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MANUFACTURING INTRALOGISTICS CONCEPTS FOR A BATTERY ASSEMBLY LINE

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ABSTRACT

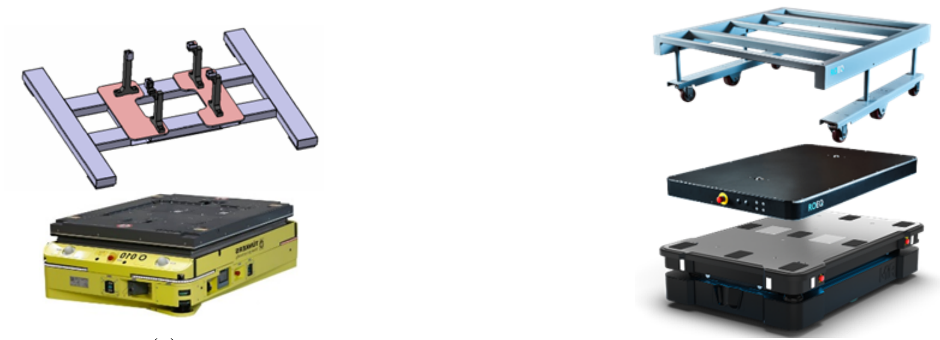
This paper designs intralogistics concepts for an electrical battery pack production setup inspired by our industry partner, featuring automated and manual workstations. In accordance with the principles of Industry 4.0, autonomous mobile robots (AMRs) and automated guided vehicles (AGVs) are employed to carry out material supply and product transportation, respectively. The complexity rises due to the interdependencies among production, material supply, and product transportation. The proposed intralogistics concepts aim to optimize throughput while utilizing AGVs and AMRs efficiently. Using real-world data from the industry partner, the efficacy of these concepts is shown via simulation across varying fleet sizes and product types, with extendable implications for high-mix-low-volume production and autonomous manufacturing systems.

1 INTRODUCTION

European governments, in alignment with the Green Deal and Fit for 55, aim to reduce greenhouse gas emissions, with transportation accounting for 12% of total emissions in the Netherlands (Olivier and Peters 2017). This drive necessitates a transition to electric vehicles across industries, including maritime and scooters. As a result, vehicle manufacturers seek a stable supply of batteries, considering the emerging battery market's limited players. Some consider producing batteries in-house to mitigate supply risks and potentially increase profits by selling excess batteries. However, designing an efficient battery assembly line, including intralogistics activities, using automated material handling devices, to manufacture various types of batteries is challenging due to the interdependency between manufacturing and material/product transport operations. VDL Nedcar, a Dutch vehicle manufacturer and partner in the Green Transport Delta ÍC Electrification collaboration, faces this challenge. This research originates from their need to assess the impact of various intralogistics concepts on battery assembly line performance.

Within this collaboration, a demo line for battery assembly (BDL) is constructed at VDL Nedcar. Materials to produce battery packs are supplied to the workstations by autonomous mobile robots (AMRs), while products are transported between the workstations using automated guided vehicles (AGVs). Figures 1a and 1b represent AGVs and AMRs with their carriage supports, skid, and scart, used in product and material transportation, respectively. Both AGVs and AMRs have limitations concerning loading capacity, speed, and battery life. In addition, different product types, i.e., different product flows and process times, at each workstation may affect intralogistics decisions. It can be even more challenging in high-mix-low-volume (HMLV) industries, where many product types at low volume are made. Therefore, defining the number of AGVs and AMRs and their ways of working, i.e., intralogistics concepts, under various products and practical constraints, is one of the key factors influencing the system efficiency, i.e., throughput rate and vehicle utilization. In light of these challenges, our paper focuses on intralogistics concepts for AGVs in this new manufacturing setting, and their efficiencies with regard to the fleet sizes of AGVs and AMRs.

We survey related works in the literature to have best practices in similar manufacturing environments. First, the main player in the BDL, AGVs, is reviewed. They are path-guided vehicles that can carry products or materials on predefined paths, i.e., marked grid lines. AGVs are the key factor that can make decisions favoring flexibility in production; therefore, they have been used widely in the last decade (De Ryck et al.



(a) (b)

Figure 1: Smart robots at VDL Nedcar (a) AGV + skid and (b) AMR + scart.

2020). Bilge and Ulusoy (1995) are among the first that consider the use of AGVs in simultaneous machine scheduling and material handling. Fontes and Homayouni (2019) and Rahman and Nielsen (2019) are other studies considering the use of AGVs in intralogistics. Some common objectives are minimizing the makespan, maximizing the throughput rate, and looking for the required number of vehicles within the system. Recently, AGVs have been used together with digital twin applications. Lichtenstern and Kerber (2022) propose a data-based digital twin system including AGVs and different network topologies for the production floor to achieve a target throughput rate via simulation modeling.

