material handling compared to automated material handling is necessary.

The advantages of using robots in material handling are their cognitive abilities, intelligence, adaptability, and capacity to respond to unexpected events [8]. Robots offer integrated process control, the capability of handling heavy and sharp components, exact playback of defined paths, reliable performance of repetitive tasks, guidance through servomotors, and high precision [8][9]. Conversely, humans possess several advantages besides high availability, such as their ability to handle complex components, reliable execution of complex joining processes, motive power, and flexibility [7]. A suitable occupation for humans consists of tasks that require a high level of precision, innovative thinking, and intricate problem-solving skills that require high flexibility. In contrast, the tasks assigned to robots are characterized by their repetitive nature, involving the handling of substantial workloads. How precise a robot is in carrying out tasks has been researched in shooting activities [10]. When using AGVs, laying material in piles also requires precision to avoid damage to the packaging.

This research aims to develop a material handling model and measure the system reliability performance, comparing the performance between semi-automated and fully automated material handling systems in production lines with deterministic path lines and workstation operating times. The model simulation calculates three performance values: the average pallet time in the system, the number of pallets delivered, and the resources utilities in percentage. The analysis section also discusses the cost comparison between semi-manual (hand pallet) and automatic systems with AGV.

The number of AGVs that meet the target demand is determined by using mathematical models. Simultaneously, the discrete simulation model is utilized to derive parameter values for comparing manual performance with AGV. The simulation output serves as the basis for the company's decision-making processes, as it involves modeling the system through discrete simulation methods. The queuing theory system is employed to assess the utilization of resources within the system.

However, it is unfeasible to obtain a comprehensive understanding of a system's necessary performance solely through a mathematical approach. The simulation process is crucial for determining the actual value of system performance. Simulation models are suitable tools for depicting complex systems, particularly in cases where mathematical model development proves difficult [11]. Simulation involves replicating a particular scenario of a given problem by constructing a model that can be tested and improved [12].

This research differs from prior studies on AGV, which focused on pre-implementation aspects of AGV at strategic, technical, and operational levels. For example, previous research has examined strategic and technical levels, such as scheduling problems [13], and operational levels, such as planning AGVs to meet demand [14]. This research compares the impact of transitioning from the semi-manual material handling system with hand pallets to an automated system with AGV. The findings of this research can serve as a valuable resource for management in making informed decisions. The output of this research provides an overview of the industry and the impact of the transition from manual material handling to automated material handling. This article contributes to identifying the impact of the transition from semi-manual to fully automatic material handling systems by changing the hand pallet system to AGV to transport materials on the production floor. However, this is limited to production lines with deterministic path lines and workstation operating times.

This article is organized as follows. The following part discusses the AGV simulation research challenge, demonstrating that most AGV simulation research focuses on implementation methodologies. The materials and methods section cover the research methods, model conceptualization, data collection, simulation, verification, validation, replication, and explanation of the case study, which is the material handling of milk powder packaging. The results and discussion sections present the comparison of performance between semi-manual or human system material handling and material handling using an AGV, and the last is the conclusion section.

AGV Simulation Research Problem

Over time, robots have evolved from being technical tools to taking on the role of mechanical coworkers [15]. Robots often assist with material handling activities, i.e., an AGV (Automated Guided Vehicle). Fedorko et al. classified AGV into two groups: traditional and autonomous. Traditional AGV is characterized by a pre-defined route placed on the floor or located on the floor, followed by a reading device, a part of each traditional AGV. Meanwhile, autonomous vehicles are characterized by free movement, easy and simple integration, and reasonable response to obstacle detection [16]. Other researchers have a different view. Fottner et al. discussed that in terms of planning and control for material transportation, there are two large groups, namely, using vehicles and conveyors. The use of the vehicle planning area includes System design, Task assignment, Empty vehicle management, Routing, and Deadlock avoidance. As for the activities, there are picking, packaging, and handling [17].

AGV is one of the robots that handle material and work autonomously. The movement of the AGV is controlled by a navigation system that processes information obtained from sensor readings [18]. AGV is often used in manufacturing industries, warehouses, distribution centers, and terminals [19]. One of the advantages associated with the utilization of AGV is the potential reduction in labor costs and the risk of accidents resulting from human error due to the absence of a driver [20]. AGVs are commonly used for repetitive movements, long routes, and various purposes [21].

Apart from using AGV, material handling automation can also use Autonomous Intelligent Vehicles (AIV). AIV is a term used to describe a type of autonomous vehicle that combines autonomous driving capabilities with advanced AI systems. These vehicles are designed to operate independently, using AI algorithms to perceive their environment, make decisions, and adapt to changing conditions [22].

Planning using AGV can be categorized into three levels: strategic, tactical, and operational, as represented in Table 1. Guide-path design is classified as strategic planning because it affects the number of vehicles and the complexity of the vehicle scheduling [23], such as problems related to assignment scheduling, determining the optimal quantity of AGVs required within the system, and the engineering of AGV tracks.

The solution to the problem can be solved using an algorithm [13, 24, 25, 26, 27, 28]. Path planning and simulation models are also categorized at the strategic level [19]. Tactical level planning is studied to estimate the number of vehicles needed, vehicle scheduling, idle vehicle positioning, and battery management [29].

Table 1. Research on Planning Operated by the AGV

Simulation Problem	Method	Source
	Strategic	
Combined tasks with several AGVs	Multi-Decision Point Model with Simulated Annealing Algorithm	[27]
AGV scheduling	Queuing Theory and Simulated Annealing Algorithm	[21]
	Tactical	
The energy efficiency of the AGV battery	Dynamic Shortest Path Problem	[19]
AGV schedule problems with battery restrictions	Mixed-Integer Linear Programming (MILP)	[13]
	Operational	
Planning routes and avoiding obstacles to avoid collisions between robots	Deep-Q-Learning with Neural Network Algorithm	[30]
Planning AGVs to meet demand and conflict prevention	Path Planning Scheduling	[14]
Scheduling AGVs to meet demand and conflict prevention	Path Planning Queuing System	[31]
Shortest route planning and conflict prevention	Dynamic Routing Method	[31]

The problems that occur at the operational level are vehicle routing and conflict resolution [21].

Design objects can utilize either a single AGV or multiple AGVs. However, it is essential to note that these design objects are currently limited to the prototype stage of manual handling. Several studies have researched modeling with multi-AGV [32, 33, 34]. The previous research about AGV can be seen in Table 1. In a simulation with an autonomous vehicle, assessment criteria in the form of system performance parameters are required. The main difference between the use of robots in material handling and the use of humans is speed. Thus, delivery, traveling, or waiting times are usually the primary assessment criteria of system performance [35]. The amount of output or system throughput is another performance system metric [36]. A variable that is observed as simulation output is resource utility [37]. Currently, the cost and quality of the robot's work are not discussed in some simulation research because these metrics are typically obtained from historical company data rather than simulations.

METHOD

Case Study of Milk Powder Packaging

A model simulation of material handling that compares the manual and the use of AGV was developed based on the operation of a company in West Java, Indonesia. The company operates in the fast-moving consumer goods (FMCG) industry. Management needs supporting information on the impact of the transition from human to robot. The current manual system's reliability rate is 73%, representing the ratio of pallets transported compared to demand. The company has decided to replace the manual operation with an automated one using AGVs. The system's complexity is formed because pallets must be distributed to 8 production lines with different jobs and processing times on the proper delivery time and quantity.

The study's object is the transportation of pallets from the warehouse to the production floor, particularly in the parking area. The existing material handling process was done with hand pallet tools using nine workforces for three shifts each day. The factory layout and the logical flow of the pallet delivery system depict real-world conditions. The factory layout determines the distance traveled and the travel time. At the same time, the logic flow represents the order in which pallets are delivered in a system with eight production lines. The layout of the packaging material delivery process is shown in Figure 1.

