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Artificial Intelligence and Internet of Things Logistics Optimization: Research on Logistics Robot-Based Optimization – A Case Study of the Amazon Model

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Abstract. With the impressive rise in e-commerce, the implementation of artificial intelligence (AI) and Internet of Things (IoT) in automation of the warehouse became faster. Mobile robots may be widespread in warehouses; nevertheless, their effectiveness proves to be unsatisfactory as they cannot navigate and coordinate effectively, namely breakdown between the implement system and Enterprise Resource Planning, Warehouse Management System lead to low performance. To reach the integrative optimization, this paper implement the in depth case study approach, and the analysis of Amazon logistics model was taken. Using a review of technical literature, industry reports, and publicly available performance data, this paper analyzes the application of the artificial intelligence technologies, including AI bot collaboration and path optimization, at Amazon in a manner that is synergistic. The review reveals that this holistic strategy has enabled innovation in major operation data such as throughput, inventory precision, and scalability. Precisely, the combination of AI and IoT with ERP/WMS systems contributes greatly to the responsiveness of the systems, as well as the effectiveness of decision making which results in a tangible change in the inventory accuracy (more than 95 percent), picking efficiency (by up to 40 percent), and space utilization (by 20 percent-35 percent). The research points out that to become optimized logistics in the Industry 4.0 age, it is important to have technological integration and not isolated automation.

Keywords: AI bot, IoT, Amazon, ERP, WMS

1. Introduction

Digitization of the logistics sector is not a technological trend anymore, but a primary necessity of the industry survival and growth. It is projected that E-commerce will increase by 56 percent of retail sales in the United States in 2024, the direct result of which is an enormous need in the logistics space and processing efficiency. Yet, this booming trend has shown the gist behind the inefficiencies of the traditional warehousing systems.

To begin with, the high dependency on traditional manual labor is now a major constraint to scalability. Manual processes are slow and are also subject to errors. There are also empirical data that indicate that the accuracy rate of manual inventory management is sometimes not over 65 without the assistance of intelligence [1]. This is the source of data bias which directly contributes to the failure of order. Second, despite the widespread introduction of autonomous mobile robots AMRs or RFID systems, they tend to be quite an isolated system frequently exhibiting an automation silos behaviour. The greatest impediment in this direction is the inability to connect the oldest robots to the current WMS and ERP systems and therefore prevent the expensive benefits of automated equipment to perform to the theoretical promise [2]. The absence of a single real-time data stream will result in delays in the process of decision-making and, accordingly, does not make the enhanced expensive equipment perform to the theoretical extent.

At present, the fundamental contradiction within e-commerce logistics business is a rapid growth in market demand and an inadequate reaction of operating systems. This study seeks to design a viable integration system through the study of the Amazon Company. The following are the main research questions:

This paper will build a viable system integration architecture through the logistics model of Amazon. Its foundational research material is as below: First, how to create a viable integration platform that would enable a dynamic closed loop between artificial intelligence, the Internet of Things, and core business systems. Second, it evaluates the concrete quantitative gains that artificial intelligence algorithms (reinforcement learning and shortest paths algorithms) can introduce in the solution of multi-robot collaboration problems, path planning problems, and space optimization. Lastly, it assesses the effects of this model of integration to the accuracy of inventory, space use and total operating expenses.

2. Literature review and theoretical foundation

2.1. The evolution of warehousing technology

The history of warehousing technology development has been rather long since Mechanization to Logistics 4.0. The first warehouses were just storage units [3]. The next industrial revolution introduced mechanized machinery like forklift and conveyor belts. Automation starts in the 1950s with the introduction of Automated Storage and Retrieval Systems (AS/RS). The actual change happened, though, during the logistics 4.0 period in the environment of Industry 4.0. The main distinguishing feature of this phase is decentralized decision-making. Cyber-Physical Systems (CPS) in the logistics 4.0 will allow people, machines, logistics, and production to talk directly to each other [4].