In addition to AGVs, AMRs are more recently used autonomous robots, particularly in intralogistics operations (Fragapane et al. 2021). Unlike the AGVs, older autonomous robots, the AMRs have free space navigation systems that enable them to move in areas without marked grid lines, bringing more flexibility to the production. With the AMRs, transport operations take place at a non-constant pace. Similar to AGVs, AMRs are also employed in product transport. Draganjac et al. (2020) simulate multiple AMRs in a free space environment surrounded by obstacles to see the effect of efficient traffic management on the throughput rate in a job shop production environment. In addition, AMRs are widely used in warehousing operations at narrow aisles because of their more intelligent properties and better collaborations with humans. Selmair et al. (2022) is a recent paper focusing on efficient AMR fleet utilization in a real manufacturing environment. AMRs are modeled via simulation to feed multiple assembly lines by carrying materials from the warehouse to the product shop floor.

Although the combination of automated material supply, product transport, and manufacturing process is gaining momentum, the literature is still scarce. The existing works only consider two out of the three features. Also, the use of AMRs, i.e., free-space navigated vehicles, in intralogistics is limited. Addressing these gaps, our study introduces a new manufacturing setting that considers all the three mentioned features. The main contributions of our paper are as follows: (i) we develop a simulation model to imitate this new manufacturing setting with the interdependence among material supply, product transport, and assembly processes involving human operators and robot arms; (ii) we propose two intralogistics concepts for AGVs to behave during the processing of their carried product at a workstation; and (iii) our results, including the AGV and AMR fleet sizes, their utilization, and hourly throughput rates, obtained through simulation based on a real case study, provide managerial insights to the field of manufacturing logistics and autonomous systems. These results can be extendable through the HMLV industry with similar product characteristics.

The remainder of this paper is organized as follows. Section 2 describes the new manufacturing setting considered in our study. Section 3 then presents the solution methodology and the case study. In Section 4, the experimental setups and their results are discussed. Finally, conclusions and future research are given in Section 5.

2 SYSTEM DESCRIPTION

A shop floor that includes workstations, charging and preparation stations, and a warehouse is represented in Figure 2. Each workstation can be operated by human operators (manual workstations) and/or robot arms (semi-automated or automated workstations). This can accommodate various layout types, e.g., flow shop or job shop. The warehouse stores materials and tools needed for assembly, as well as finished products. Also, AGVs are responsible for transporting products from the preparation station to the assembly line, between the workstations within the line, and from the line to the warehouse (which all are depicted by the dashed arrows in the left of Figure 2). On the other hand, AMRs carry materials and tooling scarts/trolleys to supply the assembly line (represented by the solid arrow). Lastly, the shop floor also contains charging stations for charging activities of AGVs and AMRs due to their limited battery capacity.

In this system, we consider three types of tasks, which are assembly, product transport, and material supply. For the assembly tasks, each product will be assembled without interruption at different (manual, automated, or semi-automated) workstations for a certain processing time. The production sequences of the products may vary, depending on the product types. The assembly line operates as a pull system, allowing the current workstation to forward its product if the downstream one is free. Consequently, another product can only enter the line if its first workstation is not occupied.

The next type of task involves transporting products. The AGVs transport products between workstations upon request, creating a flexible assembly line. These tasks are reliant on the completion of the assembly tasks. Once a process finishes at a workstation, i.e., a product needs to leave that workstation, a new transport task is created. Each product transport task has a starting node (source) and an end node (destination). The nearest available AGV to the source is then assigned to carry out this task. Since AGVs follow predefined paths, the distance between two nodes is measured using the Manhattan distance. The average travel time for each path in a product transport task is calculated by dividing the total distance between two nodes by the AGV speed. Each AGV can handle one product transport task at a time. Each AGV also spends certain time units for loading and unloading at a workstation upon arrival and before departure, respectively.

The third type of task involves supplying materials, which is handled by AMRs. Each workstation has designated parking spots for AMRs, serving as pick-up or delivery points for material supply tasks. These spots are identified as both source and destination nodes. When a material supply task is requested, the nearest available AMR is allocated to perform this task. These material supply tasks depend on the assembly and product transport tasks, and vice versa. When an AGV arrives at a workstation, the assembly can begin only if there is enough material. On the other hand, the material inventory level at the workstation is checked after each process is complete. If it is lower than a threshold, a new task of the third type is created to return the material scart/trolley to the warehouse. This frees up one of the parking spots before new materials arrive. As AMRs navigate freely, the average travel time for each path in a material supply task is calculated based on the total Euclidean distance divided by the AMR speed. Each AMR can handle

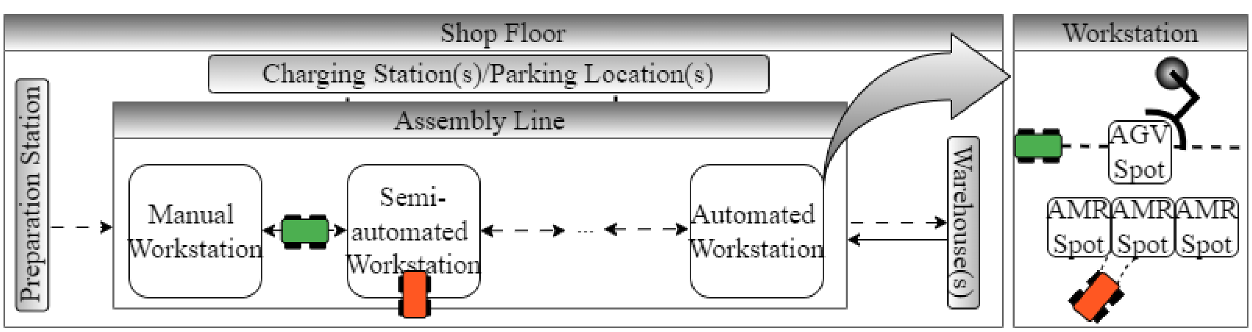


Figure 2: Left: A shop floor representation. Right: A workstation's interiors with the parking spots of (green) AGV and (red) AMRs.

one material supply task at a time. A single product is carried on a scart, while a trolley can accommodate multiple products.