In Figure 1, the AGV operator, as a material handling resource, begins at the charging station represented by a rectangular shape with a START OPT/AGV note and enters a warehouse (Wn) to pick up the packaging materials. Then, the operator or AGV moves to the production line (Pn) while carrying pallets. The current manual system's reliability rate is only 73%, representing the ratio of pallets transported compared to the demand, and has been adjusted to the company's rest hours and downtime plans. Thus, the company decided to replace the manual operation with an automated one using an AGV. The decision criteria are the lowest cost and highest system performance.

The maximum speed of the AGV without load is 7 kilometers per hour, while the AGV in the floor shop (loaded) reaches 4 km per hour for ten cycles in one line, and then the rate of AGV is 0,4. The AGV capacity is a single load, meaning one AGV can only carry one pallet - calculated values for distance in kilometers and time in hours. The available working hours are 8 hours but are only 73% effective, resulting in 5.83 hours per day. The cycle is 7.4 seconds/cycle, with 8 lines on the production floor. Table 2 shows the data required to calculate the number of AGVs needed.

Table 2. Input Data for Equation

Origin Point: Stagging Warehouse Packaging Material				
Warehouse to Packing	**Demand**	**AGV's Speed**	**Total Distance**	**Time for 1 Cycle**
Line A	10	0.4	1.37	0.95
Line B	10	0.4	1.02	0.71
Line C	10	0.4	1.05	0.73
Line D1	10	0.4	1.08	0.75
Line D2	10	0.4	1.08	0.75
Line E	10	0.4	1.07	0.74
Line F	10	0.4	1.90	1.32
Line G	10	0.4	2.10	1.46
Total	80		10.66	7.4

Based on this formulation, the AGV requirements are obtained using mathematical calculations, where the number of pallets transported by AGV is equal to the total distance multiplied by the AGV's speed and divided by the time cycle. Then, the result is multiplied by the number of production lines and sufficient working time.

The number of cycles per day is calculated by multiplying the total distance (10.66) by the AGV's speed (0.4), dividing the result by the time required for one cycle (7.40), and then multiplying the result by the effectual working hours (5.83) and the number of lines on the production floor (8). This calculation results in a total of 27 cycles per day, which means that the AGV can deliver 27 pallets per day.

The number of AGVs needed is calculated by dividing the total pallets (80 pallets) by the number of pallets one AGV can handle daily (27 pallets per AGV). This results in 2.96 ≈ 3 AGVs needed to distribute pallets. The number of AGVs required by the system is calculated mathematically by taking into account the distance between workstations on the eight existing production lines when demand is fixed. Ten pallets are at the end of the production line, each containing a load of 25-50 kg of packaging material.

There were three scenarios used in the simulation: (1) human as material handling operator, (2) allocating two AGVs, and (3) allocating three AGVs, which was developed according to the logic flow as in Figure 2. The logic flow diagram is a representation of an algorithm in diagram form.

It consists of various graphical shapes, such as circles, rectangles, diamonds, parallelograms, and other forms connected using connector lines. Each shape corresponds to a particular operation [38].

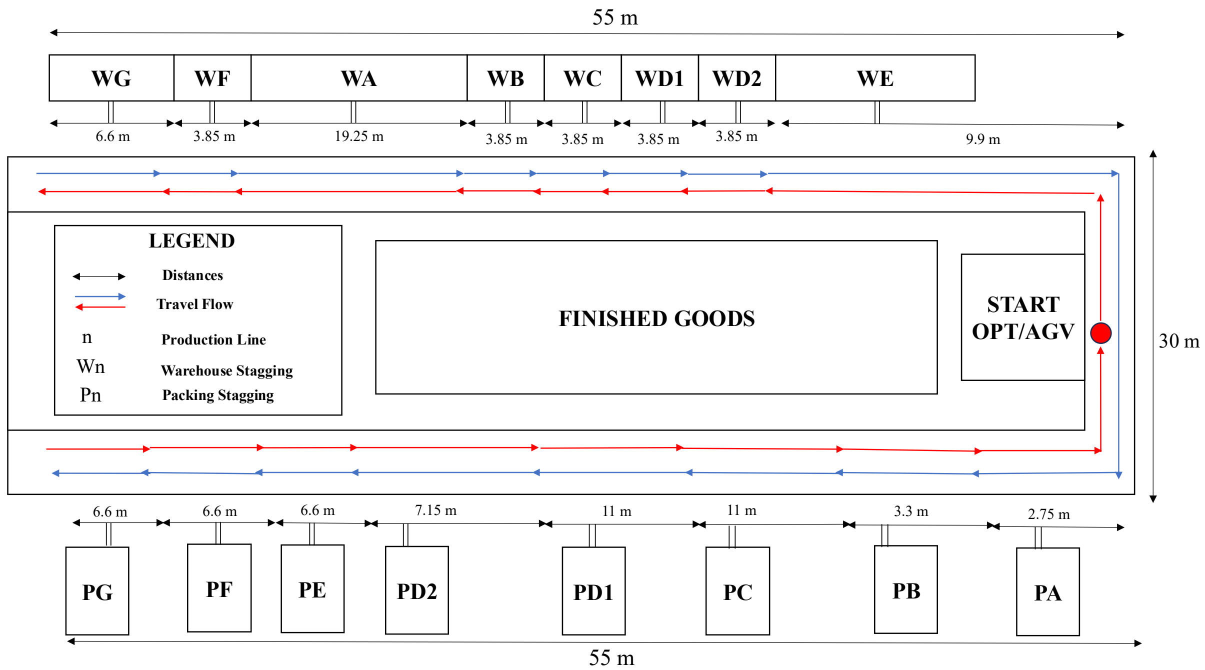


Figure 1. The Layout of The Transportation System

When the batching operator has placed the pallet in the warehouse, it is ready to take. The pallets are arranged according to the actual condition renewal based on the line with the fastest processing time. Then, the AGV will move from the charging station to take the pallet to the warehouse. Once taken from the warehouse, the powder material in the pallets will proceed to the production line area. The pallet will then be placed at the designated packing line. After sending the last assigned pallet, the AGV will transport the remaining pallets in the warehouse area to the packing line. All activities will be repeated until the end of working time or all assigned pallets are picked up.

Methods

The simulation model will be designed with updates from real-world conditions to determine the Routing of the pallets to be sent so that the system can function properly by creating a priority line sequence for each resource. Priority line order will be discussed at the displacement ratio point. According to the resource in charge of the area, the ratio of movement from Stagging Warehouse Packaging Material to Stagging Packing is determined based on the production line with the fastest total packing processing time. Assuming that the packaging material delivered meets the requirements of each line. The human system material handling model and AGV system model were modeled and simulated in four steps: (1) model conceptualization, (2) data collection, (3) simulation generation, and (4) verification, validation, and replication. Figure 3 depicts the sequence of research methods.

Model Conceptualization

At the model conceptualization stage, model development is done by imitating the existing system. The data was gathered through observation, literature review, and interviews with production department employees. Transportation time is measured using a stopwatch to determine the regular time. System performance in fulfilling demand is obtained from historical data. The decision variables represent the objective of the simulation, and the response variables act as the output of the simulation. Table 3 defines the decision variables, while Table 4 describes the response variables.

Queuing theory is used in data processing, considering the AGV as the server and the pallet as the one being served. Another type of modeling for DEMS (discrete event manufacturing system) is NLPP (non-linear programming plan), which is used to build an object's modular structure.