2.2. AI application paradigms in logistics

AI use in Supply Chain Management (SCM) has not only increased to isolated automation but also highly predictive tasks. Perception and Computer Vision: Computer vision technology has provided robots with eyes. With the usage of deep learning algorithms like YOLO (You Only Look Once) robots will be able to detect the objects in the real-time. As an illustration, the Sparrow robot of Amazon can selectively pick certain objects among millions of goods of various shapes with the help of a highly developed visual recognition system. Nonetheless, it is hard to occur in conventional robotic arms [3].

Path Planning and Reinforcement Learning: To address the issue of congestion in warehouses with the use of multiple robots, the stasis algorithms introduced by Dijkstra and the A star have been extensively employed in path planning [5,6]. In difficult and overly intricate scenarios, however, Deep Reinforcement Learning (DRL) has been more flexible. DRL enables robots to use the surrounding to obtain strategy that they optimize to avoid issues and optimize path.

2.3. Integration challenges of core business systems: ERP and WMS

ERP systems are the heart of the business where the key processes are coordinated like finance, human resources, and supply chain. The lack of connection between ERP and WMS or robotics is a widespread problem, however. Studies reveal that a sustainable digital factory structure is required to ensure intelligent manufacturing and logistics of the real meaning where intermediate technologies or API interfaces are necessary in order to interconnect the ERP and WMS in a deep fashion. This combination is of great assistance in facilitating data transformation [2].

3. System architecture in the Amazon model

3.1. Hybrid ERP strategy

Amazon has a special type of ERP strategy. Rather than depending on an individual, commercial ERP package (with SAP or Oracle), it integrates the proven commercial systems (finance, HR) with its own (core order fulfillment and warehouse management) [7].

This strategy has benefits as articulated in the three points below. First, its own system is very flexible and can be iterated quickly to fit the specifics of Amazon business, therefore, there are no restrictions of commercial software functionality. Second, the whole architecture is constructed using the AWS cloud platform, which has outstanding scalability and is enough to manage any significant increase in traffic. Lastly, APIs and middleware are used to provide data flow between systems to provide data consistency and continuity across the entire architecture.

3.2. Integrated architecture design

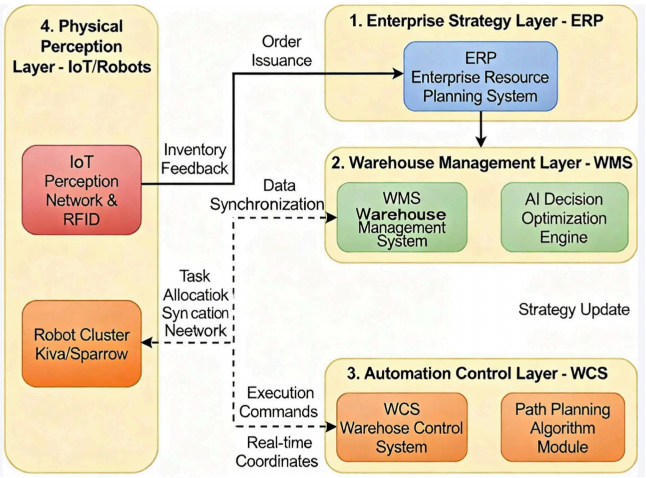

Figure 1. Hybrid ERP process

After observing Figure 1, Amazon has a unique work path, at the downlink control direction, the WMS is activated by the ERP system through a set of API interface and transmits macro-level order data to the system. Then WMS makes decisions with the help of AI, creating accurate instructions of tasks and passing them to the WCS. The WCS then moves forward to computations of the optimal path based on what is called a path planning algorithm module (e.g., like the Dijkstra algorithm or reinforcement learning) and eventually converts it into physical instructions instructed to the robot to execute the path. At the same time, the physical perception layer transmits the real-time status of goods in the uplink feedback system, through the aid of IoT and RFID. This dynamically generated status information is also fed to the W absent of the system, and eventually the link is made back to the ERP system.