Furthermore, AGVs and AMRs have battery limitations. Each AGV and AMR has a discharge and a recharge rate. If their state of charge (SoC) falls below a minimum threshold, they need to visit a charging station to recharge their battery up to a maximum threshold. These thresholds are predetermined to ensure that the charging station is reachable if needed after completing their current (product transport or material supply) task. This charging request is given priority, which allows the AGV or AMR to head straight to the charging station if the SoC is not sufficient. If no pending tasks exist, each vehicle heads to a parking location. In addition, they are equipped to detect obstacles and navigate around them, reducing the chances of collisions with other vehicles or objects on the shop floor. If an AGV or an AMR encounters an obstacle, it takes some delay for the AGV to resume its movement or for the AMR to overtake the obstacle.

The system aims to maximize the throughput rate within the planning horizon. This rate is determined by the number of completed products reaching the finished product depot inside the warehouse. We also consider the utilization of the AGV and AMR fleets to achieve a certain efficiency level. Vehicle utilization is determined by dividing the total time each vehicle spends actively operating in the assembly line by the duration of the planning horizon. In addition, during the execution of product transport tasks, AGVs may exhibit various behaviors. We introduce two distinct AGV behaviors, which are detailed as intralogistics concepts in Section 2.1.

2.1 Proposed Concepts

Whenever a product transport task is assigned to an AGV, it comes with two nodes: source (pick-up) and destination nodes. Upon arrival at the destination node, AGV can behave differently during the processing of the carried product at the workstation. At that point, we introduce two different intralogistics concepts, as shown in Figure 3, where AGVs are colored green with circled numbers 1 and 2 (while AMRs are the red carrying either a (yellow) loaded scart/trolley or a (white) empty one).

I. Figure 3a illustrates concept (I). The AGV stays at a workstation with the product until the assembly process is complete. Once the process finishes and the next destination is free, a new product transport task is generated with pick-up and destination locations. Afterward, the AGV starts moving with the product on the loaded skid to the next destination.

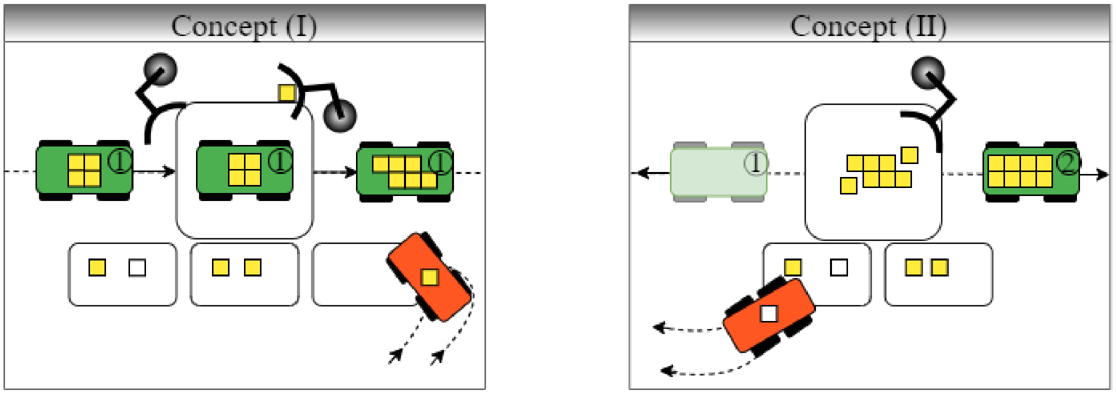
II. Figure 3b presents concept (II). The AGV drops off the loaded skid carrying the product at the destination node and promptly leaves the workstation after unloading. After the product is processed and the next destination in the product flow is free, a new task is created with pick-up and destination locations. An AGV, which may not be the same as the one that brings the product to the workstation, comes to pick up the loaded skid and leaves afterward.

3 METHODOLOGY

In this section, we present a simulation model for the system described in Section 2, in which the proposed intralogistics concepts are implemented as an input function. Simulation is chosen, because it allows capturing uncertainties in our system, for example, arrivals of different product types or delays in AGV or AMR movements when encountering obstacles in their paths. Section 3.1 presents a real case study at VDL Nedcar, while Section 3.2 describes the simulation model in more detail.

3.1 Case Study

The case study reflects the real BDL at VDL Nedcar, and relevant data are provided by our industry partner. The BDL layout can be seen in Figure 4. There are six workstations, in addition to a preparation station and a warehouse containing materials and tools, as well as finished products, which are located at the start



(a) (b)

Figure 3: (a) Concept I: AGV staying at a workstation with a product, (b) Concept II: AGV leaving the workstation after unloading a product.