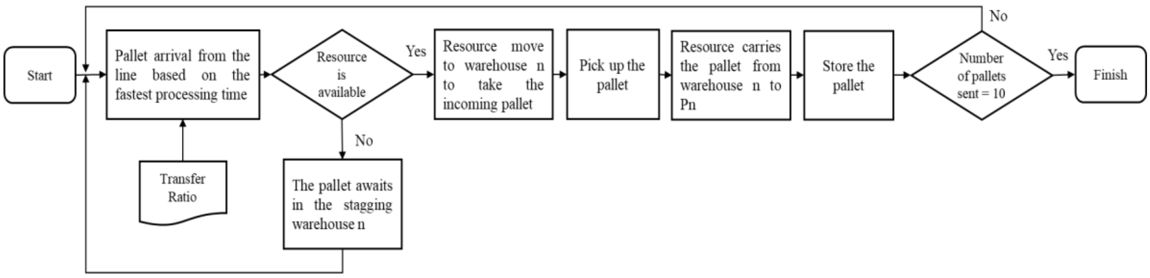


Figure 2. Logic Flow Diagram System for Resource

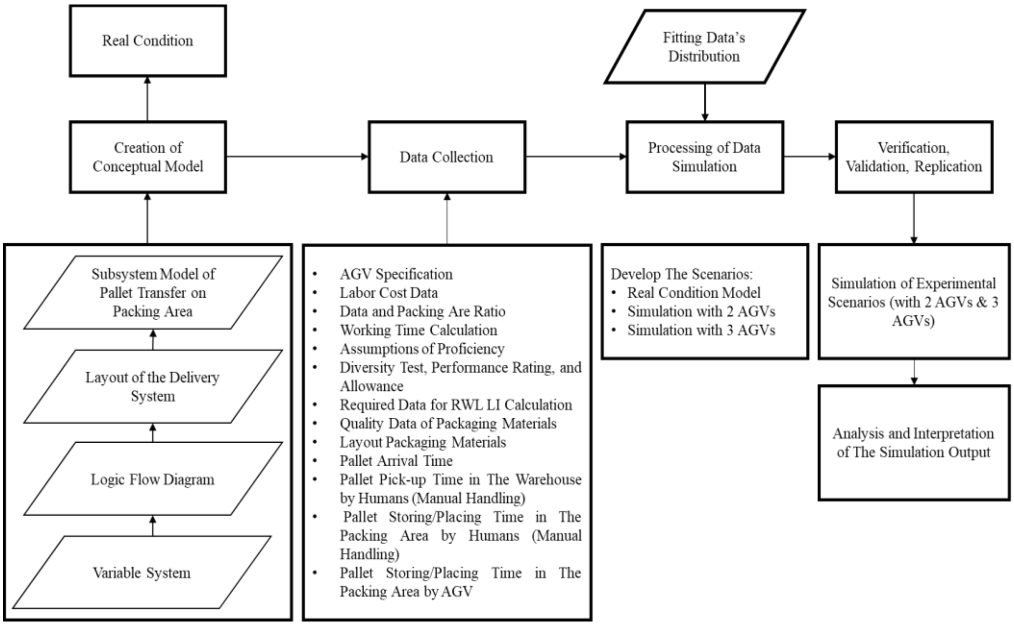


Figure 3. Research Method

Table 3. Decision Variables

Entities	Parameter	Definition	Unit
Pallet	Time between arrivals	The time it takes between the pallets to arrive at warehouse Wn	Second (s)/pallet
	The number of delivered pallets per arrival	Number of pallets in one arrival	Number of pallets
Operator	Delivery time to warehouse	The time it takes the operator to move/go to the warehouse from the starting point.	Second (s)/pallet
	Pallet pickup time	The time it takes the operator to lift the pallet	Second (s)/pallet
	Delivery time from warehouse to packing line	The time it takes the operator to move/go from the warehouse to the packing line.	Second (s)/pallet
	Pallet storing/placing time.	The time it takes the operator to store/place the pallet	Second (s)/pallet
	Number of operators	The number of packing operators every shift. For each shift, there are three operators.	Operator/pallet
AGV	Delivery time to warehouse	The time it takes the AGV to move/go to the warehouse	Second (s)/pallet
	Pallet pickup time	The time it takes the AGV to lift the pallet	Second (s)/pallet
	Delivery time from warehouse to packing line	The time it takes the AGV to move/go from the warehouse to the packing line.	Second (s)/pallet
	Pallet storing/placing time.	The time it takes the AGV to store/place the pallet	Second (s)/pallet
	Number of ideal AGV	The number of ideal operated AGVs. Based on the calculation, the operated AGV is 3 AGVs.	Unit

In Assembly and Disassembly Systems (ADS), the performance of human systems is compared to that of automation using machines [39]. This comparison is made by evaluating the performance of the global system. Previous research implemented mixed integer linear programming (MILP) to evaluate the impact of varying robot quantities on assembly system performance [40].

Table 4. Response Variables

Criteria	Parameter	Definition
Reliability	Time in system (s)	The average time each pallet is processed in the system
	Resource Utility (%)	The percentage of AGV used in the system compared to total work hours
	Number of Pallets Delivered	The number of pallets out of the system
Cost	Total Expenses (IDR)	This parameter determines the cost of acquiring AGV(s) or paying labor wages. The calculation of the AGV considers a ten-year AGV lifetime.

Data Collection

The simulation requires the operator's and AGV's speed in delivering pallets from the warehouse to the eight existing packing lines. These speed data will be used as inputs in the simulated model. A stopwatch time study measures operator and machine speed data directly. Direct observation and interviews with company management provided data such as distance between workstations, demand, number of damaged packages, and operational costs.

The model assumptions are: (1) the arrival time of the pallet on each resource is assumed to be the same for all resources; (2) the renewal determines the pallet routing so that the system is transparent, i.e., by making the priority line sequence for each resource (see logic flow); (3) the transfer ratio from warehouse to packing line is determined based on the resource's fastest packing time in the production line; and (4) the arrival of packaging materials follows the needs of each line.

Simulation

a. Fitting Distribution

The fitting distribution is identified with the Easy Fit software. The appropriate distribution is chosen based on the highest rank. Once the distribution has been determined, the data should be entered into the SPSS software tool to conduct a one-sample Kolmogorov-Smirnov test and determine the significance value ($\alpha > 0.05$).

b. Develop the Simulation Scenario

The developed scenarios represent the material handling operations to meet the demand of each workstation. The simulation runs on three scenarios: (1) human system, (2) allocate two AGVs, and (3) allocate three AGVs.

An issue that was not addressed in this study was whether states like deadlock and starvation exist in the simulation. Since the case study was limited to a continuous material flow toward each production line's last workstation, it was impossible to discuss buffer stock. Material flow is straightforward in the real world, making planning for material handling paths easier. The model would become more complex if it included unexpected disturbances and product changes.

The verification process is done by comparing the distribution and parameter data. In contrast, the validation process compares the number of delivered pallets from the observation and simulation output. The dataset consists of 30 replications per line. The hypothesis is as follows:

- H0: $\mu0 = \mu1$ means there is no difference between the observation and simulation
- H0: $\mu0 \neq \mu1$ means there is a difference between observation and simulation
- The critical region used is t-stat > t-critical two-tail.

Determining the appropriate number of replications in a simulation is typically based on the expected error range within a specific confidence interval. The simulation used 30 scenario replications to satisfy the normal distribution assumption [41]. One replication is 21,000 seconds based on adequate working time in one shift.

RESULTS AND DISCUSSION

The Discrete Event Simulation (DES) model operates a system as a discrete series of events in time. Each event occurs at a specific time and marks a change in the system's state. Extend software is used in this study's DES model for process modeling, analysis, and optimization. The conceptual model of a material handling flow model involves the time between pallet arrival and transportation time from the predecessor to the successor for eight production lines.

A stopwatch time study was used to obtain time measurement. The distribution data for each model parameter is used as the initial data before running the simulation. The mean and standard deviation are provided as data. All measurements are in seconds. The distribution tests show that the distribution of all data is uniform. The results of the fitting distribution test are given in Table 5. The minimum and maximum values of each parameter of the fitting distribution are in two decimal digits.

There are three scenarios in the simulation. The first scenario is a human system with 30 replications and a simulation time of 21,000 seconds. The pallet demand determines the number of replications, where each production line must produce ten pallets at the end of the day. The demand has been met with these 30 replications.