3.2.1. Enterprise strategy level: the decision-making hub of the ERP system (level 4)

According to Figure 1, the ERP system not only serves as a back-end management tool, but it is the heart of the whole chain of supply. Goyal clearly states that Amazon has a high level of integration of finance, procurement and sales forecasting and these are made through a hybrid ERP strategy (combinations of SAP/Oracle system). The ERP system will be able to forecast accurately the change in demand and issues by taking historical sales data [7]. It has been observed in literature that the fundamental value of the ERP system is the removal of information silos among the departments. Tong et al. note that with the help of Intermediate Table, ERP can implement the integration of data at high speed with WMS so that purchase orders can be converted into instructions related to inventory [2]. Such a high level of integration enables Amazon to enjoy very large responsiveness in situations where the quantity of SKUs to be processed is high, thus lowering the order processing latency to a great deal [7].

3.2.2. Warehouse management layer: intelligent collaboration of WMS and AI (level 3)

Resource scheduling and optimal logic in the warehouse are the duties of the WMS layer. Conventional WMS can consider only the entry and exit of goods whereas in intelligent warehousing incorporate potent AI engines. The WMS model suggested by Dewy et al. is AI-based [1]. It is concerned with the precision of inventory optimization through the combination of the waterfall approach and design thinking. Experience indicates that the accuracy of inventory in AI-related WMS can be improved significantly by 65% in the case of manual management to more than 95 percent and the ghost inventory can be reduced significantly. Also, Majumder and Nuruzzaman underlined the breakthroughs that AI made into the use of space. The system will be able to dynamically change the position where goods must be stored depending on their rate of turnover and size using smart slot algorithms. This dynamic structure does not only enhance the use of warehouse volumes by 20%-35% but also reduces the mean travel of the robots by achieving the transformation of the static warehouse to dynamic mobility [8]. Warehouse Management Systems that are traditional are more of a record-keeping system, whereas in smart warehousing must transform into an active decision-making engine. According to the study conducted by Dewy et al. which makes it clear that modern WMS not only optimizes the inventory accuracy but also introduces intelligent chatbots as a human-computer interaction interface, enabling the operators to request the real-time inventory status in the form of natural language [1]. Moreover, to resolve the problem of data silo between the ERP and WMS, Tong et altroses a data integration technology based on Intermediate Tables. This technology creates a buffer area in the real practice of the ERP and WMS, which guarantees the standardization of business logic and data uniformity [2].

3.2.3. Automation control layer: path planning and algorithm logic (level 2)

The layer of WCS is an important interface between the digital instructions and the physical actions. Path planning is the main ingredient in robot collaboration situations to avoid congestion. Lila notes that Amazon makes a large number of calls to shortest path algorithms (including the Dijkstra algorithm) to find optimal routes for robots in real time so that they can navigate around each other in a problem context where thousands of AMRs are moving simultaneously [6]. Elnady and Ozana go even deeper to discuss the extensive use of reinforcement learning in this level. RL can develop dynamic strategies with the help of continuous interaction with the surroundings and enables the robots to realize adaptive navigation, in comparison to preset paths. The algorithm is not only capable of increasing the working efficiency of a particular robot but also realizes the traffic control and dynamic scheduling of the multi-agent systems with a 15 per cent to 45 per cent order cycle time reduction.

3.2.4. Physical sensing layer: IoT and robotic execution (level 1)

Samanya explained how robots (e.g. Amazon Kiva, Proteus) put the human to goods model to the goods to person model and thus pick items even more efficiently (about 40 percent better) [3]. IoT serves as endings of this layer. In their study of Warehouse 4.0, Alzandy et al. discovered that RFID, real-time sensors, and computer vision (CV) allowed achieving real-time warehouse transparency [9]. In one instance, the interactive dialogue AI application in the example provided by Manolescu et al. stated that the interactive dialogue AI can be used not only to allow operators to interact with the IoT devices using natural language, but to reduce the hurdles faced by human operators [10]. These IoT devices constantly send data to the upper-level system on their location, status, and environmental state and create a closed loop [8].

To solve the problem of latency of cloud-based in decision-making, the edge AI is added to the system architecture. In line with the architectural design presented by Kalathil, lightweight machine learning models are run on the gateway or on the AMR robot itself [11]. This implies that the robot will be able to respond to dynamic obstacles in milliseconds without responding to cloud commands. This decentralized intelligence minimizes a significant level of the network load.