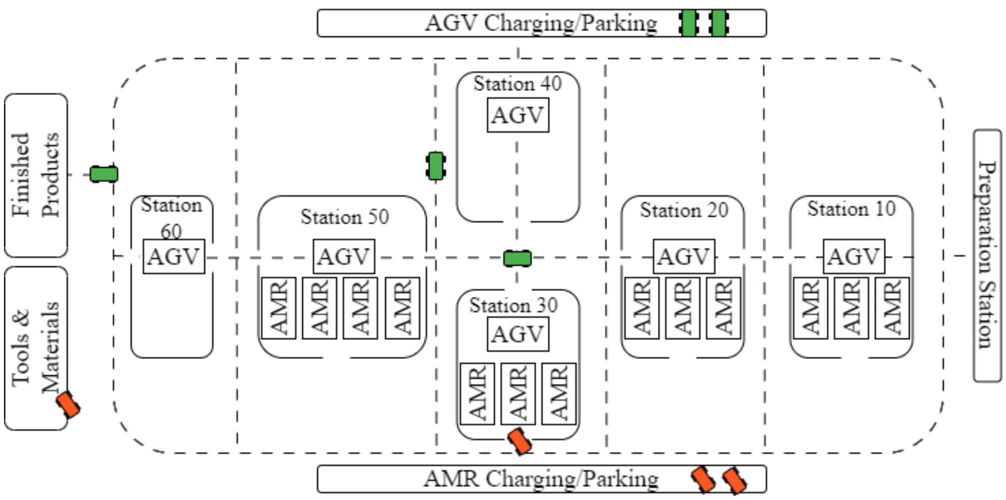
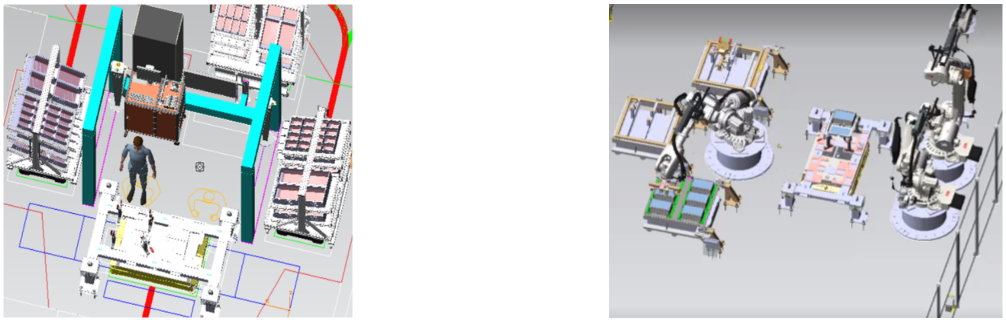


Figure 4: Layout of the BDL.

and end of the BDL. Additionally, the AGV/AMR charging and parking stations are located separately on both sides of the assembly line. The workstations, preparation station, and warehouse (composed of finished product inventory and tools & materials warehouse are connected via bi-directional paths, i.e., dashed lines, which guide AGVs. The other areas are free spaces that only AMRs can navigate. Inside each workstation, there is a single AGV spot to which the product is delivered. Also, multiple AMR spots are located next to operators or robot arms, for material supply (see Figure 5). Manual workstations, e.g., stations 10 and 30, are operated by a human operator surrounded by three material trolleys and a product on the top of the AGV skid (Figure 5a). On the other hand, automated workstations, e.g., stations 20 and 50, are operated by two or three fixed, industrial robot arms (Figure 5b).

We assume there are always work orders at the preparation station. Consequently, station 10 initiates the production whenever it is free. There is no setup time and no priority among different product types. Process times are determined according to the product type and the number of assembled modules in that product. The BDL operates three shifts per day, each 8 hours. For AGVs and AMRs, their parameters are given in Table 1.



(a) (b)

Figure 5: Digital twin of BDL: (a) Stations 10 and 30, (b) Station 20.

Table 1: AGV and AMR parameters.

Parameter	**AGV**	**AMR**
AGV average speed / AMR max speed	1.0 m/s	1.6 m/s
Acceleration rate	-	1.0 m/s^2
Minimum threshold (for recharging)	10%	10%
Maximum threshold (for recharging)	90%	90%
Discharge rate	0.0041 %/s	0.0041 %/s
Recharge rate	0.0363 %/s	0.0363 %/s
Loading / Unloading time	3 s	3 s
AGV delay time / AMR overtaking time (if obstacles)	5 s	5 s

3.2 Simulation Model

We build a simulation model for the described system, hybridizing three simulation perspectives: discrete event modeling (DES), agent-based modeling (ABM), and system dynamics (SD). The model is developed in AnyLogic 8.8.4 (Anylogic 2023). The battery pack assembly, product transport, and material supply tasks are modeled using DES. Every item used in the DES is defined as an agent. Therefore, ABM is used for modeling battery packs, AGVs, AMRs, scarts, trolleys, and charge tasks. Inside the AGV and AMR agents, we used SD to configure the SoC control. The discharge rate of AGV and AMR batteries are used as outflows, whereas the recharge rate is used as inflows to the SoC calculation.