Table 5. Parameter Value

Pallet Delivery Process on Human System		Pallet Delivery Process on AGV System	
Parameter	***Value***	***Parameter***	***Value***
The time between pallet arrivals		(226.72;258.13)	
Loading	(142.16;152)	Loading	(37.39;46.82)
Unloading	(150.25;158.6)	Unloading	(47.55;54.94)
Path line WA	(136.32;146.75)	Path line WA	(145.98;149.92)
Path line WB	(87.93;104.37)	Path line WB	(96.35;102.98)
Path line WC	(78.7;89.31)	Path line WC	(88.34;92.78)
Path line WD1	(73.27;79.89)	Path line WD1	(78.77;82.89)
Path line WD2	(64.97;70.22)	Path line WD2	(68.43;73.23)
Path line WE	(50.85;63.72)	Path line WE	(59.13;64.78)
Path line WF	(147.89;151.95)	Path line WF	(156.45;159.89)
Path line WG	(164.03;169.91)	Path line WG	(172.34;177.78)
Path line PA	(182.73;188.53)	Path line PA	(191.35;194.87)
Path line PB	(144.09;148.43)	Path line PB	(151.21;155.77)
Path line PC	(162.53;167.52)	Path line PC	(168.45;173.45)
Path line PD1	(178.72;184.42)	Path line PD1	(186.33;190.52)
Path line PD2	(186.16;191.12)	Path line PD2	(194.45;199.18)
Path line PE	(191.72;198.04)	Path line PE	(201.34;206.55)
Path line PF	(299.91;306.98)	Path line PF	(314.56;318.83)
Path line PG	(332.35;339.41)	Path line PG	(346.21;351.93)

The AGV speed is fixed here so that the data is homogeneous and does not require much repetition. The model was developed based on the system's existing condition, where each resource handles each area. The second scenario is allocating two AGVs in the model. Meanwhile, the third scenario is allocating three AGVs in the model. The description for each scenario is as follows.

1st Scenario: Human-System Model

In this scenario, each operator controls a different production line. Ten pallets are required for each line. The delivered pallets are prioritized based on the fastest packing time. The queuing system is FIFO (First In, First Out), which means that the pallet that arrives first will be served first, and the other pallets will have to wait until the last pallet is delivered. The daily demand to be transferred is 80 pallets over 8 hours of work. One point of origin is the warehouse, with eight production lines as destinations, as shown in Figure 4.

Pallet picking is based on the task area of the packing operator. The packing operator in one shift is three people. Operator 1 serves the A-B production line, Operator 2 serves the C-D production line, and Operator 3 serves the E-G production line. After the pallet is ready, the operator will take it from the warehouse and send it to the targeted production line. The renewal shop floor conditions in the simulation was developed by applying the pallet routing concept, which states that pallet picking is based on the transfer ratio.

Meanwhile, the area with the fastest total processing time is determined based on data collection of the workstation processing time. The number of arrival packaging corresponds to the needs of each production line. The packing line with two areas has a transfer ratio of 0.5002 and 0.4997, respectively. The packing line with three areas has a transfer ratio of 0.3364, 0.3339, and 0.3296, respectively.

The operator's work speed is assumed to be the same for the nine operators divided into three work shifts. The following is the distribution of work among the three operators. Operator 1 served two lines, A and B, with packing line A taking 25 minutes and packing line B taking 36 minutes. As a result, operator one will send the pallet to packing line A first, followed by packing line B. Operator 2 is responsible for three lines: C, D1, and D2.

Packing line C takes 97 minutes, while D1 and D2 take 24 and 47 minutes, respectively. As a result, operator two will send the pallet first to packing line D1, then to packing line D2, and finally to packing line C. Operator 3 will serve three lines: E, F, and G. Packing line E requires 25 minutes. Packing line F requires 24 minutes, and packing line G requires 16 minutes. The pallet will then be sent to packing line G first, then to packing line F, and finally to packing line E by operator 3.

After simulating the human system scenario, validation tests are performed on the simulation output. The number of pallets is used in the validation test. The t-stat value is -1.877, and the t-critical two-tail value is 1.969, according to the t-test results. H_0 should not be rejected because the t-stat value is outside the critical range. The null hypothesis states no difference between the observed and simulated delivered pallets. It can be interpreted that there is no difference between observation and simulation. In other words, the output data represents the existing system.

2nd Scenario: Two AGVs

Two AGV models are made to simplify a system with minimum investment cost. AGV 1 will serve packing lines A, B, C, and D1; AGV 2 will serve D2, E, F, and G. The simulation is set with 30 replications and a simulation time of 21,000 seconds. The second scenario is shown in Figure 5.

The second scenario simplifies the first by dividing the eight packing lines into two service areas. Each line has a requirement of ten pallets, with the priority of pallet delivery based on the fastest completion time of the process. The transfer ratio in each packing line area is 0.2515, 0.2505, 0.2495, and 0.2485, respectively. The queuing system is similar to the first scenario with FIFO (First In, First Out). The work distribution among AGV 1 and AGV 2 is as follows. AGV 1 serves four lines: A, B, C, and D1. Line A takes 25 minutes; line B takes 36 minutes; line C takes 97 minutes while packing line D1 takes 24 minutes.