4. Core algorithms and technical implementation

Millions of Kiva robots must work in simultaneous collusion mode at Amazon fulfillment centers. It is not only a navigation issue, but a multi-agent coordination issue. Shortest path algorithm, the system is based on an adaptation of the A* algorithm by Dijkstra to compute the globally optimal path of the robot.

The basic formula is as follows

$$d\,[v] = \min(d\,[v], d\,[u] + w\,(u, v))$$

d[v] is the distance from the starting point to node v, and w (u, v) is the weight (distance or time cost) from node u to v [6].

Hybrid Algorithm Architecture, to solve the issues that the traditional algorithm has (this includes packages being dropping down or robots malfunctioning temporarily), the A*-RL Fusion algorithm was implemented. It is a technique that applies the A* algorithm to the global optimal path search and, at the same time, further uses the reinforcement learning (RL) approach to address the local dynamic obstacle avoidance. As it was found, this mixed solution may cut the replanning latency by half [5]. To solve the problem of a communication bottleneck in the context of multi-robot cooperation, a decentralized coordination mechanism with the help of GNNs was introduced. GNNs enable robots to take decisions through learning the topological relations in the surrounding. The GNN-assisted Proximal Policy Optimization (PPO) algorithm has 40 times faster replanning speed in comparison with traditional methods [5].

4.1. Intelligent grasping and perception: 6D pose estimation and contact point optimization

6D Pose estimates 6D Pose Estimation although traditional YOLO models cost-effectively offer 2D bounding boxes, as shown above, these are not sufficient to supply robotic arms with guidance in complex robotic grasp actions. Current systems combine RGB-D sensors with 6D pose estimation algorithms (e.g. Dense Fusion or Point Net++) that allow robots to cognize depth and spatial orientation of objects. At the grasping stage, Contact-GraspNet are used in the process of Contact-Point Optimization. The model is not based on established object CAD models and instead analyzes cloud data with the aim of forecasting the best point. When handling novel objects. The success rate of grasping with this method is up to 95% [5].

4.2. Task scheduling and swarm intelligence

Task assignment in the case when thousands of robots are working at the same time is an archetypical NP-hard problem. To solve the deadlock and congestion problems in large-scale fleets, a system, from one side, uses Enhanced Ant Colony Optimization (ACO), called Metaheuristic Algorithm. This algorithm makes use of virtual pheromones that are made by RFID to ensure that congested routes are marked to be avoided by the ensuing robots. This approach has been proven empirically to decrease the rate of deadlock by 62 percent [5]. Congestion-Aware MARL is applied to optimization of task allocation at real-time based on dynamic changes in the order priorities, named Multi-Agent Reinforcement Learning (MARL). MARL than the classical heuristic scheduling can forecast upcoming congestion using real-time traffic heatmap, and consequently, significantly enhances the total throughput by 30 per cent [5].

4.3. Intelligent slotting & demand awareness

Conventional fixed slotting techniques result in the duplication of space and efficiency wastage. Dynamic Slotting Optimization, calathi notes that on combining real-time SCADA system data it is possible to use AI models to examine prior order data, sales velocity, and seasonality curves [11]. According to the algorithm, the suggestion is to locate high turnover SKUs immediately before the packing station and slow-moving categories in high-density storage. Demand-Sensitive Resource Assignment. When demand is surged on a large-scale sales occasion such as Black Friday, AI models can forecast recent increases in demand and cause the WCS system to act. To illustrate, forecasted hot-selling products can be pre-staged to more convenient places by the system and this saves the picking time per order by 10%.

5. Performance evaluation and empirical analysis

5.1. Inventory accuracy

Manual inventory count is based on time consuming labor, and it is also inaccurate. With the implementation of automated system of tracking according to RFID and IoT, the precision of the established inventory records has increased to 95 to 100 percent or even higher whereas in the manual mode, this is 70 percent. The Ghost Inventory is eliminated using real-time data synchronization and removes any difference between the system data and the physical inventory cable of eliminating sales loss because of stockouts, the input error rate becomes 85 percent less [9]. A fundamental indicator of WMS system is inventory accuracy. As a result of a study by Dewy et al, the computing of Inventory Record Accuracy (IRA) will no longer be a manual sampling with the introduction of AI-assisted automated inventory counting.