In our model, there are three distinct flows. The first flow involves battery pack and AGV agents, representing the assembly and product transport tasks, which move through various process and transport blocks. After the process block of a workstation is accessed and an assembly task is completed, a material supply task is created, if necessary, for agents such as scarts, trolleys, and AMRs. This task then progresses through transport blocks, constituting the second flow. Lastly, a charging task agent is created, if needed, for an AGV or AMR at the end of a product transport or a material supply , respectively. This flow holds the highest priority among the others, promptly seizing the specified AGV or AMR. The SD mechanisms in the AGV or AMR agents remain active at all times, managed by a *statechart*, and operate in parallel to the movements in other flows.

4 COMPUTATIONAL EXPERIMENTS

We first provide a description of the experimental setups in Section 4.1. We then study and compare the performance of the proposed intralogistics concepts in Section 4.2.

4.1 Experimental Setups

In this paper, we set up two types of experiments; one is a deterministic setup, while the other is a stochastic setup. The deterministic setup is shown in the second column of Table 2. Here, we start with one AGV and one AMR, then gradually increase the fleet sizes up to 9. We also consider only one type of product. We focus on Product Type 1, with the product flow and process times listed in Table 3. The process times in the second column of Table 3 show how long it takes to process the product at the corresponding stations in the third column. For example, Product Type 1 takes 175 s at station 30, which is the third station in the product flow. The performance measures are analyzed in the planning horizon of 10 shifts (i.e., 288 000 s).

For the stochastic setup, as shown in the third column of Table 2, the experiments again start with a single AGV and AMR, gradually increasing to 6 and 5, respectively. Work orders arrive at the preparation station with different product types stochastically generated according to the percentages indicated in the last column of Table 3. Notably, the first and fourth product types are among the most demanded ones at VDL Nedcar. The fourth product in Table 3 revisits station 50 (represented as 50^*), which creates a unique production flow among the others. In order to cope with revisiting, we now consider buffers in stations 30 and 50. In concept (I), buffers are the AGVs themselves, while in concept (II), there is a physical product space at stations 30 and 50. We look at the performance measures, as well as their 95% confident interval, across five replications of a run spanning a monthly production cycle of 20 working days with three shifts per day (i.e., 1 728 000 s). A warm-up period of one week is selected to ensure statistically reliable results, in addition to the carefully chosen run length and number of replications.

All experiments are performed on a computer with an 11^{th} Gen Intel(R) Core(TM) i5-1135G7 CPU @ 2.40 GHz, 16 GB RAM, and Windows 11 operating system.

4.2 Output Analysis

Computational results for the deterministic and stochastic setups are provided in Sections 4.2.1 and 4.2.2, respectively. The hourly throughput rate is observed under intralogistics concepts (I) and (II) and various fleet sizes of AGVs and AMRs. The AGV and AMR utilizations are evaluated to suggest the most effective combination of AGV and AMR fleet sizes while maximizing the throughput rate.

Table 2: Simulation experiment setup.

Factors	**Deterministic Setup**	**Stochastic Setup**
Fleet Size of AGVs	1 - 9	1 - 6
Fleet Size of AMRs	1 - 9	1 - 5
Product Types	1	1 - 5
Intralogistics Concepts	(I), (II)	(I), (II)

Table 3: Product type information.

Product Type	**Process Times (s)**	**Product Flow**	**% Product Type**
1	65.6, 68, 175, 85, 199, 129	10-20-30-40-50-60	0.35
2	65.6, 168, 239, 85, 199, 129	10-20-30-40-50-60	0.10
3	65.6, 193, 260, 85, 199, 129	10-20-30-40-50-60	0.10
4	65.6, 18, 199, 209, 85, 100, 129	10-20-50-30-40-50*-60	0.35
5	65.6, 168, 239, 85, 199, 129	10-20-30-40-50-60	0.10

4.2.1 Deterministic Experiments

We create three-dimensional surface graphs with heat maps to show how different combinations of AGV and AMR fleet sizes, along with intralogistics concepts (I) and (II), affect the performance measures. Figure 6 displays the results in two columns. The first column (Figures 6a, 6c, and 6e) shows results for concept (I), while the other column (Figures 6b, 6d, and 6f) is for concept (II). X, Y, and Z axes represent AGV fleet size, AMR fleet size, and a performance measure (hourly throughput rate or average fleet utilization). The color changes from black to white indicate increasing values. The details of the results can be seen here.

In Figure 6a, increasing the AGV fleet size boosts the hourly throughput rate more than the AMR fleet size does. Notably, having one to two AMRs with fewer than 5 AGVs significantly enhances throughput. Beyond 5 AGVs, adding up to three AMRs significantly increases throughput, but the benefit decreases with more AMRs. Similarly, increasing beyond 6 AGVs leads to diminishing returns in the increment in throughput. AGV utilization generally stays high, reaching or staying close to one when the AGV fleet size is below seven, as seen in Figure 6c. In Figure 6e, AMR utilization tends to be lower than AGV utilization and stays around 0.50 when the fleet size is below three. These results imply that to ensure efficient vehicle use, AGV fleet sizes should ideally be higher, possibly twice as much as the AMR fleet size.