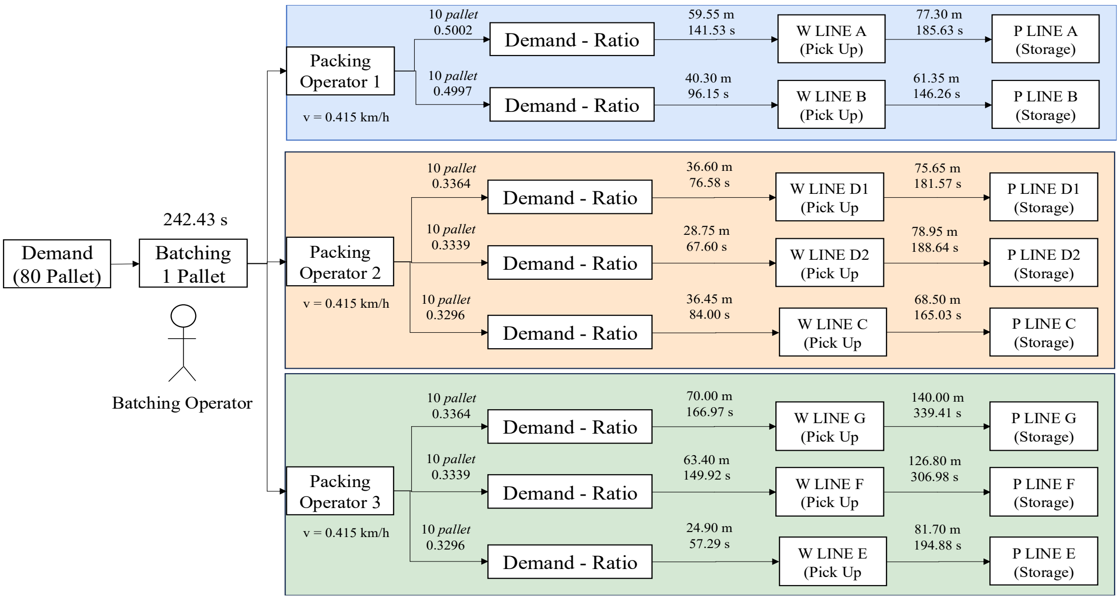


Figure 4. The Material Handling Used Hand Pallet

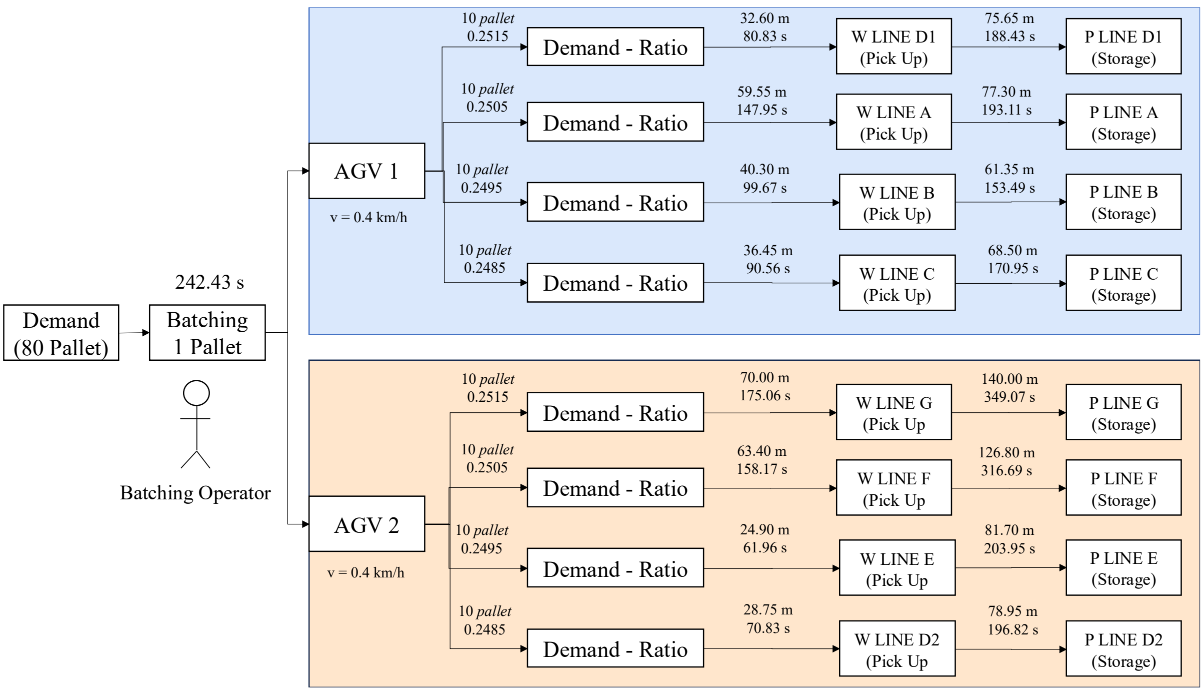


Figure 5. The Full Automation of Material Handling System (2 AGVs)

Hence, AGV 1 will send the pallet to line D1 first, then proceed to lines A, B, and C. On the other hand, AGV 2 serves four lines: D2, E, F, and G. Line D2 takes 47 minutes, line E takes 25 minutes, line F takes 24 minutes, and packing line G takes 16 minutes. Hence, AGV 2 will send the pallet to line G first, then continue to lines F, E, and D2.

3rd Scenario: Three AGVs

The third scenario represents the first scenario but replaces the three operators with three AGVs in the system. AGV 1 will serve lines A-B, AGV 2 will serve lines C-D1-D2, and AGV 3 will serve lines E-F-G, considering the total work time balanced between the three AGVs.

In this scenario, the respective AGVs serve the three areas. Each line requires ten pallets, with the priority of pallet delivery based on the fastest completion time of the packing process. Line area 2 has a transfer ratio of 0.5002 and 0.4997, respectively, while line area 3 has a transfer ratio of 0.3364, 0.3339, and 0.3296, respectively. The work distribution among AGV 1, AGV 2, and AGV 3 is as follows. AGV 1 serves lines A and B, where line A takes 25 minutes and line B takes 36 minutes. Thus, AGV 1 will send the pallet to packing line A first and then continue to line B. AGV 2 serves lines C, D1, and D2. Line C takes 97 minutes, line D1 takes 24 minutes, and line D2 takes 47 minutes. Hence, AGV 2 will send the pallet to line D1 first, then continue to line D2, and finally to line C. On the other hand, AGV 3 serves lines E, F, and G. Line E takes 25 minutes, line F takes 24 minutes, and line G takes 16 minutes. Hence, AGV 3 will send the pallet to line G first, then to line F, and finally to line E.

Simulation Result Comparison

System reliability is the percentage of non-failures that occur within a unit of time [42]. AGV provides system reliability of 100% as it can meet demand promptly with a 100% success rate. The summary of the simulation results can be seen in Figures 6 and Figure 6. When the human system scenario is compared to the AGV scenario (both the second and third scenarios), the average time in the system is reduced from 23.29% to 36.27%, as illustrated in Figure 6.

Meanwhile, the average time in the system between scenarios with 2 AGVs and 3 AGVs is the same. The main reason for the time reduction between the human system and the scenario with AGV is the different methods for picking up and storing pallets. The significant factor is time because the AGV has higher turning movement accuracy than the human operator, resulting in a shorter time. The idle time for each scenario can also be used to assess resource utility. This resource utility can be used to select the best scenarios.

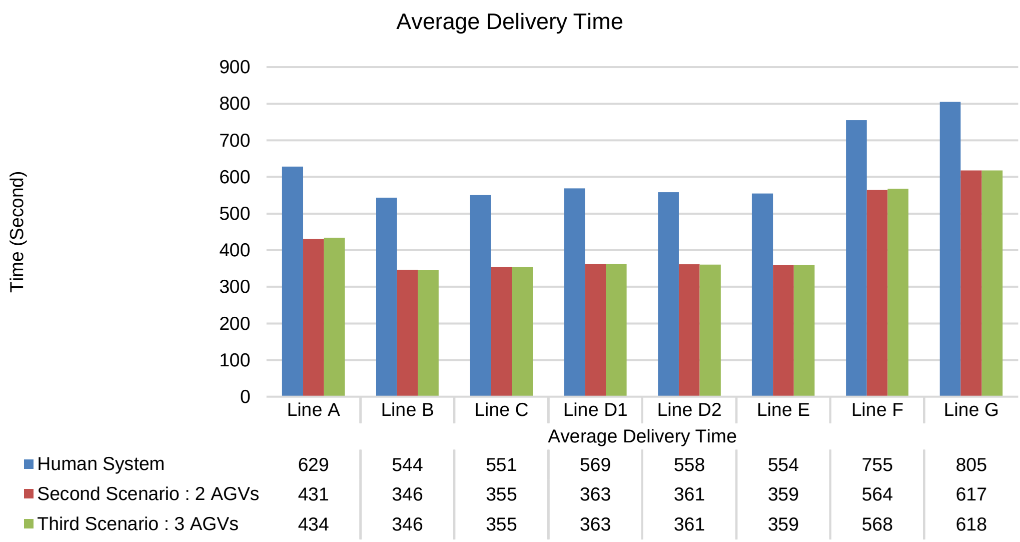
Figure 6 shows that the number of pallets delivered in the third scenario is nearly three times the demand. The target demand, however, is only for ten pallets. If the company operates three AGVs, it will result in idle resources.

At the same time, the pallet delivered in the second scenario corresponds to the current demand. The second scenario divided the packing line into two sections and used two AGVs. As a result, there was no indication of idle resources. The second scenario is preferred because it meets the target demand while leaving no idle resources. The simulation does not perform idle time calculations but Extend V.4. software automatically calculates the average value and declares the utility of AGVs. For example, line A in the third scenario has an output of 27 pallets, while the need is only ten units, resulting in a resource utility of 30%. While using 2 AGVs, the maximum number of pallets sent is 14 or 10/14, 71% in line A. Figure 6 proves that the most efficient number of pallets sent according to demand is when using 2 AGVs.

Discussion

This discussion will compare the performance of semi-manual material handling systems to fully automatic with AGV. The comparison focused on system reliability, represented by pallets' time in the system and demand fulfillment. Then, the cost and quality aspects between semi-manual and automatic will also be compared.