This calculation formula is given below:

$$IRA = \left(\frac{Number\ of\ Correct\ Records}{Number\ of\ Records\ Checked} \right) \times 100\%$$

In this case, IRA will be the accuracy rate of inventory records; this will be numerator or number of correctly noted items and will be denominated by the number of records reviewed. This formula examines the accuracy of information in the warehouse management system through statistical comparisons of the records in the system and the real inventory. To measure the accuracy of the inventory records, the Inventory Record Accuracy Ratio (IRA) is an appropriate measure of it and its method of calculation is presented in formula (1). The empirical study made RFID and AI verification systems to continuously advance the IRA to an unstable position in the manual mode (as low as 23.05%), all the way to the ideal matching rate of 100% by removing the ghost inventory caused by a mistake in human input [1].

5.2. Operational efficiency and throughput

Selecting Efficiency, robots have replaced the jobs that were performed by human beings. The outcomes reveal that the picking efficiency has been boosted by around 40 percent due to the same. This implies that the warehouse can place many orders within the same time frame [9].

The Automated system of task distribution, Cycle Time, has the capability to generate order prioritization in real-time. Extensive studies show that this minimizes the total order cycle time (time between ordering a product and receiving it) by 15-45% [8].

5.3. Space utilization

The volumetric space utilization rate in the warehouse has increased by 20%-35 through reallocating slots intelligently and adaptively through AI algorithms. This is especially essential in downtown micro-satisfaction centers were Moreover, AI may decrease unused spaces. This can be managed by an AI system that detects areas of the warehouse that are not used (accessed very rarely) and can be removed to make the warehouse layout more effective.

5.4. Cost-benefit analysis

The initial investment (CapEx) is also high, though the decrease of its offices operating costs (OpEx) is enormous. Regarding the labor cost, automation will result in less low skilled handling employees that need to be employed thus leading to a reduction of labor shortages and reduced labor costs. AI-driven predictive maintenance can predict failures of equipment. As an example, Penske applied an AI system to save 30 percent on maintenance costs and greatly lowered the necessary time to deal with unexpected vehicle/equipment downtime [12].

Table 1. Tradition modes and automation mode

KPI	Traditional manual/semi-automatic modes	AI-driven automation mode	Increase
Inventory accuracy	65% - 70%	95% - 99%	+30%
Picking efficiency	benchmark value	Increase 40%	+40%
Space utilization	benchmark value	Increase 20% - 35%	+20~35%
Order accuracy	93% - 95%	98%	+5%
Data input error	8-10times/month	1-2times/month	Decrase 85%

Table 1 also indicates that AI is a serious savings to the asset management costs. Kalathil underlined causal maintenance on the premises of the SCADA information. With the help of AI models, it is possible to identify anomalies (like the bearing fatigue) several weeks before physical breakdowns happen by analysis of the frequency of vibration and current of a conveyor belt or an AGV [11].

This reactive to predictive maintenance does not just minimize the heavy SLA fines in case of unexpected downtimes, but also maximizes maintenance labor scheduling when the business is at its lowest ebb, inherently lowering the growth of the operating expenses (OpEX).

6. Conclusion

The paper blends both literature and empirical evidence to establish that one of the key features of the contemporary logistics change is deep integration of AI, IoT and core management systems (ERP/WMS). Integration is the hallmark, the success of Amazon is not only based on its robots but also the fact that it has developed a closed-loop data system that considers the entire value chain starting with ERP and ending with the final consumer robots. This integration does away with information silos and allows real time decision making. Measurable hooks matter: AI technology brings quantifiable and substantial returns be it through the more accurate inventory (>95%), more effective use of the space (+35%) or better Picks (+40%).

In the case of logistics companies who want to gain a competitive advantage, this technological transformation must be reinforced, no longer a choice, but compulsory. With the construction of smart infrastructure companies are also able not only to proceed to enhance the efficiency of present operations, but also to create resilience to future uncertainties in the supply chain. Moreover, the efficiency will not be the only concern of future research, as the significance of energy sustainability will be touched upon by using vehicle-to-grid (V2G) technology.

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