Overall, Figures 6a, 6c, and 6e recommend using an AGV and AMR fleet size of 5 and 3, respectively, for optimal efficiency. This combination is near the white surface and marks the beginning of stability from both perspectives. It achieves a throughput rate of 15.83 with high utilization rates, 0.98 for AGVs and 0.50 for AMRs. Deviating the AGV and AMR fleet sizes by one from this value causes significant decreases in the throughput rate, or does not result in a significant increase. Moreover, both AGV and AMR utilization rates are high but not at their maximum, indicating efficient resource use without overloading the system.

Under concept (II), Figure 6b shows throughput rate increases as fleet sizes grow, similar to concept (I). Nevertheless, the increase is slight. Increasing AGV fleet size has a larger impact on throughput rate than increasing AMR fleet size. Significant increases in throughput rate occur with up to 5 AGVs, but the effect of additional AMRs diminishes beyond three. In Figures 6d and 6f, we see intriguing trends in AGV and AMR utilization. Initially high, both utilization rates decline as fleet sizes increase. AGV utilization drops more rapidly than AMR utilization. When the number of AMRs exceed three, their utilization falls below 0.50, similar to AGV utilization when exceeding three. Towards the end of the surfaces, AGV utilization declines faster than AMR utilization, suggesting AGV fleet size ideally exceeds AMR fleet size. Overall, AGV and AMR fleets are efficiently utilized by up to 3 AGVs and 2 AMRs. Despite the decrease in their utilization beyond these fleet sizes, there are still observable increases in the throughput rate. Hence, based on the neighboring values, we recommend stopping at the fleet sizes of 4 AGVs and 3 AMRs, where the throughput rate is almost 12.

When comparing concepts (I) and (II), several key insights emerge. Firstly, concept (I) outperforms concept (II) consistently once the AGV fleet exceeds three units. This is because increasing the number of AGVs in concept (II) means more assembly operations happen, thus more material supply is needed. This increases the number of AGV and AMR transport activities within the planning horizon, causing more congestion in the assembly line, thus reducing the throughput rate. Hence, we recommend concept (II) for the fleet size of fewer than 4 AGVs. Secondly, concept (I) maintains higher AGV utilization due to continuous engagement in workstations, while concept (II) sees declines as AGVs return to the parking stations after tasks. Thirdly, both concepts show high AMR utilization, especially with smaller AGV fleets, boosting production capacity and material supply. However, expanding beyond 6 AGVs becomes impractical due to the number of workstations. Therefore, we advise against more than 6 AGVs in concept (I) and cautious consideration in concept (II). Finally, when analyzing concept (II), where AGVs are more flexible (i.e., leaving the workstations after unloading products), we observe their inefficient utilization rates, which could imply several limitations on the production processes. Therefore, enhancements for the production processes in the BDL may lead to reduced fleet sizes of both AGVs and AMRs while maintaining the same throughput rate.