The change from human power pushing hand pallets to AGVs has a speed difference. AGV has a maximum speed of 0.7 km/hour, and an average of 0,4 km/hour is used in this simulation. Time study measurement of a human with a hand pallet carrying a load of 25 to 50 kg, calculated with a stopwatch, has a 1.2 meters per second speed. Research on human walking speed found a value of 1.31 meters per second or 4.716 km/hour [43]. As stated in the introduction section, operations that need power, speed, and repetitive uniformity are well-suited for robotic automation. The research findings demonstrate that AGV systems exhibit a system reliability of 100%, resulting in a notable 30% decrease in time compared to semi-automated material handling. This reduction in time in the system will affect the number of pallets successfully delivered, increasing from 73% to 100% of the demand met.



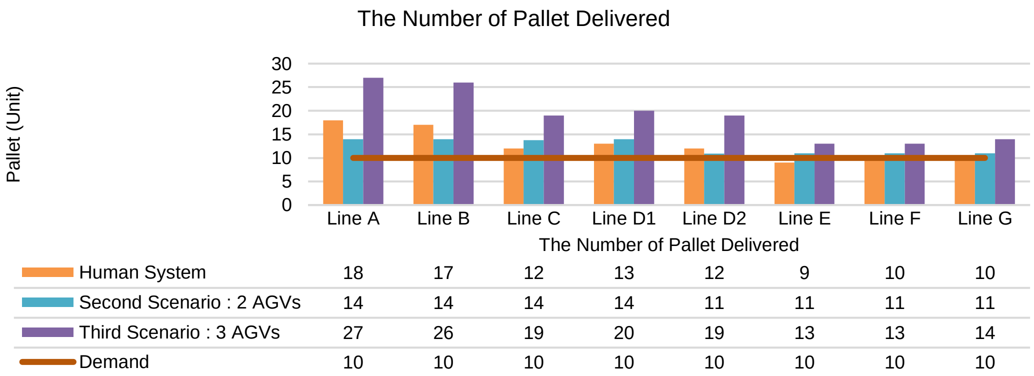


Figure 6. Simulation Result

Another benefit is cost savings. Even though the simulation was carried out with only 30 replications, representing one day's performance, the robot's consistent speed ensures data homogeneity. The simulation results suggest that operating 2 AGVs is sufficient to meet the demand. Cost calculations are done manually based on the required number of AGVs. Data on human system operating costs is secondary data from the company, as are costs for AGVs.

The detailed comparison in terms of cost for all scenarios is shown in Table 6. Cost calculations for AGVs use a lifetime assumption of 10 years. The cost of the human system encompasses various components such as wages for labor, expenses related to transportation, allowances for meals, and health insurance. The human system is calculated at the cost of 9 workers. In contrast, the expenses associated with the AGV scenario encompass the initial capital investment, ongoing operational costs, and maintenance expenditures. The operational cost for one AGV is 60 million IDR per year. The maintenance cost is 10 million IDR per year for each AGV.

The investment cost for one AGV is 50 million IDR. Table 6 shows that the total cost of using AGV (2 AGVs or 3 AGVs) for material handling is cheaper than semi-manual material handling by humans, with a very significant cost difference. The outcomes of this research showed cost savings in material handling and increased system reliability due to shorter system time. The economic benefit of operating two AGVs instead of nine human workers is 667.2 minus 240, or 427.2 million per year, resulting in a 64% decrease in material handling costs. Material handling cost savings can also be made on storage costs if the amount of material stored in the warehouse can be reduced with more precise demand forecasting technology [44].

Table 6. Cost Comparison of Scenarios (In Million IDR)

Cost/year	Human System	2 AGVs	3 AGVs
Regular Wage	505.2		
Transportation Cost	54		
Meal Allowance	54		
Health Insurance	54		
Investment Cost		100	150
Operational Cost		120	180
Maintenance Cost		20	30
Total	**667.2**	**240**	**360**

It can be concluded that replacing the semi-manual material handling system with automation, i.e., AGV, could increase the system's reliability while reducing the material handling cost and the number of damaged packages; in other words, reliability, cost efficiency, and quality increase due to material handling automation. The findings stated that automation is now an indispensable part of our world, which helps us produce more efficiently, precisely, and with lower costs. Melo & Corneal investigated the current material flow of completed goods within an automotive component supplier factory. They also investigated the market's technological choices to assess whether implementing automation for material handling would be a reasonable investment. Their investigation included using discrete event simulation to evaluate various layout techniques in conjunction with the performance of mobile robots. The study's findings revealed that the tandem layout, which required a minimum of three robots, was the most advantageous solution for the unique conditions found in the factory [45].

A trade-off arises regarding material handling expenses when deciding between utilizing machinery or relying on human labor. However, when it is determined that utilizing AGVs yields notable financial benefits, the decision-making process will incline towards adopting robotic systems for material handling. The enhancement of productivity and efficiency is attained through the transition from semi-automatic to fully automated processes.

The predominant challenges persist and are generally rooted in policy and organizational matters. The transition from semi-automation to full automation requires standardized work procedures [46] and changes in organizational structure and authority distribution [47].

Dimény and Koltai stated that sometimes robots are not an economically viable option for automation and suggested a combined system with both manual and automated [40]. Winkelhaus et al. [36] define a hybrid system as one in which autonomous robots and human order pickers collaborate in warehouses within a shared workspace to achieve a common goal. Regarding throughput and total costs, the simulation results showed that hybrid order picking generally outperformed pure manual or automated order picking operations. In addition, using robots dramatically increases worker safety and health conditions. However, in this study, robots excel in cost criteria compared to humans, even when investment costs are considered.

The impact of industrial automation is not only on the production floor; Mantzaris Myloni mentioned that automation also impacts the organization [48]. The result aligns with Margherita and Braccini, where Industry 4.0 technologies affect organizational performance in the manufacturing industry implementing TQM [49]. This transformation from human operators to automation with robots must be continued with other impacts outside the production floor as a suggestion for future research.

Automation can be applied on the production floor and, more broadly, in the production and supply chain networks. Nitsche et al. found that using automation, especially in facilitating decision-making processes in the supply chain, can increase logistics network resilience and enhance organizational performance due to autonomous decision-making in informational processes [50].

Autonomous systems are also studied in intralogistics. Autonomous intralogistics systems facilitate the independent and decentralized management, implementation, supervision, and enhancement of internal material and information movements. This is achieved through collaboration and interaction with other systems and human operators. Footner et al. examine the five stages of achieving autonomy. These stages are categorized as follows: (0) absence of automation, (1) assistance system, (2) partial automation, (4) conditional automation, (5) high automation, and (6) autonomy [17]. The current status of the case study in this research remains at level 2, characterized by partial automation, as the implementation of automation has been limited to material handling processes. To enhance organizational adaptability, a corporation must engage in deliberations regarding the potential of conditional automation as a subject for future study.

Collaboration with industry partners is needed to ensure a successful material handling system for an industrial environment [22]. Automated material handling gradually replaces manual processes as robotics and machine programming technology advances. Furthermore, the increased use of autonomous mobile vehicle (AMR) technology in the field is evidence of Industry 4.0's influence on material handling. In addition to cost savings, improved working conditions, line supply and kitting, inter-process connection, end-of-line handling, and pallet handling, users of this automated system report several other advantages.

CONCLUSION

This study conducted a comparative analysis of system performance in material handling for packaging materials, specifically examining the differences between operators utilizing hand pallets and those utilizing AGVs. The developed model exhibits potential utility for various industries, particularly industries utilizing hand pallets. According to the mathematical computation, 2.9 is the quantity of Automated Guided Vehicles (AGVs) required to fulfill the demand. Nevertheless, two Automated Guided Vehicles (AGVs) would be adequate for the given scenario based on the simulation results. The decision to utilize two Automated Guided Vehicles (AGVs) proves advantageous in terms of cost, as it is more economical than employing nine operators.