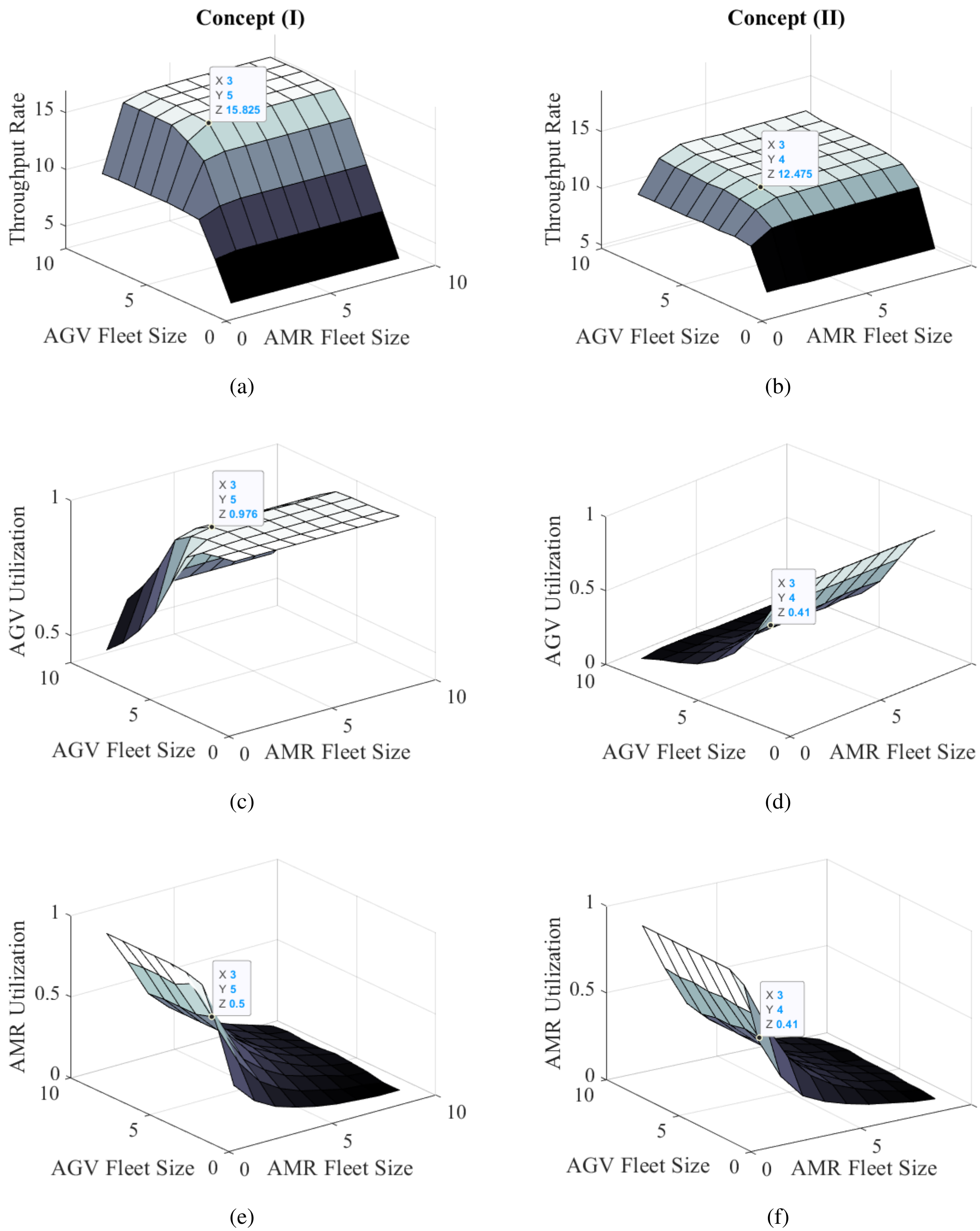


Figure 6: Hourly throughput rate (a) and (b), Average utilization of the AGV fleet (c) and (d), and Average utilization of the AMR fleet (e) and (f), under concepts (I) and (II), respectively.

4.2.2 Stochastic Experiments

Figure 7 displays the means of the performance measures, with 95% confidence intervals, for concepts (I) and (II). In all subfigures of Figure 7, the X-axis represents AMR fleet size, and the Y-axis represents a performance measure (hourly throughput rate or average fleet utilization). Varying line patterns reflects the changes in the AGV fleet size. Figures 7a, 7c, and 7e represent the performance metrics under concept (I), while concept (II) is depicted in Figures 7b, 7d, and 7f. The detailed results of these experiments can be seen here.

Figures 7a and 7b show an increasing trend of mean throughput rates from left to right with larger AMR fleet sizes. Larger AGV fleets consistently produce more throughput, evident by the black solid lines at the top. Notably, changes in the AGV fleet size, from one to four, have a more significant impact on the throughput rate, compared to changes in the AMR fleet size. On the other hand, increasing the AMR fleet size from one to two has a significant effect, particularly when the AGV fleet size exceeds four.

Figures 7c and 7d show a decrease in mean AGV utilization as the AGV fleet size increases across all combinations of the AGV and AMR fleet sizes. For one AGV in Figure 7c, mean utilization is almost 100%, but it drops to around 70% with 6 AGVs. The AGVs are efficiently utilized most of the time, while the AMR utilization is lower and depends on the AGV fleet size (see Figures 7e and 7f). The highest AMR utilization occurs with only one AMR, but it decreases when the AMR fleet size increases. However, under both concepts, from bottom to top, the AMR utilization increases when having more AGVs, because the assembly line works more.

In general, there is no notable change in the mean hourly throughput rate when we move away from the combination of 5 AGVs and 2 AMRs. In Figure 7a, the corresponding confidence interval ranges from 11.40 to 11.51. Across all AGV and AMR combinations, we observe a considerable drop in the average hourly throughput rate compared to the deterministic setup. This decline is due to different product types with longer process times and revisiting needs. The average AGV fleet utilization is moderate, around 0.86 (refer to Figure 7c), while the AMR fleet utilization is relatively lower, around 0.62 (refer to Figure 7e), indicating potential inefficiencies in resource allocation within the assembly line.

4.2.3 Further Discussions

In both setups, increasing fleet sizes result in lower fleet utilization, which indicates workstation bottlenecks. The hourly throughput rate decreases due to longer process times and more stations to visit. Therefore, it is essential to have buffers in place before production begins, particularly at the most heavily demanded workstations, which are stations 30 and 50. Two buffer implementation methods are possible: using AGVs as buffers stationed at designated workstations, or allocating physical space for products to wait with their attached skids. However, careful management is required as buffer capacity is limited. In our experiments, priority is given to the flow with a larger quantity of products. Consequently, for station 50, we allow products from station 40 to arrive first, followed by products from station 20 if available simultaneously. Alongside buffers, the system can be safeguarded from becoming stuck by organizing arrivals of different product types and avoiding mixed production on the line. Implementing batch production, where products are sequenced based on their similar characteristics, could offer a viable solution.

5 CONCLUSION AND FUTURE RESEARCH

This paper presents a new setting that integrates AMRs for material delivery, AGVs for product transportation, and production processes involving humans and robots through simulation modeling with a real case study. This benefits not only our industry partner but also other industries planning to invest in smart production environments with similar characteristics.

Two intralogistics concepts are tested via a simulation model under deterministic and stochastic product variations. Concept (II) achieves higher throughput rates, especially with fewer than 4 AGVs. Nevertheless, AGV utilization remains consistently higher in Concept (I), particularly with fleets of the same size. Both

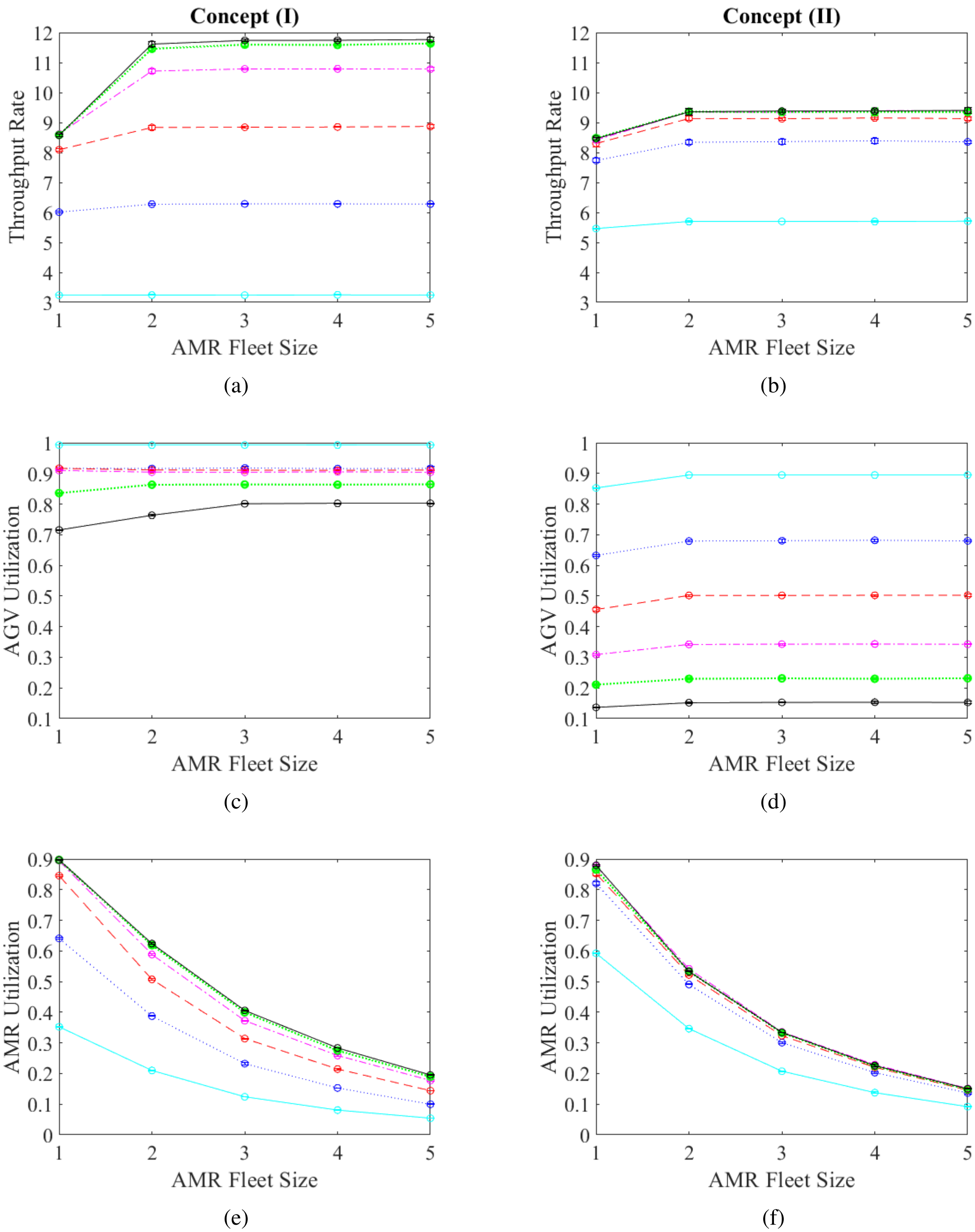


Figure 7: Mean hourly throughput rate (a) and (b), Average utilization of the AGV fleet (c) and (d), and Average utilization of the AMR fleet (e) and (f), under concepts (I) and (II) respectively, with 95% confidence intervals; 1 AGV (—), 2 AGVs (···), 3 AGVs (- - -), 4 AGVs (-·-), 5 AGVs (···), 6 AGVs (—).

concepts increase AMR utilization with smaller AGV fleets, but their impact diminishes beyond certain numbers of AGVs and AMRs. In the stochastic scenarios, throughput rates drop due to longer process times and production flow variations. Buffers, either AGVs or physical spaces, are essential to manage revisits and flow changes. Batching similar products can speed up processes and reduce buffer requirements.

For future research, we plan to extend our experiments to include a hybrid logistics concept where each AGV can choose whether it stays with the product or not based on different conditions, e.g., process times at the workstations. This aims to design smaller fleet sizes that can achieve the same throughput rates.

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