The simulation results show that the AGVs guarantee 100% system reliability while reducing the average system time by 32%. Furthermore, AGVs outperform human systems due to lower material handling expenses, from 667.2 million IDR to 240 million IDR per year, and decreased damage packaging from 29% to 0%. For future research, this study can be expanded by considering the impact of the transition from human labor to machines in material handling on other organizational aspects.

FUNDING

This research was funded by the Directorate General of Research and Community Service, Ministry of Research, Technology and Higher Education of Indonesia, under the scheme of 'Penelitian Fundamental - Reguler'in 2023

REFERENCES

[1] M. Çelik, C. Archetti, and H. Süral, "Inventory routing in a warehouse: The storage replenishment routing problem," *European Journal of Operational Research*, vol. 301, no. 3, pp. 1117–1132, Sep. 2022, doi: 10.1016/j.ejor.2021.11.056.

[2] A. Erro-Garcés and M. E. Aramendia-Muneta, "The role of human resource management practices on the results of digitalisation. From Industry 4.0 to Industry 5.0," *Journal of Organizational Change Management*, vol. 36, no. 4, pp. 585–602, 2023, doi: 10.1108/jocm-11-2021-0354.

[3] M. Jiang, K. H. Leung, Z. Lyu, and G. Q. Huang, "Picking-replenishment synchronization for robotic forward-reserve warehouses," *Transportation Research Part E: Logistics and Transportation Review*, vol. 144, p. 102138, Dec. 2020, doi: 10.1016/j.tre.2020.102138.

[4] K. Azadeh, R. De Koster, and D. Roy, "Robotized and Automated Warehouse Systems: Review and Recent Developments," *Transportation Science*, vol. 53, no. 4, pp. 917–945, 2019, doi: 10.1287/trsc.2018.0873.

[5] Z. Gao, T. Wanyama, I. Singh, A. Gadhrri, and R. Schmidt, "From Industry 4.0 to Robotics 4.0 - A Conceptual Framework for Collaborative and Intelligent Robotic Systems," *Procedia Manufacturing*, vol. 46, pp. 591–599, 2020, doi: 10.1016/j.promfg.2020.03.085.

[6] G. Fragapane, R. de Koster, F. Sgarbossa, and J. O. Strandhagen, "Planning and control of autonomous mobile robots for intralogistics: Literature review and research agenda," *European Journal of Operational Research*, vol. 294, no. 2, pp. 405–426, 2021, doi: 10.1016/j.ejor.2021.01.019.

[7] A. Hentout, M. Aouache, A. Maoudj, and I. Akli, "Human–robot interaction in industrial collaborative robotics: a literature review of the decade 2008–2017," *Advanced Robotics*, vol. 33, no. 15–16, pp. 764–799, Aug. 2019, doi: 10.1080/01691864.2019.1636714.

[8] J. T. Licardo, M. Domjan, and T. Orehovački, "Intelligent Robotics—A Systematic Review of Emerging Technologies and Trends," *Electronics (Basel)*, vol. 13, no. 3, p. 542, Jan. 2024, doi: 10.3390/electronics13030542.

[9] C. Petzoldt, M. Harms, and M. Freitag, “Review of task allocation for human-robot collaboration in assembly,” *International Journal of Computer Integrated Manufacturing* vol. 36, no. 11, pp. 1675–1715, Nov. 2023, doi: 10.1080/0951192X.2023.2204467.

[10] D. Hendriana et al., “Advanced shooting target with bullet collector, semi-automatic bulls-eye paper positioning and automatic shooting score,” *SINERGI*, vol. 29, no. 1, p. 51, Jan. 2025, doi: 10.22441/sinergi.2025.1.006.

[11] A. M. Law, *Simulation Modeling and Analysis*, 6th ed. Arizona: McGraw Hill, 2024.

[12] R. Blanco, G. Patow, and N. Pelechano, “Simulating real-life scenarios to better understand the spread of diseases under different contexts,” *Scientific Reports*, vol. 14, no. 1, p. 2694, Feb. 2024, doi: 10.1038/s41598-024-52903-w.

[13] N. Singh, Q.-V. Dang, A. Akcay, I. Adan, and T. Martagan, “A matheuristic for AGV scheduling with battery constraints,” *European Journal of Operational Research*, vol. 298, no. 3, pp. 855–873, 2022, doi: 10.1016/j.ejor.2021.08.008.

[14] X. F. Zhao, H. Z. Liu, S. X. Lin, and Y. K. Chen, “Design and Implementation of a Multiple AGV Scheduling Algorithm for a Job-Shop,” *International Journal of Simulation Modelling*, vol. 19, no. 1, pp. 134–145, 2020, doi: 10.2507/ijsimm19-1-co2.

[15] A. Pasparakis, J. de Vries, and M. B. M. R. de Koster, “In Control or under Control? Human-Robot Collaboration in Warehouse Order Picking,” *SSRN Electronic Journal*, 2021, doi: 10.2139/ssrn.3816533.

[16] D. Clauer, J. Fottner, E. Rauch, and M. Prüglmeier, “Usage of Autonomous Mobile Robots Outdoors - an Axiomatic Design Approach,” *Procedia CIRP*, vol. 96, pp. 242–247, 2021, doi: 10.1016/j.procir.2021.01.081.

[17] J. Fottner et al., “Autonomous Systems in Intralogistics – State of the Art and Future Research Challenges,” *Logistics Research*, vol. 14, Jan. 2021, doi: 10.23773/2021_2.

[18] A. Yadav, A. Gaur, SM. Jain, DK. Chaturvedi, and R. Sharma, “Development Navigation, Guidance & Control Program for GPS based Autonomous Ground Vehicle (AGV) using Soft Computing Techniques,” *Materials Today: Proceedings*, vol. 29, pp. 530–535, 2020, doi: 10.1016/j.matpr.2020.07.309.

[19] E. Mejri, S. Kelouwani, Y. Dube, N. Henao, and K. Agbossou, “Energy Efficient Order Picking Routing for a Pick Support Automated Guided Vehicle (Ps-AGV),” *IEEE Access*, vol. 10, pp. 108832–108847, 2022, doi: 10.1109/ACCESS.2022.3212797.

[20] N. Thylén, C. Wänström, and R. Hanson, “Challenges in introducing automated guided vehicles in a production facility – interactions between human, technology, and organisation,” *International Journal of Production Research*, vol. 61, no. 22, pp. 7809–7829, Nov. 2023, doi: 10.1080/00207543.2023.2175310.

[21] L. Xie, H. Li, and L. Luttmann, “Formulating and solving integrated order batching and routing in multi-depot AGV-assisted mixed-shelves warehouses,” *European Journal of Operational Research*, vol. 307, no. 2, pp. 713–730, Jun. 2023, doi: 10.1016/j.ejor.2022.08.047.

[22] M. C. Cronin, M. A. Awasthi, M. A. Conway, D. O’Riordan, and J. Walsh, “Design and Development of a Material Handling System for an Autonomous Intelligent Vehicle for Flexible Manufacturing,” *Procedia Manufacturing*, vol. 51, pp. 493–500, 2020, doi: 10.1016/j.promfg.2020.10.069.

[23] J. Xin, L. Wei, A. D’Ariano, F. Zhang, and R. Negenborn, “Flexible time–space network formulation and hybrid metaheuristic for conflict-free and energy-efficient path planning of automated guided vehicles,” *Journal of Cleaner Production*, vol. 398, p. 136472, Apr. 2023, doi: 10.1016/j.jclepro.2023.136472.

[24] Z. Jiang, W. Chen, X. Zheng, and F. Gao, “Research on vehicle path planning of automated guided vehicle with simultaneous pickup and delivery with mixed time windows,” *IET Collaborative Intelligent Manufacturing*, vol. 6, no. 2, Jun. 2024, doi: 10.1049/cim2.12105.

[25] Y. Chen and Z. Jiang, “Multi-AGVs Scheduling with Vehicle Conflict Consideration in Ship Outfitting Items Warehouse,” *Journal of Shanghai Jiaotong University (Science)*, vol. 29, no. 3, pp. 492–508, Jun. 2024, doi: 10.1007/s12204-022-2561-z.

[26] H. Sang, Z. Li, and M. F. Tasgetiren, “An Effective Optimization Method for Integrated Scheduling of Multiple Automated Guided Vehicle Problems,” *Tsinghua Science and Technology*, vol. 29, no. 5, pp. 1355–1367, Oct. 2024, doi: 10.26599/TST.2023.9010087.

[27] X. Wang, W. Wu, and Z. Xing, “Multi-decision points model to solve coupled-task scheduling problem with heterogeneous multi-AGV in manufacturing systems,” *International Journal of Industrial Engineering Computations*, vol.

14, no. 1, pp. 49–64, 2023, doi: 10.5267/j.ijiec.2022.10.003.
[28] Q. Liu, N. Wang, J. Li, T. Ma, F. Li, and Z. Gao, "Research on Flexible Job Shop Scheduling Optimization Based on Segmented AGV," *Computer Modeling in Engineering & Sciences*, vol. 134, no. 3, pp. 2073–2091, 2023, doi: 10.32604/cmes.2022.021433.
[29] M. De Ryck, M. Versteyhe, and F. Debrouwere, "Automated guided vehicle systems, state-of-the-art control algorithms and techniques," *Journal of Manufacturing Systems*, vol. 54, pp. 152–173, Jan. 2020, doi: 10.1016/j.jmsy.2019.12.002.
[30] L. Jiang, H. Huang, and Z. Ding, "Path planning for intelligent robots based on deep Q-learning with experience replay and heuristic knowledge," *IEEE/CAA Journal of Automatica Sinica*, vol. 7, no. 4, pp. 1179–1189, Jul. 2020, doi: 10.1109/JAS.2019.1911732.
[31] Y. Lian, W. Xie, and L. Zhang, "A Probabilistic Time-Constrained Based Heuristic Path Planning Algorithm in Warehouse Multi-AGV Systems," *IFAC-PapersOnLine*, vol. 53, no. 2, pp. 2538–2543, 2020, doi: 10.1016/j.ifacol.2020.12.293.
[32] G. Yang, M. Li, and Q. Gao, "Multi-Automated Guided Vehicles Conflict-Free Path Planning for Packaging Workshop Based on Grid Time Windows," *Applied Sciences*, vol. 14, no. 8, p. 3341, Apr. 2024, doi: 10.3390/app14083341.
[33] K. Shi, M. Zhang, Z. He, S. Yin, Z. Ai, and N. Pan, "Scheduling of Multi-AGV Systems in Automated Electricity Meter Verification Workshops Based on an Improved Snake Optimization Algorithm," *Symmetry (Basel)*, vol. 15, no. 11, p. 2034, Nov. 2023, doi: 10.3390/sym15112034.
[34] X. Zhou and J. Zhu, "An Improved Bounded Conflict-Based Search for Multi-AGV Pathfinding in Automated Container Terminals," *Computer Modeling in Engineering & Sciences*, vol. 139, no. 3, pp. 2705–2727, 2024, doi: 10.32604/cmes.2024.046363.
[35] M. Qi, X. Li, X. Yan, and C. Zhang, "On the evaluation of AGVS-based warehouse operation performance," *Simulation Modelling Practice and Theory*, vol. 87, pp. 379–394, Sep. 2018, doi: 10.1016/j.simpat.2018. 07.015.
[36] S. Winkelhaus, M. Zhang, E. H. Grosse, and C. H. Glock, "Hybrid order picking: A simulation model of a joint manual and autonomous order picking system," *Computers and Industrial Engineering*, vol. 167, p. 107981, May 2022, doi: 10.1016/j.cie.2022.107981.
[37] M. Shakeb Ashraf, K. Pal Singh, W. Ullah Khan, and M. Ali, "AGV's effect on the performance of flexible manufacturing system in stochastic environment," *Materials Today: Proceedings*, Apr. 2023, doi: 10.1016/j.matpr.2023.03.795.
[38] S. Ghilardi, A. Gianola, M. Montali, and A. Rivkin, "Petri net-based object-centric processes with read-only data," *Information Systems*, vol. 107, p. 102011, Jul. 2022, doi: 10.1016/j.is.2022.102011.
[39] R. Slama, O. Ben-Ammar, H. Tlahig, I. Slama, and P. Slangen, "Human-centred assembly and disassembly systems: a survey on technologies, ergonomic, productivity and optimisation," *IFAC-PapersOnLine*, vol. 55, no. 10, pp. 1722–1727, 2022, doi: 10.1016/j.ifacol.2022.09.646.
[40] I. Dimény and T. Koltai, "Minimising workers' workload in partially automated assembly lines with human-robot collaboration," *IFAC-PapersOnLine*, vol. 55, no. 10, pp. 1734–1739, 2022, doi: 10.1016/j.ifacol.2022.09.648.
[41] S. G. Kwak and S.-H. Park, "Normality Test in Clinical Research," *Journal of Rheumatic Diseases*, vol. 26, no. 1, p. 5, 2019, doi: 10.4078/jrd.2019.26.1.5.
[42] N. Yousefi, D. W. Coit, and S. Song, "Reliability analysis of systems considering clusters of dependent degrading components," *Reliability Engineering and System Safety*, vol. 202, p. 107005, Oct. 2020, doi: 10.1016/j.ress.2020.107005.
[43] E. M. Murtagh, J. L. Mair, E. Aguiar, C. Tudor-Locke, and M. H. Murphy, "Outdoor Walking Speeds of Apparently Healthy Adults: A Systematic Review and Meta-analysis," *Sports Medicine*, vol. 51, no. 1, pp. 125–141, Jan. 2021, doi: 10.1007/s40279-020-01351-3.
[44] H. Setyaningrum, I. K. Sriwana, and I. Mufidah, "Inventory optimization model using Artificial Neural Network method and Continuous Review (s,Q)," *SINERGI*, vol. 29, no. 1, p. 143, Jan. 2025, doi: 10.22441/sinergi.2025.1.013.
[45] A. F. Melo and L. M. Corneal, "Case study: evaluation of the automation of material handling with mobile robots," *International Journal of Quality Innovation*, vol. 6, no. 1, 2020, doi: 10.1186/s40887-020-00037-y.
[46] P. Brown, T. Ly, H. Pham, and P. Sivabalan, "Automation and management control in dynamic environments: Managing

organisational flexibility and energy efficiency in service sectors," *The British Accounting Review*, vol. 52, no. 2, p. 100840, 2020, doi: 10.1016/j.bar.2019.100840.

[47] H. Benbya, T. H. Davenport, and S. Pachidi, "Artificial Intelligence in Organizations: Current State and Future Opportunities," *SSRN Electronic Journal*, 2020, doi: 10.2139/ssrn.3741983.

[48] K. Mantzaris and B. Myloni, "Human resources under technological transformation: what HR professionals believe in an international scale," *Employee Relations: The International Journal*, vol. 45, no. 1, pp. 172–189, 2022, doi: 10.1108/er-06-2021-0244.

[49] E. G. Margherita and A. M. Braccini, "The impact of Industry 4.0 technologies and the soft side of TQM on organisational performance: a multiple case study analysis on manufacturing organisations," *The TQM Journal*, vol. 36, no. 3, pp. 812–831, 2022, doi: 10.1108/tqm-01-2022-0022.

[50] B. Nitsche, J. Brands, H. Treiblmaier, and J. Gebhardt, "The impact of multiagent systems on autonomous production and supply chain networks: use cases, barriers and contributions to logistics network resilience," *Supply Chain Management: An International Journal*, vol. 28, no. 5, pp. 894–908, 2023, doi: 10.1108/scm-07-2022-0282.